SPECTRUM REQUIREMENTS FOR DEDICATED SHORT RANGE COMMUNICATIONS (DSRC)

Public Safety and Commercial Applications

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Federal Highway Administration
Turner-Fairbank Research Center
6300 Georgetown Pike
McLean, Virginia 22101

by

ARINC
2551 Riva Road
Annapolis, Maryland 21401
and
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332-0821

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LIST OF ACRONYMS

AEI - Automatic Equipment Identification
AGC - Automatic Gain Control
AHS - Automated Highway System
ASK - Amplitude Shift Keyed
CRC - Cyclic Redundancy Check
CVO - Commercial Vehicle Operations
CW - Continuous wave
DSRC - Dedicated Short Range Communications
EIRP - Effective Isotropic Radiated Power
ELP - Electronic License Plate
ETC - Electronic toll collection
ETTM - Electronic Toll & Traffic Management
FCC - Federal Communications Commission
FHWA - Federal Highway Administration
GaAs - Gallium arsenide
HAR - Highway Advisory Radio
IR - Infrared
ISM - Industrial, Scientific and Medical
ISP - Information service provider
ITS - Intelligent Transportation System
LMS - Location and Monitoring Service
NTIA - National Telecommunications and Information Administration
OOK - On/Off Keying
RF - Radio frequency
RFID - Radio Frequency Identification
RTTT - Road Traffic and Transport Telematics
TDMA - Time division multiple access
TIRS - Transportation Infrastructure Radio Services
TMC - Traffic Management Centers
WIM - Weigh in motion

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1.0 INTRODUCTION

This is the third in a sequence of papers that present the factors involved in identifying the radio frequency spectrum required for both current and future DSRC operations. Since the proposed applications, signal characteristics and channel allocation have been evolving over the course of the spectrum requirement analysis these papers have represented the information available at the time of printing. The first paper was titled "Spectrum Requirements for Vehicle To Roadside Communications (VRC)," dated October 1995, and discussed the basic requirement to have a sufficient number of channels and spectrum available to accommodate all the potential applications of this communications method. The second paper was titled, "Updated Spectrum Requirements for Dedicated Short Range Communications formerly Vehicle To Roadside Communications (VRC)," dated March 1996, and added more detail on the interference potential between applications and an environmental perspective. This current paper presents more information on applications, additional considerations in channel assignments, a change in potential signal characteristics, more information on channel bandwidth calculations and information on channel reuse distances. The development of the expectations for this communications area has matured sufficiently that this paper presents a firm estimate for DSRC spectrum requirements.

1.1 Intelligent Transportation Systems

The Intelligent Transportation Systems (ITS) will reflect the result of using advanced and emerging technologies in such fields as information processing, communications, control, and electronics on our U.S. intermodal transportation infrastructure to improve the safety and increase the efficiency of the current transportation system. The goals of ITS are to reduce energy use, increase economic productivity, increase public mobility, and encourage the application of new technologies to initiate new industries. [l]

1.2 Dedicated Short Range Communications

1.2.1 Purpose and Description

1.2.1.1 Purpose

A critical component of the ITS is dedicated short range communications (DSRC) and the applications that use this communications method. Each DSRC application, when used, occupies some specific bandwidth within the electromagnetic spectrum. This paper presents a discussion of the radio frequency (RF) bandwidth required for implementation of all of the currently proposed DSRC applications. It also explains how that bandwidth relates to a request for allocation of a portion of the managed RF spectrum.

1.2.1.2 DSRC Description

DSRC consists of short-range communications devices that are capable of transferring high rates of data over an air interface between mobile or stationary vehicles and normally stationary devices that are mounted to structures along the roadway or are hand-held [2,3] There are several methods that are currently being used to accomplish this communication including optical beacons, spread spectrum radio, infrared (IR) beacons, and RF beacons. The paragraphs that follow describe typical current applications of these technologies; they do not necessarily present the maximum capability of each technology, for example in other than highway applications.

1.2.2 Optical Beacon Description

Optical beacon technology is currently being used only for traffic signal preemption and priority. Optical beacon technology consists of three basic elements: an optical emitter, an optical detector, and a phase selector that is usually connected to a traffic signal controller. The optical emitter produces high intensity encoded optical pulses and is mounted on an emergency vehicle. The optical detector receives the pulses and sends the corresponding electrical signals to the phase selector. The phase detector discriminates between valid emitter signals and other sources of optical energy and sends signals to the traffic signal controller to activate the desired green signal for the emergency vehicle. The optical beacon is capable of communicating the vehicle presence, category, three digit ID number and an activation range setting.

Optical signal preemption and priority systems are currently being used for emergency vehicles in some locations where fog and dense rain are unusual occurrences, line-of-sight is not a problem, but technician RF licensing is a concern. A high data rate is not required in these applications and they are used where a range of up to 2500 feet is desired. The qualifications for application of an optical preemption system are listed below:

- The vehicles are used to respond to emergency situations or operate in the mass transit system;
- The number of vehicles is small;
- The vehicles are not expected to leave the area to use other DSRC systems; and
- The environmental conditions are favorable.

For those applications that are peculiar to emergency and transit vehicles and meet the above listed conditions the optical systems have been installed as acceptable priority control equipment. However, it is not designed to transmit a high data rates and only transmits one way, so it is not a system that can implement two way high data rate applications.

1.2.3 Spread Spectrum Radio Description

Spread spectrum technology is currently being used for traffic signal preemption and priority. It consists of two groups of elements: a transmitter, compass, and vehicle antenna; and a detector antenna and receiver module. The transmitter and compass are mounted in the emergency vehicle. The compass provides directional information to be transmitted to the traffic controller. The vehicle antenna is mounted on the roof of the emergency vehicle. The detector antenna is mounted on the traffic signal support device, receives RF signals, and sends them to the receiver module. The receiver module is connected to the traffic signal controller. It decodes the signal and sends requests to the traffic signal controller to activate the desired green signal for the emergency vehicle. Data rates of up to 256 Kbits/sec can be achieved in the 902 to 928 MHz band and ranges of 3000 feet and greater are typical.

Spread spectrum radio signal preemption and priority systems are currently being used for emergency vehicles in some locations where all weather operation is desired; line-of-sight could be a problem, but technician RF licensing is not a concern. A high data rate is not required in this application, and it is used where a range of 3000 feet or more is desired. Although a high data rate is not required in the signal preemption application, some equipment types are capable of transmitting up to 256 Kbits/sec in the 902 to 928 MHz band and more at higher frequencies; however, for high data transmission rates, expensive transceivers are required on both sides of the link. Therefore, since it may be too expensive for some other applications, it would probably not be economical to use this technology for all applications.

1.2.4 IR Beacon Description

Typical IR beacon technology consists of three basic elements: an infrared transceiver, beacon head, and a beacon controller. The IR transceiver, which is part of the in-vehicle unit, receives data from the beacon head in the down link signal, and replies with its own encoded IR uplink signal. It is usually mounted in the vehicle behind the windshield. The beacon head is usually mounted on the traffic signal support pole, mast or wire. Its function is to transmit the encoded IR signal to the in-vehicle unit and receive the uplink from the in-vehicle unit. The beacon controller is connected to the beacon head by a wire link through which it establishes the timing and protocol of the data output, sends the data to be transmitted, and collects the information received from the in-vehicle unit. The beacon controller is also connected to the application computer from which it collects data to be sent, and to which it sends the data collected. The data rates are 500 Kbits/sec downlink and 125 Kbits/sec uplink. The range is about 197 to 262 feet (60 to 80 meters).

Infrared beacons have been used to demonstrate toll collection capability, are being used for traffic information and route guidance, and could be used for transit vehicle data upload. IR systems are being used in Europe, Japan and in a demonstration system in the United States for traveler information systems and route guidance. However, the IR beacon is not currently being widely deployed in the United States. If the IR beacon were used as an alternative DSRC system in places where nationwide interoperability would not be required, it could be used for a community specific local traffic information and route guidance system. It could also be used in those applications, such as transit vehicle data upload, where the vehicle type is specifically designed for the application, the number of vehicles is relatively small, and the vehicles are not expected to leave the area to use other DSRC systems.

1.2.5 Safety Warning System™ and the Safety Alert™ Traffic Warning System

The Safety Warning System™ and the Safety Alert™ Traffic Warning System are being developed to provide advance warning of hazards on the roadway. These warning systems consist of a small radar frequency transmitter and a radar detector. The radar detector is similar to the familiar equipment used to detect police radar activations. The radar frequency transmitter would be attached to hazard signs or other equipment and broadcast a code on a 24 GHz carrier that the radar detector could use to either activate on, or decode and display a message. The radar transmitter is expected to be an inexpensive device compared to an RF beacon, but the radar detector would cost more than the ordinary RF tag.

This system is a one-way communication device that sends warnings of railroad crossings, school zones, fog, and other hazards to vehicles with radar detectors. It serves the function of providing position-related hazard information. It can not be used for applications requiring two-way communication.

These systems are a positive first step in the direction of enhancing the traffic warning capability by using electronics. However, these systems currently have a limitation that is applicable to nationwide deployment. Radar detectors are not allowed by law in several states. This will, unless the laws are changed, limit the deployment of these devices.

1.2.6 RF Beacon Description

RF beacon technology consists of three basic elements: a transponder (tag), transceiver (reader), and transceiver antenna (beacon). But this delineation is not always clearly observable as some configurations combine the transceiver and the antenna into one unit and call it a beacon. The tag is also capable of being divided into an antenna and an electronics package. The tag is a processor-controlled data transfer device (read only) or low-power transceiver (read-write) that stores data. Some tags are designed to be mounted on the inside of the vehicle (i.e., windshield or dash), some are designed to be mounted on the outside of the vehicle (i.e., trailer door), and others may have the antenna located outside of the vehicle (i.e., on the windshield, license plate, or bumper), with the electronics mounted inside the vehicle body. The tag responds to communications sessions initiated by the reader.

The reader is a transceiver with a more powerful processor and transmitter than the tag. The reader controls all communications sessions and is usually installed in a cabinet alongside the roadway with the antenna mounted on a structure overlooking the roadway. Reader antennas can also be incorporated into existing traffic signs to minimize the need for additional roadside structures (improve safety) and to camouflage the antennas (minimize vandalism). In addition, readers are made in portable and handheld versions. Portable readers would be used in applications such as portable signs and handheld readers could be used by vehicle inspection personnel.

Two basic designs of RF tags-active and backscatter-are currently in use. The active design transmits a return signal, while the backscatter type reflects and modulates the reader signal. Active tags have a longer range than the backscatter designs given the same reader antenna output power. However, the active tag would need a complicated transmitter to transmit at different frequencies. Therefore, it would need to be larger, cost more and use more power than similarly capable backscatter tags. The backscatter tag has the ability to respond to different frequencies that the reader may use without requiring more circuitry and packaging space. In addition, backscatter tags usually cost less than active tags. Backscatter tags are available in two types: semi-active and passive. The semi-active tag contains a battery or can be connected to the vehicle power supply to provide operational power for the processor, memory and modulation circuits. But it does not use power to transmit RF energy, it only reflects the beacon's signal. The passive tag receives all of its power from the beacon signal. The specifications for several RF Beacon systems are listed in Appendix A.

The capabilities of the tags are indicated by four types, as listed below:

Type I - read-only, limited permanent storage (128 - 256 bits), and usually passive backscatter design;
Type II - read/write, substantial programmable memory (512 bits - 16 Mbits), and active or semi-active design;
Type III - read/write, substantial programmable memory (512 bits - 16 Mbits), active or semi-active design, user interface (lights, sound, display), and an interface to an on-board computer or smart card reader; and
Type IV - read/write, substantial programmable memory (5 12 bits - 16 Mbits), active or semi-active, user interface (lights, sound, display), integral smart card reader, and an interface to an on-board computer.

Currently, both active and backscatter RF tag types are used to implement the different DSRC applications. For example, in open road information transfer, where two or more vehicles are communicating and a substantial line-of-sight distance is desired, the active type would require less reader output power and would be less subject to interference. The interference improvement results from the higher signal output of the active tag. This allows the reader receiver sensitivity to be much less than the backscatter tag and therefore less susceptible to other signals.

However, where precise location is required with only one vehicle at a time, the backscatter system would require less power from the tag, cost less, and be more compatible with small separation distances between applications. The backscatter system can also perform open road information transfers at distances approaching 100 feet. Therefore, both the Federal Highway Administration (FHWA) ITS Architecture Team and the Intelligent Transportation Society of America CVO (Commercial Vehicle Operations) Technical Committee support the use of both types of tags. However, a primary incentive to rapid DSRC implementation is the development of national DSRC interoperability that is most cost-effective for the public. As more experience is gained with DSRC applications, a single tag type that supports the interoperability requirement, in a cost-effective way, is expected to emerge,

1.2.7 Communications Technology Focus

Optical beacons, IR beacons, spread spectrum radio, the Safety Warning System™, the Safety Alert™ Traffic Warning System, and RF beacons each have characteristic advantages and disadvantages that encourage their use in particular circumstances. However, customer utilization, and economic, management, and manufacturing efficiencies can be gained from developing a standard system for common applications. The applications where standardization is of most concern involve the private vehicle system and the commercial vehicle system. Representatives from some vehicle manufacturers have said that the in-vehicle DSRC component will have a very low chance of being installed in production vehicles by the manufacturer until the communications interface is standardized. The method gaining most acceptance in DSRC for implementing common high data rate ITS applications is the RF beacon.

The RF beacon has several advantages. It can:

- provide two-way communications;
- provide a high data rate that is sufficient for all applications;
- focus on a very small communication zone or communicate with every vehicle on the roadway; and
- operate in all weather conditions.

The in-vehicle unit can be made inexpensively, and comparable systems are available from several manufactures. Therefore, since the RF beacon technology is being used in all the current types of applications and can be used in all of the proposed ITS applications, the following sections of this paper will discuss the considerations for implementing RF beacon technology.

1.3 Bandwidth Requirement Development

The following sections of this paper explain the characteristics of the recommended RF DSRC communication implementation and develop the requirements for the bandwidth to support it. Section Two explains the nature and purpose of the applications being supported. Section Three discusses how the applications use DSRC communications and explains the need for a number of communications channels. Section Three continues by working out a rationale for channel assignment and explains how it is implemented to accomplish the communications requirements. Section Four explains the method used to develop a data rate from the amount of data to be transmitted and the circumstances of the transmission. Section Four also shows the result of the data rate computations, develops a channel data rate, and determines the bandwidth needed to support the DSRC communication requirements. Finally, Section Five explains the current DSRC uses of the RF spectrum, and details the rationale for suggesting a particular spectral location for the required bandwidth.

2.0 DSRC APPLICATIONS

The following ITS applications are being implemented or are being considered for implementation with DSRC [2,3]:

- In-vehicle signing;
- International border clearance;
- Electronic clearance;
- Safety inspection;
- Fleet management;
- AEI and Freight management;
- Off-Line verification;
- Electronic License Plate (ELP);
- Traffic network performance monitoring;
- Intersection collision avoidance;
- Emergency vehicle signal preemption;
- Transit vehicle signal priority;
- Transit vehicle data transfer;
- Traffic information dissemination;
- Automated highway system-to-vehicle communications;
- Electronic toll collection (ETC);
- Parking payments / Access control; and
- Drive-thru payments

Those applications that are implemented or sponsored by government (public) agencies are considered public safety applications and those implemented by private business concerns are considered commercial. Many of the applications, including electronic clearance, intermodal freight management, ETC, and traffic network performance monitoring are already being implemented. Commercial vehicle operations (CVO) applications include several of those listed above and are expected to be some of the first seeing wide implementation. Implementation characteristics for the remaining applications are currently being developed. Hazardous material incident response has been removed from the list since it will be accomplished through wide area communications. However, because a scenario of operation is necessary to compute bandwidth requirements, the preliminary operational characteristics described in the following sections are assumed for the applications being evaluated.

2.1 In-Vehicle Signing

In-vehicle signing refers to the display (and annunciation, where necessary) of available roadside sign information inside the vehicle. In-vehicle signing may be used to enhance the effectiveness of information available from the roadside and provides the driver with a more effective way to receive sign information when driving in poor weather conditions or over difficult terrain. If a DSRC-equipped road sign is obscured by snow or a dust storm, the driver sees the information that the sign was installed to present on a display inside the vehicle. This information can include advisory, regulatory, and warning signs.

The currently proposed method of implementing sign-to-vehicle communications is beacon technology, which is especially applicable for regulatory and warning signs. Beacon technology allows the driver to receive notification of an important, critical, or dangerous road situation, specific to a location, only when that situation is present in the roadway. Data about ice on the roadway or speed limit changes because of road construction are primary candidates for beacon communications. Beacon technology usually transfers information in milliseconds which, in combination with the consideration of vehicle speed, makes beacons preferable for use in position-, condition-, and time-critical communications applications. Beacons also have the advantage of transferring information in all light and weather conditions. In addition, in-vehicle signing equipment can display the information in the vehicle for a much longer period than non-instrumented signs, especially in poor visibility conditions.

In-vehicle signing can be compared with a safety feature such as anti-lock brakes. Just as anti-lock brakes improve the wet-road performance of a normally adequate brake system, in-vehicle signing improves the performance of road signs where hills, foliage, snow, fog, rain, dust, or lack of nighttime illumination present visibility problems.

An alternative source for sign information is in-vehicle navigation systems, which are updated through wide-area communications equipment and are suitable to support advisory and static regulatory signs. The navigation system signs would be documented and updated by the information service provider (ISP) supporting the navigation system.

2.2 International Border Clearance

All vehicles are required to stop at international border checkpoints where they undergo inspections for clearance to pass across the border. For commercial vehicles, this inspection requires a significant amount of time. International border clearance is the process of electronically transferring data between a commercial vehicle and the border checkpoint so that the vehicle can pass the checkpoint with minimal or no delay. The efficiency of border crossings would be substantially improved if the vehicle could be pre-cleared to cross and only verified at the border.

International border clearance could be implemented using beacon technology since it allows the agency collecting and analyzing data to easily and quickly transfer data to and from a specific vehicle moving through the communications zone of the checkpoint specific locations at a moderate rate of speed. In-vehicle signing can be used to advise the driver to either bypass or park for inspection at the border checkpoint.

2.3 Electronic Clearance

Currently, commercial vehicles are also required to stop at state checkpoints where they undergo routine weight, credential, and safety checks. For lengthy trips, a vehicle may be required to stop and undergo similar checks a number of times. The top priority of the CVO user service is for commercial vehicles to be able to travel the nation’s highways without having to make these stops.

Electronic clearance is the process of electronically transferring data between a commercial vehicle and the roadside checkpoint so that the vehicle can pass the state checkpoint without stopping. Domestic electronic clearance will allow commercial vehicles operating with either interstate or intrastate registration to pass state checkpoints at main line speed without stopping.

Electronic clearance will be implemented using beacon technology since it allows the agency that is collecting and analyzing data to easily and quickly transfer that data to and from a specific vehicle moving through the communications zone of the checkpoint at a high rate of speed. As with International Border Clearance, in-vehicle signing can be used to advise the driver how to proceed. If the vehicle is given the pull-in message, it may be only weighed and allowed to proceed or it may be given a safety inspection (Section 2.4).

2.4 Safety Inspection

A safety inspection is a check of the safety characteristics of a commercial vehicle while it has been pulled off the highway at a fixed or mobile inspection site. The inspecting agency wants the inspection to be thorough and fast so that the agency can check as many vehicles as possible that are likely to have safety violations. Beacon technology will be used to speed the inspection process because it does not require a physical connection to the vehicle, and it can transfer registration data, previous inspection data, and on-board sensor data at high transfer rates. Other equipment will also be used to measure the condition of the inspected vehicle.

Data will also be uploaded to the vehicle after the inspection, and in-vehicle signing technology may be used to instruct the driver to proceed or to notify the driver that the vehicle is to be considered out of service.

2.5 Fleet Management

A DSRC fleet management application allows fleet or individual operators to extract or upload data to and from commercial vehicles to support fleet management functions. This function will be performed through the common interface used for electronic clearance and safety inspections. Beacon readers can be placed at many locations, including terminals, warehouses, fueling facilities, commercial scales, and truck stops.

2.6 Automatic Equipment Identification (AEI) and Freight Management

AEI enables intermodal freight management to accommodate the need to track freight as it transitions from one mode of transportation to another. All tracking is expected to use AEI beacon technology (See Appendix B). Most transponders would be simple read-only tags attached to containers, but more complex electronic lock tags would also be required to indicate whether tampering had occurred with the container in border-crossing operations. The same AEI link would also be used to track individual containers in storage locations, as in freight yards and warehouses, for non-transportation-related location fixing.

2.7 Off-Line Verification

Off-line verification is a check of the data in a tag's memory when a vehicle has been stopped for any reason by an enforcement agency. Beacon technology will be used to provide a fast, common interface for data. Power unit and electronic lock tags can transmit data to a hand-held reader carried by an enforcement agent. This application will reduce the time required to obtain the data needed by the enforcement agency and will allow the commercial vehicle to quickly return to the road and the enforcement agent to return to other enforcement activities. This application can also be used by commercial operations to verify the proper operation and data content of the tag before it leaves a commercial facility.

2.8 Electronic License Plate (ELP)

The ELP application allows an enforcement agency to check the license plate number, state and expiration date, contained in a tag's memory when the tag is built into a standard size license plate. This application will reduce the time required to obtain queries on vehicles about to be stopped and allow traffic to be screened for stolen or unlicensed vehicles. Furthermore, traffic can also be screened for vehicles suspected of involvement in criminal activity. However, the largest impact of implementing the ELP is that all vehicles in a state will have a common RF interface device to the outside world and encourage commercial applications, such as Parking Payment and Drive-Thru Payment, that are dependent on common vehicle interfaces. This application will employ mobile, stationary, and portable readers.

2.9 Traffic Network Performance Monitoring

In traffic network performance monitoring, traffic management centers (TMC) monitor traffic flow parameters, such as density and speed, to detect incidents and other traffic-slowing conditions. Where high densities of vehicles that have tags for in-vehicle signing and other functions are being used, beacon technology allows the TMC to communicate with these vehicles for probe information. This enables the TMC to obtain a higher-density probe vehicle population and therefore more accurate information. The increased accuracy allows the TMC to improve its capability to determine the occurrence and location of incidents and congestion.

2.10 Traffic Information Dissemination

Traffic information dissemination is a form of in-vehicle signing that is used to warn drivers of congested traffic situations or incidents. Beacon technology provides communications to vehicles that have tags for in-vehicle signing information or other functions but may not subscribe to an ISP for route guidance. The transmitted message may alert drivers to tune to the Highway Advisory Radio (HAR) channel for more information. This application allows important traffic information to reach more vehicles more rapidly than is otherwise possible, therefore allowing more drivers to take action to avoid congestion.

2.11 Intersection Collision Avoidance

Intersection collision avoidance is a system that tracks the position and speed of vehicles within a defined area around an intersection and alerts vehicles when they are on a collision path. Sensors in the intersection will track the vehicles, processors with associated algorithms will compute the trajectories, and a beacon communications system will communicate with the vehicles. This application will provide drivers with the information necessary to take evasive action to avoid collisions.

2.12 Emergency Vehicle Signal Preemption

Emergency vehicle signal priority preemption uses beacon technology in both an intersection and an emergency vehicle to change the timing of a traffic signal and allow the emergency vehicle to proceed through the intersection with a green light and a minimum of delay. This application also reduces the probability of an accident between the emergency vehicle and affected traffic because drivers in the emergency vehicle's path respond to a control device that they are already monitoring instead of trying to determine the location and direction of the approaching emergency vehicle and formulate an independent response.

2.13 Transit Vehicle Signal Priority

Transit vehicle signal priority uses beacon technology in both an intersection and a transit vehicle to change the timing of a traffic signal and allow the vehicle to proceed through the traffic signal with a minimum of delay. This application allows the vehicle to travel its route more efficiently, deliver passengers to their destinations as quickly as possible, and consume less fuel.

2.14 Transit Vehicle Data Transfer

Transit vehicle data transfer is the uplink of operational data from and the downlink of messages to an individual transit vehicle or a fleet of transit vehicles, using beacon technology. Beacons are positioned at transit vehicle stops along a route, and communications are initiated with tag-equipped vehicles at the stops as necessary. This application allows the transit authority to conduct fare transactions with passengers in a lower cost communications structure than is possible using wide-area wireless. The transit authority also can accurately monitor vehicle ridership, track the location and on-time status of vehicles, monitor vehicle fault indicators, provide route and operational instructions to drivers, and post accurate vehicle arrival times.

2.15 Automated Highway System-to-Vehicle Communications

Automated highway system (AHS)-to-vehicle communications allow the check-in and check-out stations of the AHS to determine the status of vehicles by using on-board sensors and to present a message to enter or exit the AHS. This application uses beacon technology so that the check stations can identify the exact location of the vehicle being checked and transfer information at a high data rate.

2.16 Electronic Toll Collection

In electronic toll collection (ETC), data is transferred from and to the vehicle’s tag, while the vehicle is in a toll area, and the toll fee is automatically deducted from the driver’s toll account or other monetary account. Beacon technology is used so that the toll collection agency can positively identify the location of the vehicle both at the time of the toll transaction and when the vehicle enters the toll road, ensuring that the driver is billed correctly. This application allows the toll agency to reduce the cost of toll collection and allows the driver to proceed through the toll area without slowing, stopping, or experiencing traffic backups.

2.17 Parking Payments and Access Control

Using the parking payments application, a vehicle enters and exits a parking area, and the parking fee is automatically deducted from the driver’s parking account or other monetary account. Beacon technology is used so that the parking agency can positively identify the location of the vehicle both at the time of the payment transaction and when the vehicle enters the parking area, ensuring that the driver is correctly billed. This application allows the parking agency to reduce the cost of parking payment collection and allows the driver to enter and leave the parking area faster. Beacon technology can also be used to transmit a message to the vehicle to proceed or that entry is not allowed into private areas, such as shipping yards, warehouses, airports, and other access restricted areas. The message is displayed in the vehicle via in-vehicle signing.

2.18 Drive-Thru Payments

Payment for products received at a drive-up service window (for example, a fast food business) could use a DSRC system to make payment more convenient. Price data could be transferred to the vehicle’s tag and payment data transferred to the beacon while the vehicle is in the service area. The fee could be automatically deducted from the driver’s selected monetary account. This method of payment would make the collection of money faster and therefore speed the service to the customer.

3.0 DSRC IMPLEMENTATION REQUIREMENTS

3.1 DSRC Installation Density Concerns

With many DSRC applications to implement, it is important that proper mitigation techniques be employed to prevent interference among or between applications. Methods for preventing interference include:

- Synchronizing transmissions;
- Synchronizing time division multiple access (TDMA) time slots;
- Maintaining specified separation between antennas;
- Changing power levels to reduce signal levels at the potential interference points;
- Operating at different frequencies; and
- Alternating channels,

The tag emits a signal at a very low level, and any local reader that is transmitting data overpowers the tag signals that other readers on the channel are trying to receive. Therefore, synchronizing transmissions, synchronizing TDMA time slots, and alternating channels are the methods most used to prevent interference between equipment in close proximity. However, when a channel cannot be synchronized, the transmitters must be moved apart. The distances required between independent, non-synchronized channels to prevent interference for both the same and adjacent channels can be calculated if the power outputs; antenna gains, pointing angles and beam pattern; receiver sensitivities; and separation distances are known. If synchronization of readers cannot be ensured, tag-on-tag conflict will occur if the tags are on the same channel and separated by less than some calculable distance. See Appendix D for sample calculations of reuse (separation) distances. Using a separate channel for each reader to communicate with these tags will reduce the required separation distance. The same situation applies to readers. Where synchronization of readers cannot be ensured, a reader-on-reader conflict will occur if the readers are on the same channel and separated by less than some calculable distance. A separate channel should allow operation with smaller separation distance.

For the mitigation analyses in this paper, the following assumptions are used:

- All beacons operate on a group of channels in the same frequency band (with one exception - the AEI tag);
- A vehicle may have more than one tag but only one tag is used to communicate with the various types of beacons at a time;
- The tags generally use a passive or semi-passive technology such as backscatter or modulated reflectance;
- The downlink (beacon to tag) uses binary Amplitude Modulation;
- The uplink (tag to beacon) is generated by modulating a subcarrier or subcarriers which then AM modulate the carrier signal being reflected; and
- The required bandwidth for a beacon is 3 - 6 MHz with an instantaneous data rate between 250 and 600 kbps.

The assumptions above are derived from the desire to develop a flexible DSRC system where the frequency is determined by the roadside beacon and the in-vehicle tags are designed to be as inexpensive as possible. These assumptions are also in line with the user requirements [4,5], and the design of many of the 902-928 MHz and 5.8 GHz DSRC systems investigated during this project. See Appendix A.

3.2 Mitigating Effects of Interference Between DSRC Systems

The widespread use of DSRC systems leads to the obvious problem of interference between individual beacon systems. The problem is especially difficult if all the beacons operate in the same frequency band and a single tag is capable of exchanging data with all beacons.

The analysis of interference mitigation will be developed in two parts. First, the problems and mitigation techniques for interference between two DSRC systems operating at the same frequency will be discussed. Next, a similar analysis will be presented for two DSRC systems operating at different specific frequencies within the same band.

3.2.1 Same Frequency DSRC Interference Mitigation

The assumptions on the operation of the DSRC systems listed above are used in this section to assess the problems and mitigation techniques associated with two beacons operating in close proximity at the same frequency. Examples of these scenarios include adjacent lanes in an Electronic Toll Collection (ETC) facility, or a mobile commercial vehicle tag reader operating near a wider area information beacon for in-vehicle signing. In the case of an ETC facility, careful design and integration make possible the coordination or cooperation between the beacons in the adjacent lanes. For the case of the mobile reader beacon and in-vehicle signing beacon, cooperation or coordination between the beacons is difficult to establish and unlikely to be used in practice. These two cases will be discussed separately in this section.

Assume an in-vehicle tag receives the signal from two beacons operating at the same frequency. The tag forms the envelope of the sum of the signals and attempts to detect the information being transmitted from the beacon. If the power levels of the received signals are roughly equal (~$\pm$3 dB), then the envelope of the sum of the received beacon signals will be distorted beyond recognition and no data will be transferred to the tag from either beacon. The in-vehicle tag will not respond to either beacon. Neither beacon will receive a response fi-om the tag and the transaction or information transfer will not be completed.

If one beacon is significantly stronger than the other, then the Automatic Gain Control (AGC) and/or the AM detector will be dominated by what is received fi-om the more powerful beacon. The data from the more powerful beacon signal will be received by the tag, and the tag will respond using the tone from the stronger beacon. The weaker beacon signal will be ignored. The stronger beacon will likewise receive the response from the tag and the transaction will be completed. Unfortunately, the beacon with the weaker signal will also receive the response from the tag which was intended for the other beacon (same frequency). The response will likely be either be received by the weaker beacon as unexpected data or will be an unsynchronized response that is unintelligible. Either case can cause problems at the weaker beacon.

Several techniques can be used to mitigate interference between interconnected beacons (i.e., the ETC facility) operating at the same frequency. Examples of methods used by existing DSRC systems include:

1. Very careful control of power levels and antenna directionality to control the transaction zone;
2. FM capture techniques that use received power level to discriminate at the beacons;
3. Time differentiation where adjacent or nearby beacons operate one-at-a-time in an interleaved fashion; and
4. Power level discrimination at the tag combined with interleaved beacons such that the tag only responds to the appropriate beacon.

Power control and antenna directionality (spatial differentiation) are used to some degree by all beacon systems. The other techniques are used to improve isolation between nearby beacons. In an ETC application, all of these techniques should be reasonably effective. An actual comparison of the effectiveness of each of these techniques and combinations of techniques would require detailed simulation or testing. Since each of these techniques are currently fielded and operating, it is safe to assume that these techniques are effective at mitigating interference between adjacent beacons.

Mitigation of interference between beacons at the same frequency is much more difficult if the beacons are not interconnected. As in the example above, a portable reader will not be physically interconnected to a fixed beacon and thus cannot use most of the mitigation techniques listed above for an integrated beacon system. Power control and antenna directionality can be used to some extent, but the location of the portable beacon relative to the fixed beacon is unknown. The portable beacon may actually be in the center of the intended coverage zone for the fixed beacon. Therefore, power control and antenna directionality will not completely mitigate interference.

Assuming the portable and fixed beacon must operate at the same frequency, the first mitigation technique that might be employed is a protocol for time sharing. The fixed beacon protocol may include a “silent” period which allows the portable beacon to operate in the same zone. This method requires the portable beacon to detect the silent period of the fixed beacon and transmit only during this time period. This method is very inefficient for both beacons. The fixed beacon must incorporate a wasted silent period at all times, even though the portable beacon may only occasionally be present. The portable beacon is also restricted to communicating in small time slots greatly reducing its total effective data rate.

Another cooperative protocol, assuming the fixed beacon uses a slotted TDMA multiple access technique, would allow the portable beacon to “capture” a slot or slots in the fixed beacon’s protocol. This protocol would be very complicated and require the portable beacon to communicate with the fixed beacon as if it were a tag, and the fixed beacon may be required to not transmit its own tone during these time slots.

The portable beacon's best technique for successful communication would use proximity (short distance) and power control to over-power the field strength of the fixed beacon in a small area. The portable beacon would successfully communicate with the intended tag, but the responses from this tag would interfere with the operation of the fixed beacon. The tag's responses to the portable beacon would be a strong interference source received also by the fixed beacon. This interference is likely to be short lived, but if the operation of the fixed beacon were time-critical (i.e., collision avoidance) the interference might have disastrous results.

In short, the problem of mitigating interference between non-cooperative interfering beacons operating at the same frequency is very difficult. It may not be feasible to implement a cooperative protocol that allows a portable beacon to operate within the coverage zone of a fixed beacon. Cost and complexity will likely be high. The best solution may be to use separate beacon frequencies. This option is discussed in the next section.

3.2.2 Different Frequency DSRC Interference Mitigation

In this section interference problems associated with nearby beacons operating at different frequencies will be addressed. It is assumed that the frequencies are all within the operating band of the tag and, as stated in the earlier assumptions, the tag uses a passive or semi-passive technology that reflects all signals within its operating band. In the previous section it was shown that cooperative or integrated DSRC systems can operate at the same frequency with good interference rejection. In this section, it is assumed that the beacons are from separate, non-cooperative DSRC systems intended to communicate with the same tags.

As in the last section, the example to be studied will be a portable beacon operating within the coverage zone of a fixed beacon. The difference this time is that the portable beacon will operate at a different specific frequency within the band of the tag. Again the portable reader will use power control and proximity to transmit a signal to the intended tag which is much stronger than that received from the fixed beacon. The simple AM detection of the tag will therefore only detect the portable beacon's signal and the tag will respond to the portable beacon.

The response of the tag read by the portable beacon will also be received at the fixed beacon. However, the fixed beacon will have filtering that only allows the reception of signals centered at the frequency it is transmitting (probably a superheterodyne receiver). Therefore, the strong signals emanating from the portable reader and reflected by the tag will be filtered out at the fixed beacon's receiver.

The use of different frequencies for two beacons operating in the same area, and the use of power and proximity control does not completely eliminate the interference problem. Since it is assumed that the tag uses a passive or semi-passive reflecting technology, the tag will incidentally reflect *all* in-band signals that it receives. Therefore, the tag responding to a portable beacon will also reflect and modulate whatever signal power is received from the fixed beacon as well. When this tag is responding to the portable reader, the coverage zone of the fixed beacon is reduced due to the interference reflected by the tag.

Figure 1 demonstrates graphically the reduced coverage zone of the fixed beacon while the portable beacon is receiving data from the tag. The light gray area is the original coverage zone of the fixed beacon; the dark gray region is the coverage while the portable beacon is receiving data from the tag.

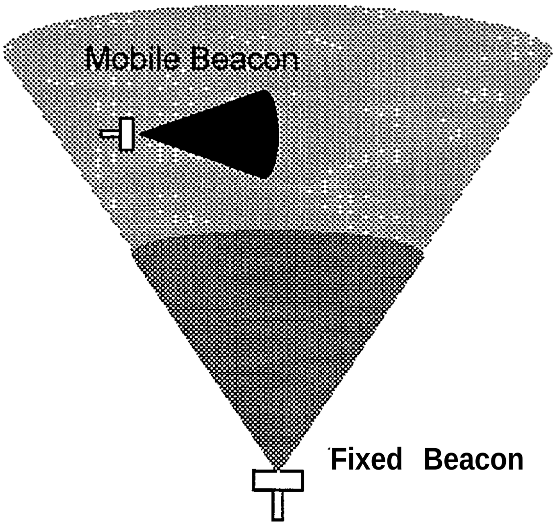

Figure 1. Coverage Zone Reduction Due to Portable Beacon

The reduced coverage range shown in Figure 1 is similar to that for a portable reader operating at the same frequency as the fixed beacon. However, the impact is much less using different frequencies since the fixed beacon will only receive its own signal level reflected incidentally from the tag read by the portable reader and not the elevated signal level from the portable beacon operating on the same channel. Also note that the reduced operating range of the fixed beacon only occurs when the tag is responding (uplinking) to the portable reader. This will likely only occur for a short period of time.

3.3 Installation Groups

Efficient use of applications may be enhanced by implementing some applications with shared equipment installations. This will allow the installation of several applications on the same channel therefore reducing the channel requirement from that required if each application were deployed separately. Applications can be shared by a set of communications equipment if they do not suffer degradation from serial transmission, reception, and processing of the data. Four installation groups are proposed. These groups and the applications they include are as follows:

- In-vehicle signing installation group-In-vehicle signing, railroad crossing warning, traffic network performance monitoring, and traffic network performance feedback;

- CVO installation group- electronic (mainline) clearance, international border clearance, safety inspection, fleet management, and inter-modal freight management;
- Intersection installation group-Intersection collision avoidance, emergency vehicle signal preemption, and transit vehicle signal priority; and
- Mobile location interrogation group - off-line verification, ELP, and commercial interrogation.

The remaining DSRC applications have operational characteristics that are not compatible with deployment in a group and can be expected to be deployed independently.

- Transit vehicle data transfer;
- Automated highway system-to-vehicle communications;
- ETC;
- Parking payments;
- Access control; and
- Drive-thru payments.

Channel requirements for all the applications implemented at a group location are included in the description of each group. However, in the next section these channel requirements will be partitioned into assignments for each application.

3.3.1 In-Vehicle Signing Installation Group

The applications in the in-vehicle signing installation group (in-vehicle signing, railroad crossing warning, traffic network performance monitoring, and traffic network performance feedback) are implemented by installing beacons at designated communication locations (see Figure 2). These locations could include places where safety could be increased by monitoring a roadway condition (ice, fog, etc.), where potentially dangerous conditions exist (construction, low visibility, etc.), or where safety could be increased at railroad crossings by warning of tracks being approached or trains about to cross the road (see Figure 3). The locations could also include places where directional information is needed or traffic speed is being tracked with antennas mounted every l/2 to l-1/2 miles along selected high-density roadways, at off-ramps, and at access ramps to implement a traffic management function as in the New Jersey Transmit program [6]. The beacon signal pattern must reach each car in each lane of the roadway and can be implemented with several different antenna mounting methods. Some of the methods include the following:

- One or more beacons (antennas) could be mounted over the roadway;
- Several synchronized or multiplexed beacons could be mounted over the roadway with one over each lane;
- For single lane or some double lane roads, the beacons could be mounted on signs or poles along the roadway; and
- For double lane roads, the beacons could be mounted on signs or poles along each side of the roadway.

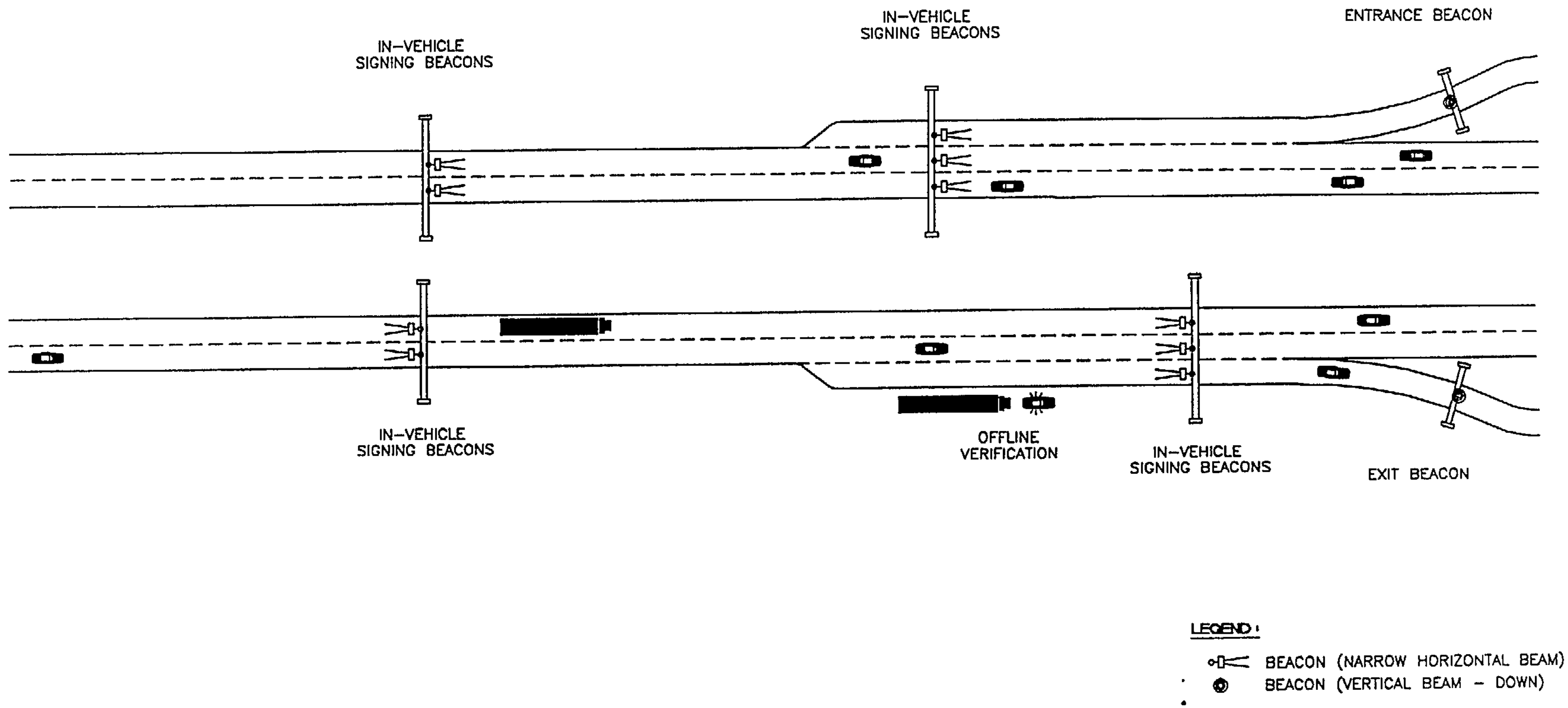

Figure 2. In-Vehicle Signing Installation Group

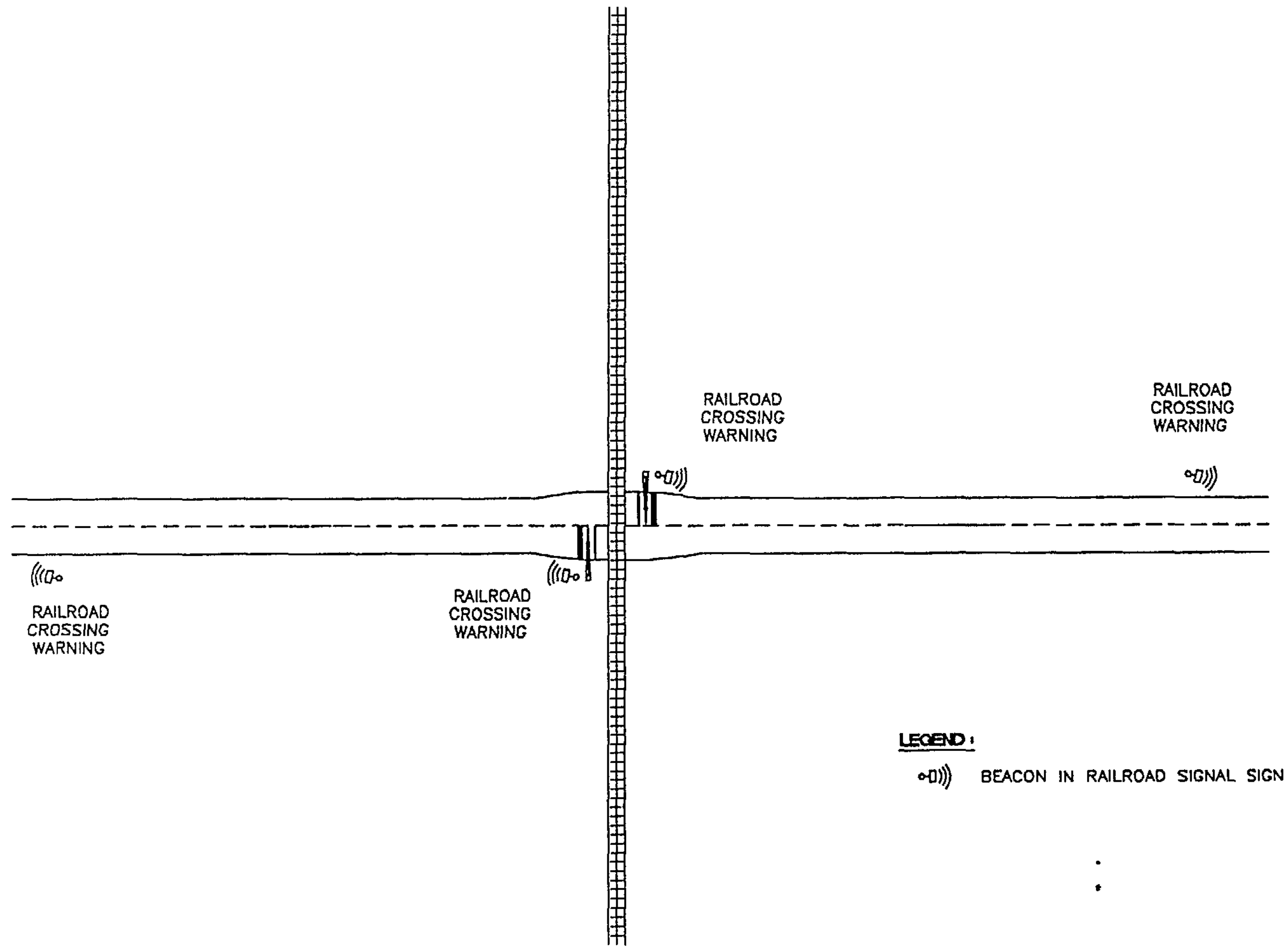

Figure 3. Railroad Crossing Warning

All the implementations except the single lane must use either a broadcast communication protocol to make a one-way transfer of data to the vehicles or a multiple access protocol to transfer data to and from the vehicles, one at a time. Some implementations may even use a broadcast mode in the multiple access protocol. Most systems are currently using a TDMA multiple access protocol with a slotted aloha access scheme. This protocol consists of frames in which there are communications time slots and activation time slots. The activation slots are usually much smaller than the communications time slots and are used by in-vehicle tags to announce their "desire" to communicate with the beacon. A tag randomly chooses an activation slot and quickly announces its identification number to the beacon. The beacon then announces to the tag, using the identification number, when it is permitted to communicate.

Using this method, the beacons at any particular location can conduct several different information transfers with any particular vehicle to implement a series of desired functions. In a traffic management application, like the Transmit program in New Jersey [6], the system would communicate with a vehicle at a beacon site and compute its travel time (link time) from its previous beacon site communication. However, in future versions, the beacon could next transmit an update of the traffic conditions or other traffic instructions to the tag as feedback from the traffic management center.

In-vehicle signing in many cases could use only one channel and a horizontally directed beacon to transmit and receive at ranges up to about 100 feet (backscatter tags) or 200 feet (active tags) in order to select and communicate with all the vehicles while they are in the communication zone. The range can be extended to between 200 and 300 feet (for both active and backscatter tags) by using a broadcast mode where the beacon transmits and the tag only receives without trying to respond. The communication distance and/or location of the beacon is determined by the amount of information to be acquired, the action the driver has to take and the vehicle speed. In cases where more advanced warning of an approaching hazard is desired, beacons are located ahead of the hazard by an appropriate distance. For instance, in the case of the railroad crossing, beacons would be mounted at the crossing and 300 feet to l/2 mile in advance of the crossing. Beacons that use more power can be received by tags at distances further than 300 feet, when necessary, but at the cost of increasing the interference-preventing separation distance between beacons. Most beacons can be installed out of interference range at the two-way l00-foot-range power settings, except in some cases of off-ramp or on-ramp installations. In these instances, another channel could be used to prevent interference. The portable in-vehicle-signing beacon implementation would be used for construction, temporary warning or emergency applications. The message of the portable beacon could also be broadcast by nearby fixed in-vehicle-signing beacons where the hazard is in the coverage of the fixed beacon. However, a portable warning sign could be needed downstream of a stationary beacon where it could cause interference by transmitting upstream into a fixed beacon's capture zone. In this case, the portable beacon would need a second channel to prevent interference. Therefore, in-vehicle signing could possibly require two channels for its implementation. However, a mobile location interrogation could also be required at any point along the instrumented roadway, and an additional channel for that application would be needed to prevent interference. The area of the in-vehicle-signing installation would need the allocation of three channels.

3.3.2 CVO Installation Group

The applications in the CVO installation group are electronic clearance (screening), international border clearance, safety inspection, fleet management, and intermodal freight management. Electronic clearance is currently implemented by installing weigh in motion (WIM) scales in the roadway, antennas above the roadway, and tags to the windshield or front of commercial vehicles. Currently, in some applications, a WIM scale and one antenna are installed at the outside lane of the roadway about l/2 mile before the weigh station to allow time for the vehicle to pull in if necessary (see Figure 4). As a vehicle passes through a capture zone beneath the beacon, the beacon sends signals to and receives signals from the tag to implement the transaction. The second beacon is installed in front of the weigh station. Vehicle classification sensors are used to identify passing trucks that need clearance and this beacon determines if the trucks are authorized to bypass the weigh station. Another WIM scale and third beacon is installed at the entrance of the weigh station to allow the vehicle to have another weight check before it is given the static scale pull-in signal and to update the tag with this information acquired at the weigh station. A fourth beacon is installed at the exit of the weigh station to update the tag with the latest information acquired at the weigh station. Each of these beacons is installed out of the range of the others and all use the same channel. Interference is prevented by careful power level setting and directional orientation of the beacon. The maximum range setting of the beacons used is about 100 to 200 feet.

A safety inspection area is provided for vehicle inspections. These areas are not currently, but could be, instrumented with hand-held readers to allow the downloading of data from the tag and uploading of inspection data to the tag. Vehicle inspection readers may need a separate channel, depending on the separation distance, equipment, and propagation characteristics of the site. In addition, a mobile location interrogation system operating in this area would require an additional channel. The CVO installation would need an allocation of three channels.

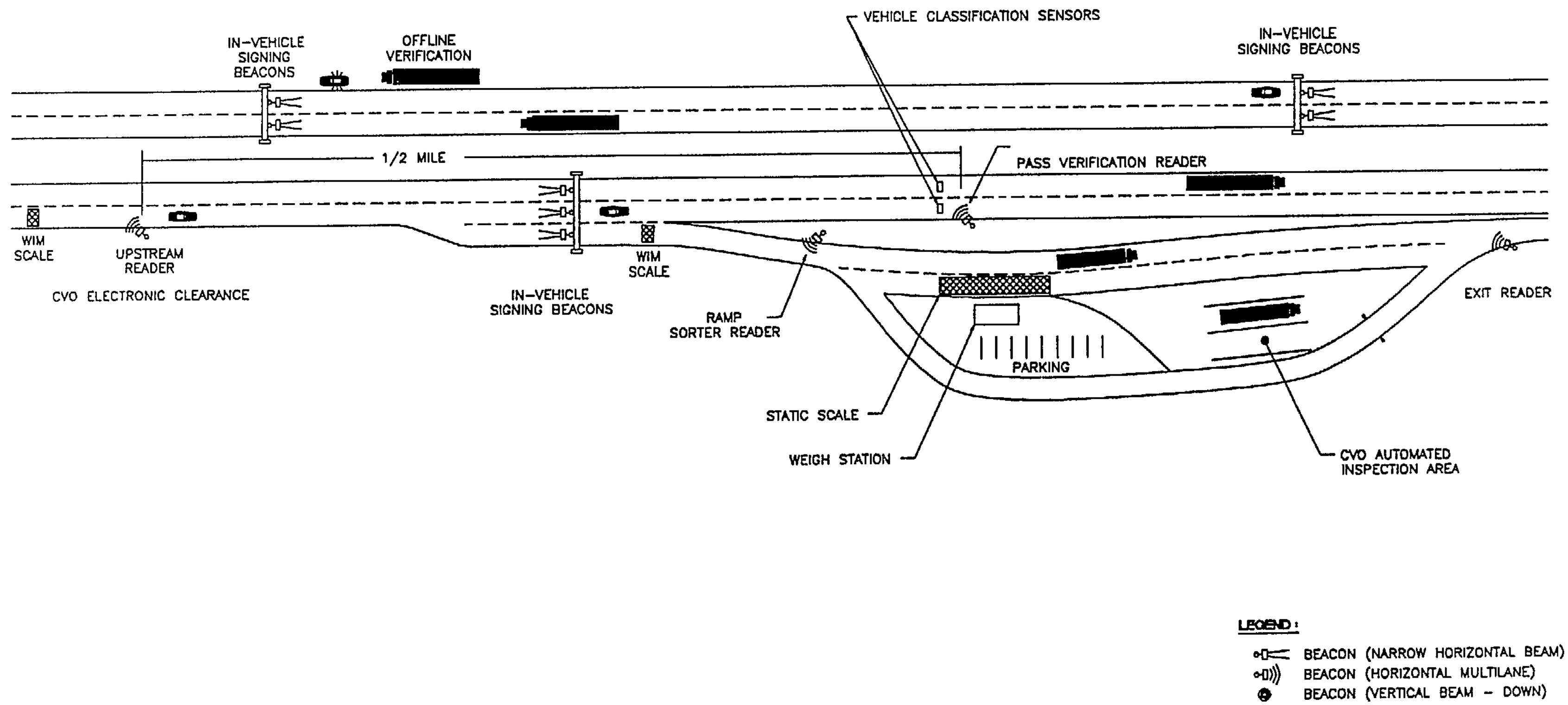

Figure 4. CVO Installation Group

International border clearance could be implemented by installing antennas above the roadway, attaching tags to the windshield or front of commercial vehicles and attaching a lock tag to the cargo door of the trailer (See Appendix B). One set of antennas are installed above the roadway about l/2 mile before the border crossing (see Figure 5). As the front of the vehicle passes through a capture zone beneath the second beacon, the second beacon sends signals to and receives signals from the tag to implement the clearance interrogation. After the vehicle clearance information is transferred and the back of the vehicle has cleared the first beacon. The first beacon interrogates the lock tag on the back of the trailer to determine if the cargo door has been opened since it was inspected. The travel time between the second and third beacon would allow the transaction to be processed and a clearance message prepared for the third beacon. The third lane sorting beacon would be installed at the entrance of the truck inspection area to provide the by-pass or park clearance message to the vehicle. The fourth verification beacon would be installed in the bypass lane of the truck inspection area to determine if passing trucks are authorized to bypass the inspection area.

Hand-held readers would be used in the inspection area on tag equipped vehicles that were instructed to park. This would allow the downloading of data from the tag and uploading of inspection data to the tag. Vehicle inspection readers may need a separate channel, depending on the separation distance, equipment, and propagation characteristics of the site. A sixth beacon would be installed at the exit of the weigh station to update the tag with the latest information acquired at the inspection station. The maximum range setting of the beacons used is about 100 feet.

In addition, a mobile location interrogation system operating in this area would require an additional channel. In-vehicle signing would also require a channel if operated in the area. The CVO international border clearance installation would need an allocation of four channels.

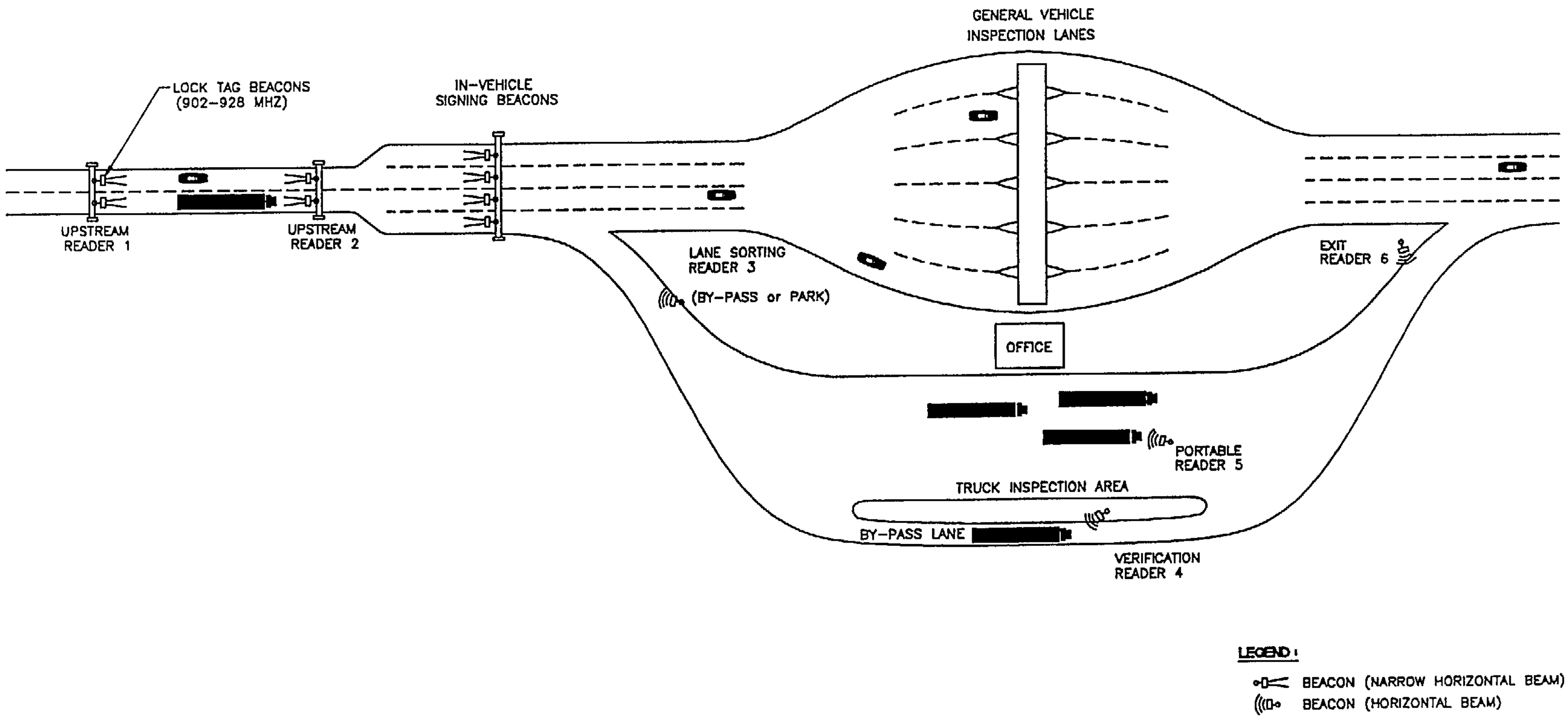

Figure 5. CVO Installation Group – International Border Clearance

3.3.3 Intersection Installation Group

The applications in the intersection installation group (intersection collision avoidance, emergency vehicle signal preemption, and transit vehicle signal priority) are implemented by installing readers at intersections and nominally would use two channels to prevent cross-reads from intersecting lanes (see Figure 6). However, if the beacons are sufficiently separated and an appropriate synchronization scheme is employed one channel could be used. Intersection beacons are expected to use TDMA slotted aloha protocol or similar to communicate with multiple vehicles in the multiple approaching lanes.

The intersection collision avoidance application would, when activated, override all other communication by commanding all tags to listen at the first available frame. The communication would be a one way information flow so the beacon could use its maximum range. The implementation of collision avoidance will also require a series of beacons installed upstream of the intersection. The upstream beacons are needed because for some vehicle speeds the beacon range is not greater than the stopping distance plus the reaction distance of the driver. For example, the stopping distance used in road design for a car at 43.5 miles/hour is 98 feet, and the reaction time of drivers is between 0.2 to over 2 seconds, so at that speed the expected reaction distance is between 12.8 and 127.6 feet, which could make the total distance needed greater than a 200 foot beacon range [7]. A beacon range of from 100 to 200 feet does not allow the intersection beacon enough time to handle faster speeds, slow reaction times, or wet or snow cover conditions. The upstream beacons must be installed to expand the coverage to include more potential collision situations.

The advance notification of an approaching emergency vehicle is also handled by beacons upstream of the traffic flow by 1000 to 3000 feet either as intersection beacons or separate installations. The location of the emergency vehicle and its direction of travel toward the intersection are passed by wireline to the computer controlling the intersection beacons in the figure. The intersection beacons verify the emergency vehicle’s arrival and departure to restore normal traffic function. This function could require a separate channel.

Because the transit vehicle data transfer readers are also installed near intersections, a separate channel from the one or two used in the intersection should be used to reduce the possibility of interference. The additional channel is needed because the transit vehicle dedicated short range link may occur for several seconds, may not be synchronized with the intersection equipment, and the intersection readers must communicate on an emergency basis, with no delay or interference, to vehicles in a critical status.

Other applications within the interference zone of the intersection installation group, such as a portable in-vehicle signing application, would need to use another channel. Also, a mobile location interrogation could be required at any point approaching or leaving the intersection and would need an another additional channel to prevent interference. The maximum unrestricted channel allocation for the intersection installation group could be six.

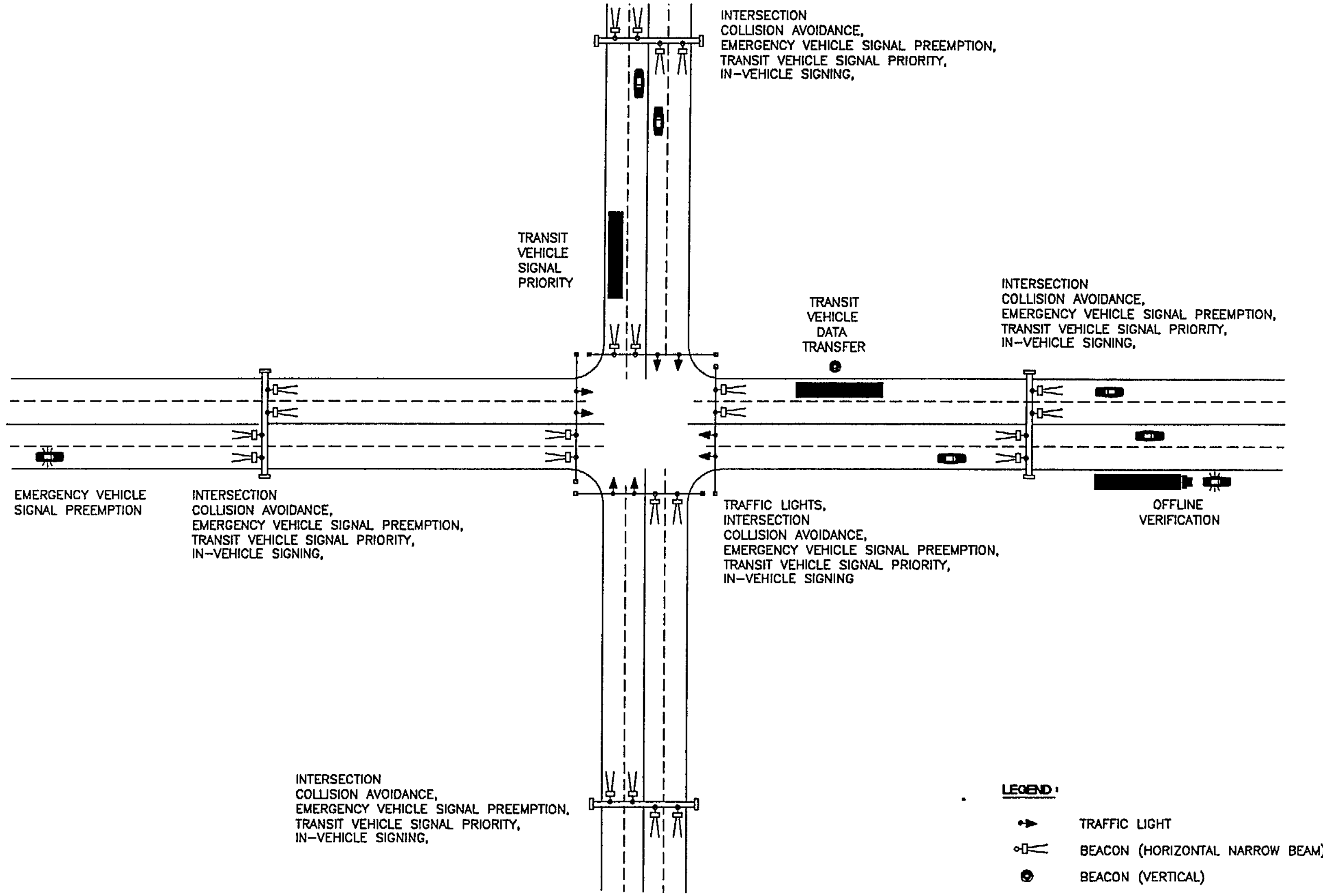

Figure 6. Intersection Installation Group

3.3.4 Mobile Location Interrogation Group

The mobile location interrogation group consists of the off-line verification, ELP and the commercial interrogation applications. The off-line verification applications use hand-held readers to download information from vehicles that are, stopped, disabled, or involved in incidents (see Figure 6). The ELP application uses mobile, stationary, or hand-held readers to download information from vehicles that are in traffic. The commercial interrogation applications use stationary or hand-held readers to download or upload information from vehicles in freight yards and other locations. The off-line verification and commercial applications only require short-range (10 feet), low-power equipment. The ELP application needs the maximum range of about 150 feet to allow an enforcement agent to maintain a safe distance to a subject vehicle. Because these applications may need to be implemented at any location, they must use a separate channel that is not shared by the other applications.

3.3.5 Transit Vehicle Data Transfer

To accomplish transit vehicle data transfer, readers are installed at bus stops, terminals, and other designated areas. The readers pass data to and from the tag on the transit vehicle during stops (see Figure 6). Intersection installation group beacons could be installed at intersections that may be close to bus stops where beacons are installed. However, four characteristics of this installation reduce the possibility of interference. First, the transit vehicle beacon must be operated at low power to prevent interference with the intersection beacons. Second, the location of the beacon within 5 to 10 feet of the transit vehicle tag enables the transit beacon signal to be large, compared to any other source, while using low power settings. Third, the transit vehicle will shield the intersection from a large proportion of the beacon transmission. And, fourth, using a separate channel from the two channels used in the intersection eliminates the remaining interference potential. The additional channel is needed because the transit vehicle dedicated short range link may operate for several seconds, and a preventable accident could occur in that time frame if interference occurs with the collision avoidance beacons.

3.3.6 Automated Highway System-to-Vehicle Communications

Automated highway system-to-vehicle communications transfers data on the operational status and position of the AHS vehicle from the vehicle to the roadside, and transfers AHS operation instructions and AHS roadway status from the roadside to the vehicle (see Figure 7). To accomplish this, reader sets, including antennas, are installed at check-in and check-out points in the transition lanes and, optionally, at design-determined distances along the AHS roadway. AHS should require one channel to perform the required communications. Most of these highways are expected to be located in close proximity and parallel to existing highways with in-vehicle signing or other applications installed. This would create a potential source of interference if AHS did not operate on a separate channel. The maximum range setting of the beacons used is about 20 to 30 feet.

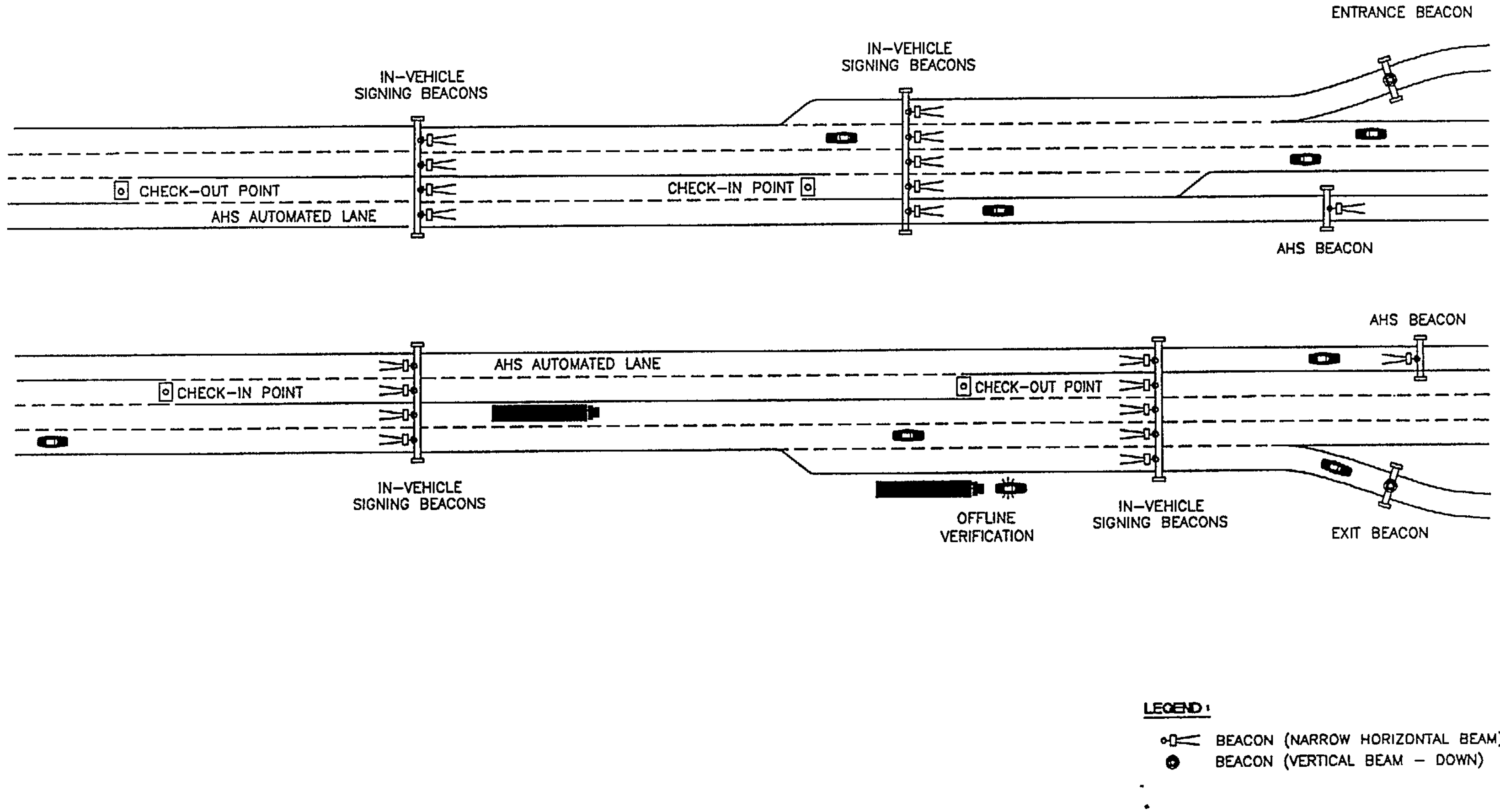

Figure 7. Automated Highway System to Vehicle Communications

3.3.7 Electronic Toll Collection (ETC)

In electronic toll collection, beacons are placed on gantries above toll lanes, and tags are attached to the windshield or license plate of vehicles (see Figure 8). One antenna is typically assigned to each lane. As a vehicle passes through a capture zone beneath the antenna, the antenna sends signals to the tag and receives signals from the tag to implement the toll transaction. To ensure communication with the designated lane and with only one vehicle at a time, beacon synchronization, power control, antenna pattern separation, and antenna multiplexing are used. These interference prevention measures allow one channel to be used for a set of lanes.

Some equipment use a second channel to provide interference-free communications with each set of adjacent lanes, creating a need for two channels. Typically, the original channel is reused if a third set of lanes is instrumented.

In addition, in many toll collection activities, antennas are mounted above the mainline highway, and a pullover toll collection area is provided for non-instrumented vehicles and vehicles whose transactions do not clear. This manual toll collection area is also instrumented with antennas and readers to allow under-funded tags to have additional funds added. This activity could either reuse a channel or require a third channel, depending on the separation distance, equipment, and propagation characteristics of the site. The maximum range setting of the beacons used is about 20 to 30 feet.

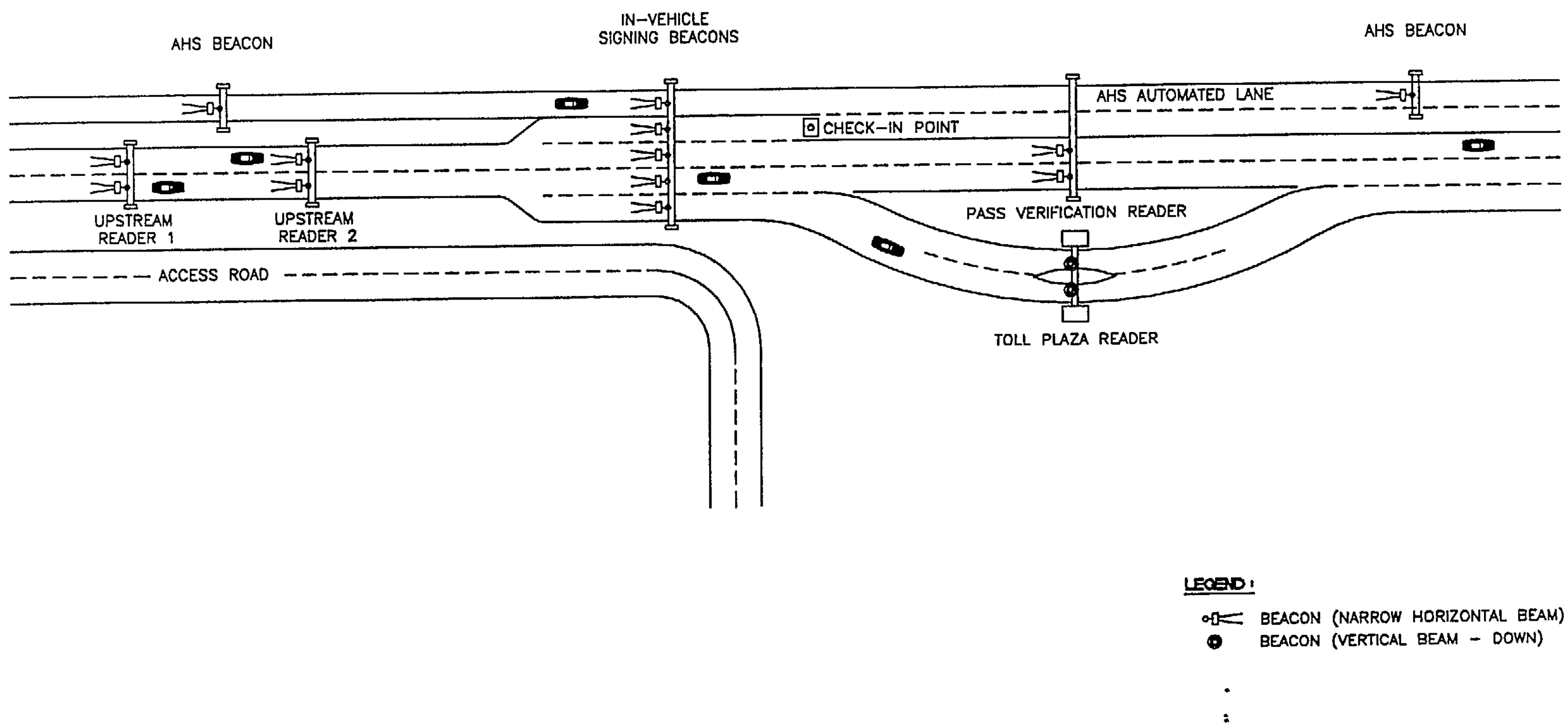

Figure 8. Electronic Toll Collection

3.3.8 Parking Payment / Access Control

The parking payment or access control application is implemented by placing antennas above the lanes entering the parking or restricted area and attaching tags to the windshield or front of vehicles (see Figure 9). One antenna is typically assigned to each lane. As a vehicle passes through a capture zone beneath the antenna, the antenna sends signals to the tag and receives signals from the tag to implement the payment or clearance transaction.

Some equipment use a second channel to provide interference-free communications with each set of adjacent lanes. Therefore, to account for multiple-lane entrance and exit plazas, two channels should be allocated. The maximum range setting of the beacons used is about 20 to 30 feet.

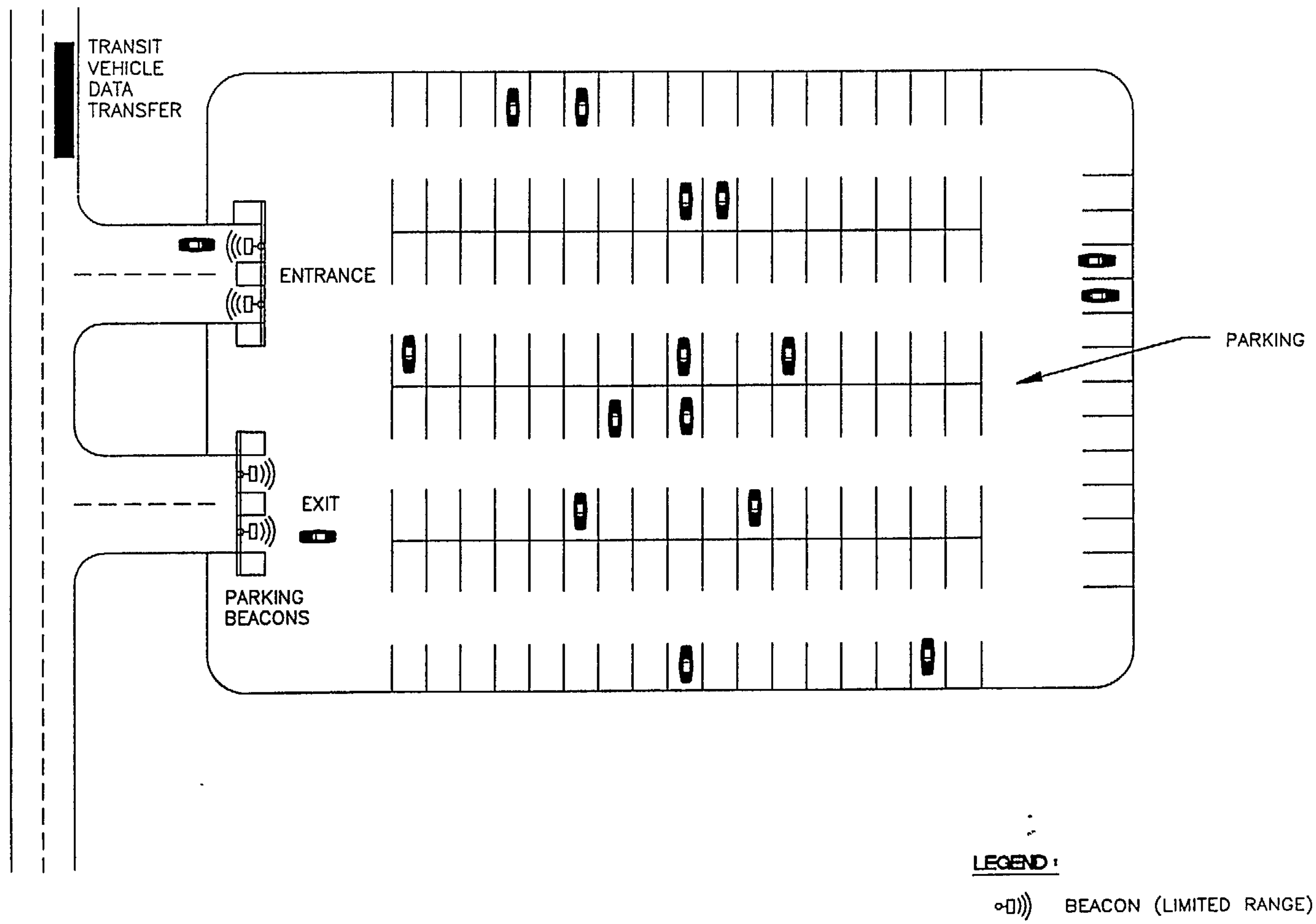

Figure 9. Parking Payment / Access Control Application

3.3.9 Drive-Thru Payments

The drive-thru payment application is implemented by placing an antenna next to the drive-thru lane and attaching tags to the windshield or front of vehicles (see Figure 10). One antenna is typically assigned to each lane. As a vehicle stops in front of the antenna, the antenna sends signals to the tag and receives signals from the tag to implement the payment transaction.

A second channel is needed to provide interference-free communications with each set of adjacent lanes or adjacent business operations. The maximum range setting of the beacons used is about 10 feet.

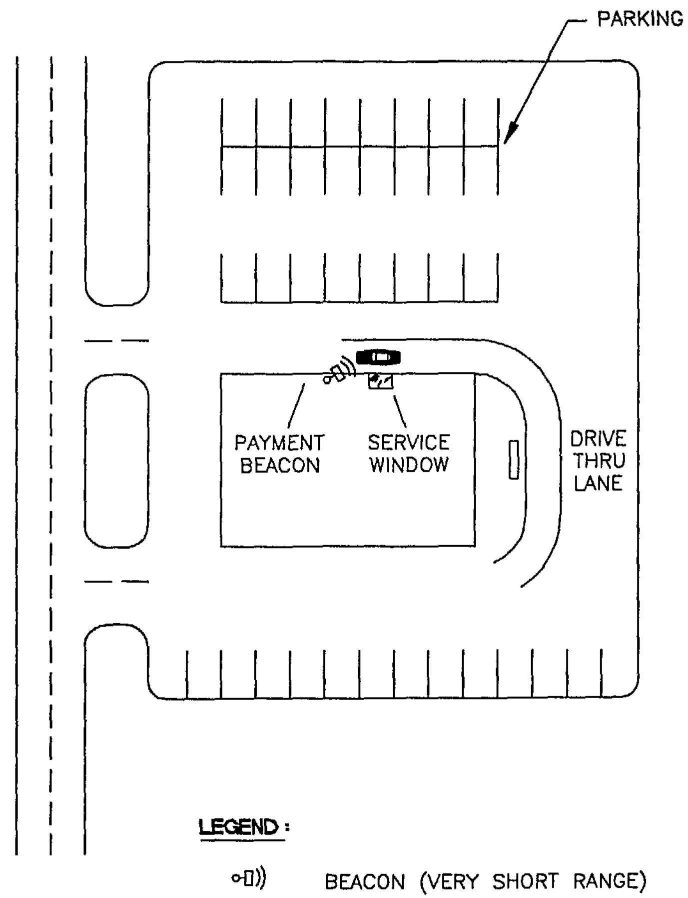

Figure 10. Drive–thru Business

3.4 DSRC Channel Requirements

3.4.1 Individualized Channel Assignment

To begin an analysis of the number of channels required to implement a full DSRC system a reasonable allocation of channels was made based on applications and installation groups. This example of a possible initial assignment of channels is given in Table 1. The channels were assigned in a way that minimizes the occurrence of two or more applications using the same channel in one location. The CVO installation group is almost always located in a different place than an ETC application. The ETC application is usually not located in a place that is near a bus stop. When public parking is located close to one of the other applications the availability of two channels would allow the two most proximate channels to be different.

Table 1. Example Initial Channel Assignment for DSRC Systems

Channel #	Description
1	Fixed In-Vehicle Signing Installation Group
2	In-Vehicle Signing (with a portable beacon)
3 & 4	Intersection Installation Group
5	Intersection Installation Group (Emergency Signal Preemption)
6 & 7	Publicly-Owned CVO Installation Group / Transit Vehicle Data Transfer / Publicly-Owned (AEI / ETC / Parking / Access Control)
8	Mobile Location Interrogation Group
9	Automated Highway Systems
10 & 11	Privately-Owned (AEI / CVO / ETC / Parking / Access Control / Drive-Thru)

The assignment of channels in Table 1 was selected for its ability to minimize the need to coordinate functions or information between applications. The in-vehicle signing installation group was assigned two channels so that a portable sign or construction information could be assigned a specific channel and reduce its interference on nearby fixed in-vehicle signing beacons. Three channels were assigned to the intersection installation group: two channels were assigned to help coordinate assignment of channels of nearby intersections and one channel to help handle emergency signal preemption. The publicly-owned CVO installation group, ETC application and short-range beacons were assigned two channels for coordination of adjacent installations or multiple beacons in close proximity. Channels were set aside for the specialized applications of mobile location interrogation and automated highway systems (channels 8 and 9). Finally, two channels were set aside for privately-controlled (owned) installations such as parking access or fee collection.

Thus far in the analysis, it has been assumed that sufficient bandwidth is available to implement the channel assignments listed in Table 1. However, there is a pressing need to limit the allocation of spectrum to allow the band to be shared more easily with other users. In an example of a similar allocation of spectrum, there are 26 MHz available in the 902 to 928 MHz band, of which only 12 MHz of continuous spectrum are assigned to DSRC applications. Therefore, the analysis will try to reduce the use of bandwidth to the minimum reasonable amount. The analysis will now address interference mitigation assuming fewer channels are available, and will address channel assignments with fewer channels available.

The number of channels required for DSRC can be reduced from those listed in Table 1 by implementing other interference-mitigating techniques. The following paragraphs will describe some of the ways to reduce the number of channels required for DSRC.

3.4.2 Eliminating Channels 2 and 4

The number of channels required for DSRC in-vehicle signing and intersection installation groups can be further reduced by eliminating the distinction between the functions. For example, in-vehicle signing will probably be handled by intersection control beacons rather than separate in-vehicle signing beacons at intersections. Only in locations away from intersections will specific in-vehicle signing beacons be used. Therefore, if the distinction between the functions of channels 1 and 2, and between 3 and 4 is removed, then the functions of the four channels can be consolidated into channels 1 and 2.

3.4.3 Eliminating Channel 5

Signal preemption is very important and requires guaranteed communications channel availability for safety and reliability. However, a separate channel is not required if specific time slots are available only for emergency communications. This would not interfere with collision avoidance because the beacon would send a code directing all tags to listen and not transmit during a collision avoidance message.

A modified slotted aloha scheme is used as an example, below, to show how it can allow virtually instant access for emergency vehicles.

Within a frame in a slotted aloha scheme there are communications time slots and activation time slots. The activation slots are usually much smaller than the communications time slots and are used by in-vehicle tags to announce their “desire” to communicate with the beacon. A tag randomly chooses an activation slot and quickly announces its identification number to the beacon. The beacon then announces to the tag, using the identification number, when it is permitted to communicate. Occasionally, two tags choose the same activation slot and they cause mutual interference such that one or both identification numbers are not received by the beacon. To allow assured communications with emergency vehicles, a single activation slot can be dedicated for emergency vehicles only and the beacon can be programmed to give first priority to the emergency vehicle tags. This, in effect, will give emergency beacons a separate “channel” in time to communicate with the beacon.

3.4.4 Consideration for the Elimination of Channel 3

The second intersection beacon channel would not be needed if the intersection beacons could use time-sharing. Intersection beacons communicating with tags in overlapping or closely spaced coverage areas could alternate communications times such that they would not both operate at the same time. However, the intersection beacon provides a collision warning signal for which every fraction of a second is critical. The intersection collision avoidance signal must not have a mandatory off time and therefore must be installed with two channels at many intersections. Therefore, channel 2 must be preserved.

3.4.5 Consideration for the Elimination of Channels 10 and 11

The private channels can be removed from the list of required channels if the distinction between public and private toll collection, parking, access control and drive-thru beacons could be removed. However, the rules for assignment and operation of these channels may be different for a public organization compared to a private organization. Additionally, even though each of the private channels is intended for very-short-range operation of 5 to 10 feet, a large deployment of private installations could make operating safety-critical systems on the same channels difficult. Finally, interference between private short-range beacons is prevented by alternating the assignment of channels between adjacent businesses or lanes of a business installation. Therefore, these two channels must remain.

3.4.6 Final Suggested Channel Assignment

The final suggested channel assignment for DSRC, after eliminating those channels as described above, is shown in Table 2.

Table 2. Final Suggested Channel Assignment for DSRC Systems

Channel #	Description
1 & 2	In-Vehicle Signing and Intersection Installation Group
3 & 4	Publicly-Owned CVO Installation Group / Transit Vehicle Data Transfer / Publicly-Owned (AEI / ETC / Parking / Access Control)
5	Mobile Location Interrogation Group
6	Automated Highway Systems
7 & 8	Privately-Owned (AEI / CVO / ETC / Parking / Access Control / Drive-Thru)

In this assignment, two channels are set aside for mobile location interrogation and automated highway systems. The mobile location interrogation channel is set aside for reasons of interference mitigation. The automated highway systems channel is set aside to handle the potentially time-critical and distinct operations of that system.

The channel assignment presented in Table 2 is one logical compromise between the desire for more channels for increased functionality and ease of implementation, and the practical limitations on available bandwidth. However, it is important to mention that, for channels used in the same installation group, it is desirable to separate the assigned frequencies as much as possible. This will further reduce the interference potential from devices located close to each other.

3.5 Deployment of the Channel Assignments

To clarify the potential deployment of beacons using the channelization plan just presented, the following paragraphs explain example deployment scenarios for each of the installation groups or DSRC applications described in Section 3.3. The Section also discusses how the assigned channels prevent interference in these deployment situations,

3.5.1 In-Vehicle Signing Installation Group Channel Usage

The applications in the in-vehicle signing installation group (in-vehicle signing, railroad crossing warning, traffic network performance monitoring, and traffic network performance feedback) are implemented by using the assigned channels as shown in Figure 11, In the case of the multi-lane highway, channel 1 is assigned to mainline antennas that are spaced l/2mile to l-l/2 miles apart. The systems use a TDMA protocol to communicate with multiple vehicles in the roadway. The antenna's coverage drops off rapidly as the pattern extends past the lanes of the roadway on either side. Therefore, the antennas are spaced far enough apart both axially and laterally to avoid interference. The beacons placed in the on and off ramps that communicate with one vehicle at a time need only a small capture zone. So, these antennas could be pointed down to minimize their signal footprint and maximize the rejection of signals from other beacons. Used this way they could also use channel 1 in most cases. However, the location of an off or on ramp close to a fixed main-line beacon would occasionally require the use of channel 2. See Appendix D for the sample calculation of reuse distance. Although, the most frequent potential source of interference would be the off-line verification, and that would use channel 5. Figure 12 shows how the channels would be used in a railroad crossing installation. Channel 1 would be used in the upstream warning beacons, placed 300 feet to l/2 mile in both directions away from the intersection. Channel 1 would also be used for both antennas at the crossing. The beacons at the crossing would not interfere with the pre-warning beacons because they would be out of interference range. Since the antennas used in this arrangement would have a high signal rejection rating in the rear antenna pattern, placing them back-to-back does not cause interference.

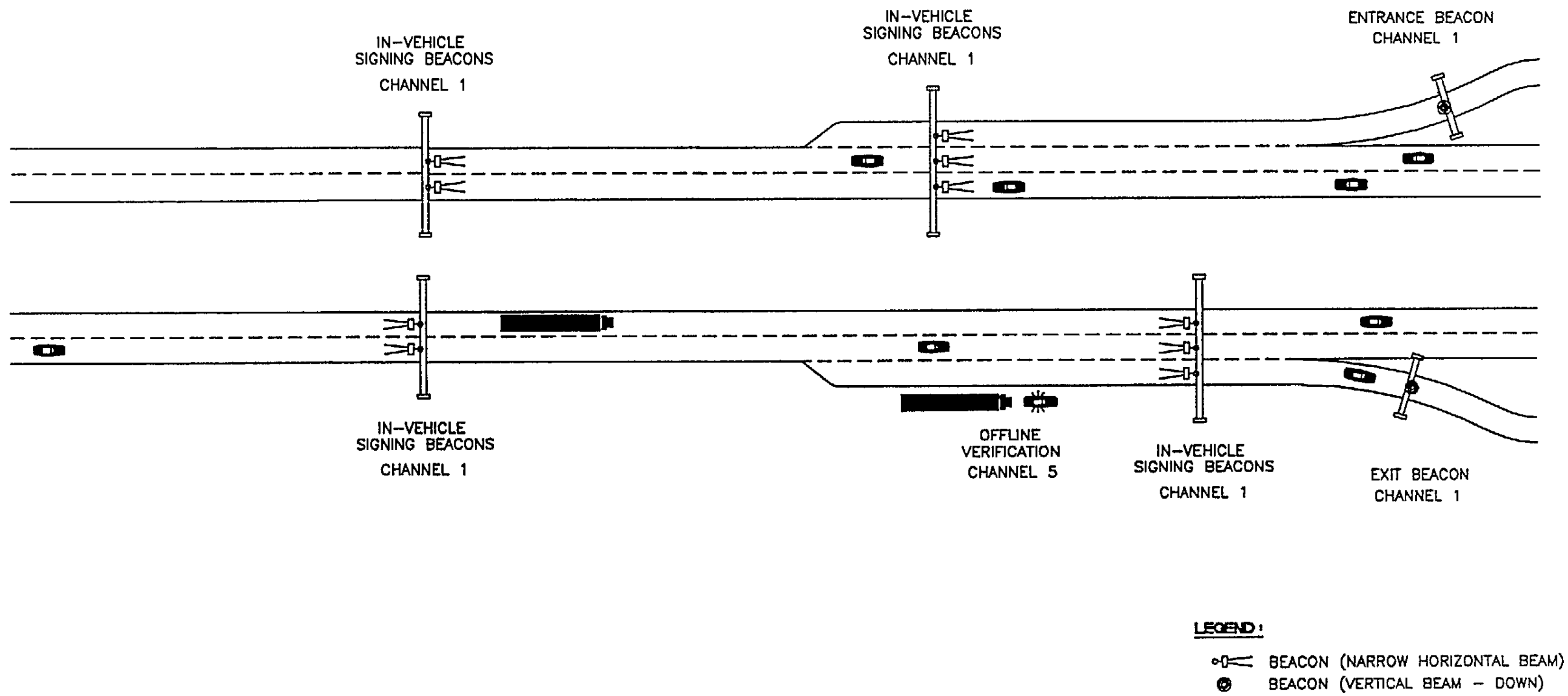

Figure 11. In-Vehicle Signing Installation Group (with channel assignments)

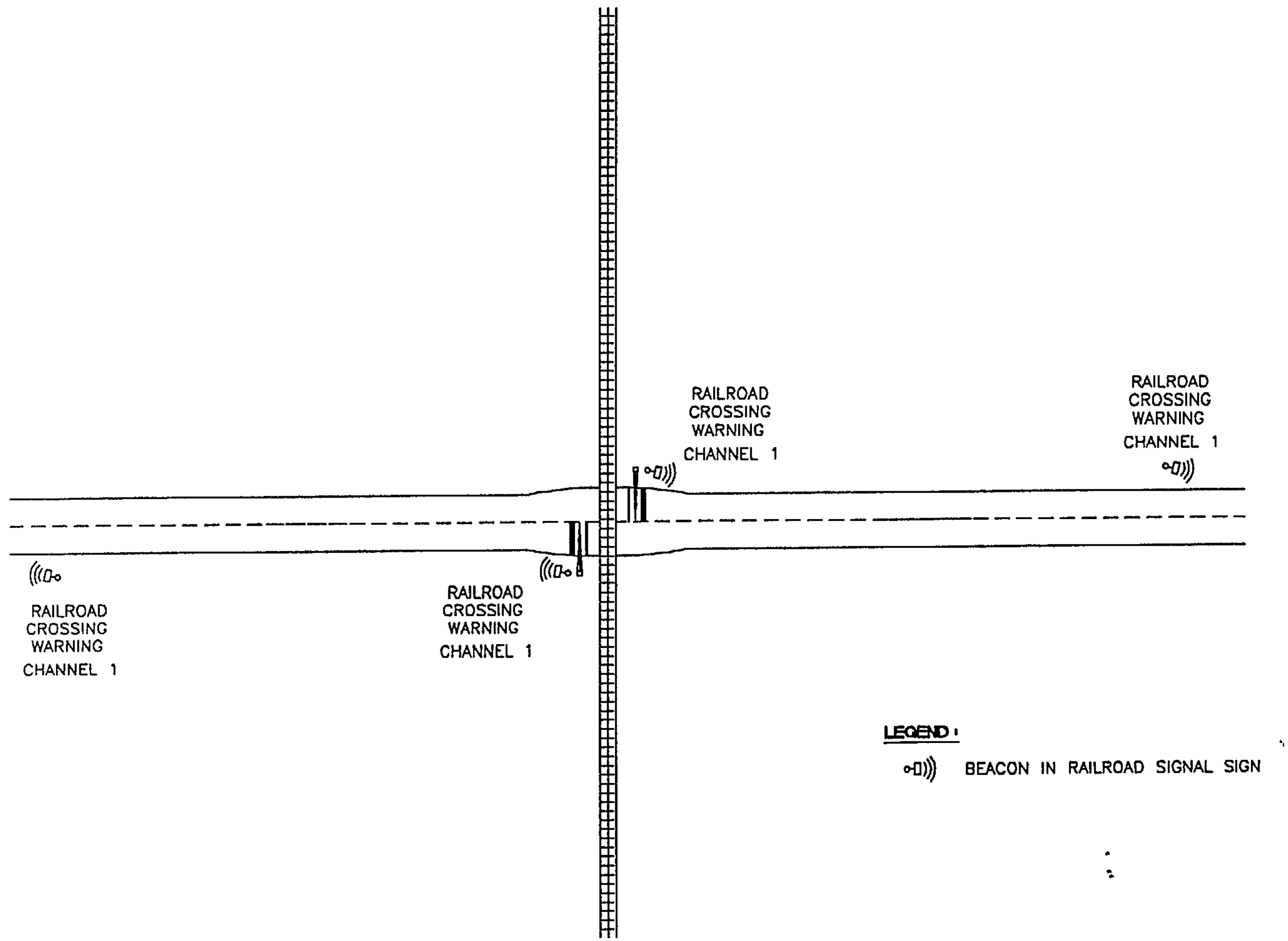

Figure 12. Railroad Crossing Warning (with channel assignment)

3.5.2 CVO Installation Group Channel Usage

The CVO installation group applications (electronic clearance, international border clearance, safety inspection, fleet management, and intermodal freight management) are implemented by using the assigned channels 3 and 4. Electronic clearance and safety inspection are implemented as shown in Figure 13. Electronic clearance is currently implemented by installing weigh in motion (WIM) scales in the roadway and antennas mounted above the roadway that are spaced about l/2 mile upstream of the pass verification reader. These beacons both use channel 3, but are spaced far enough apart axially to avoid interference. Any in-vehicle signing placed between the two would not interfere because it would be on channel 1. The beacons used in the ramp sorter position and exit reader position are directed away from the mainline of the other beacons to prevent interference. The tag update reader in the inspection area would use channel 4 to prevent interference. The most frequent potential source of interference would be the mobile location interrogation and that would use channel 5.

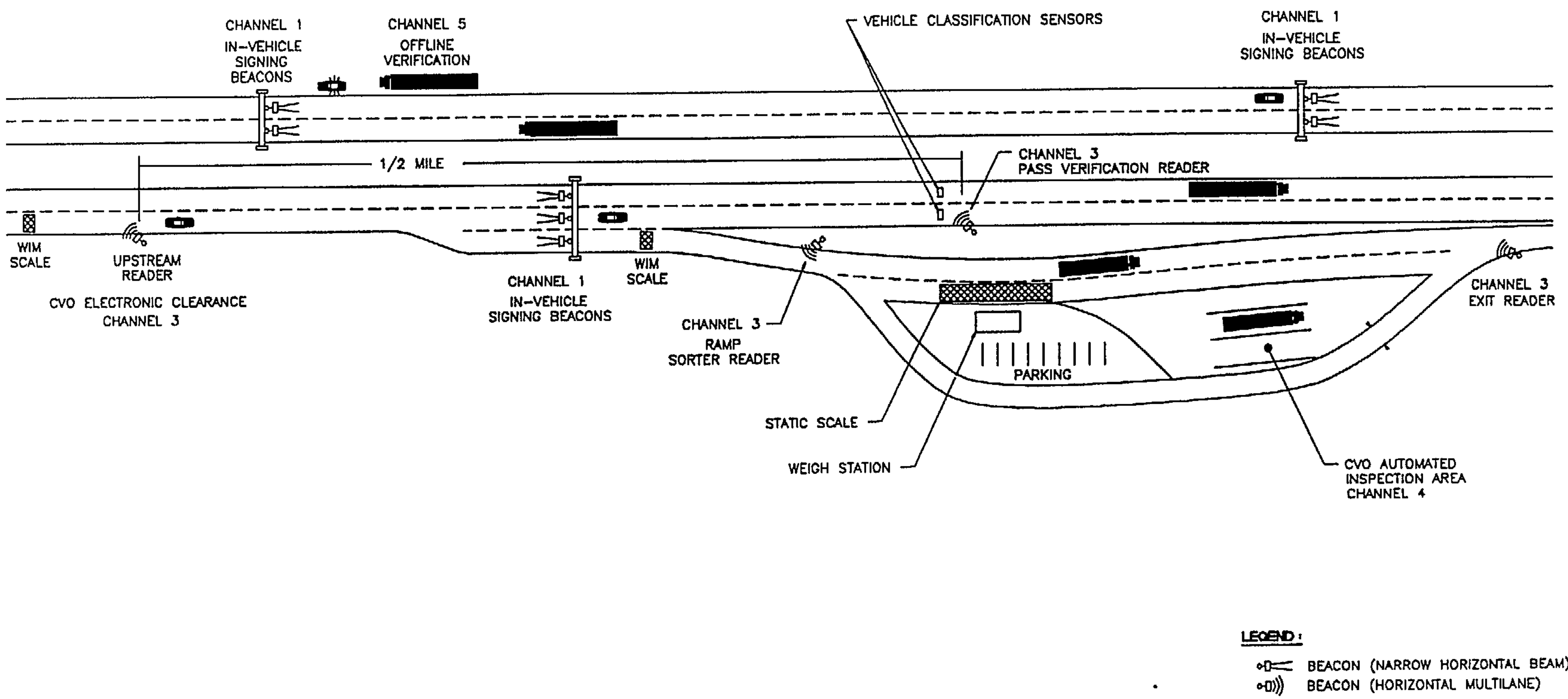

Figure 13. CVO Installation Group (with channel assignments)

International border clearance could be implemented as shown in Figure 14. One set of antennas are installed above the roadway about l/2 mile before the border crossing. The second upstream reader could use channel 4. Reader one, the lock tag reader, could use a frequency from the 902-928 MHz band or channel 4 (See Appendix B). The 902-928 MHz band is being very heavily populated with the AEI devices that identify containers and trailers for freight management. Since this is not a common application among all vehicles and the 902-928 MHz devices have propagation advantages for freight yard use it is desirable to continue using the 902-928 band for the freight management and lock tag purpose. However, if just the lock tag function were moved, the first and second beacons could both use channel 4. They would not interfere with each other because they would be used sequentially. The in-vehicle signing placed between two and three would not interfere because it would be on channel 1. The lane sorter, verification and exit beacons are sighted in different directions to prevent interference with each other and would use channel 3 to prevent interference with the portable reader in the inspection area. The hand-held reader would use channel 4.

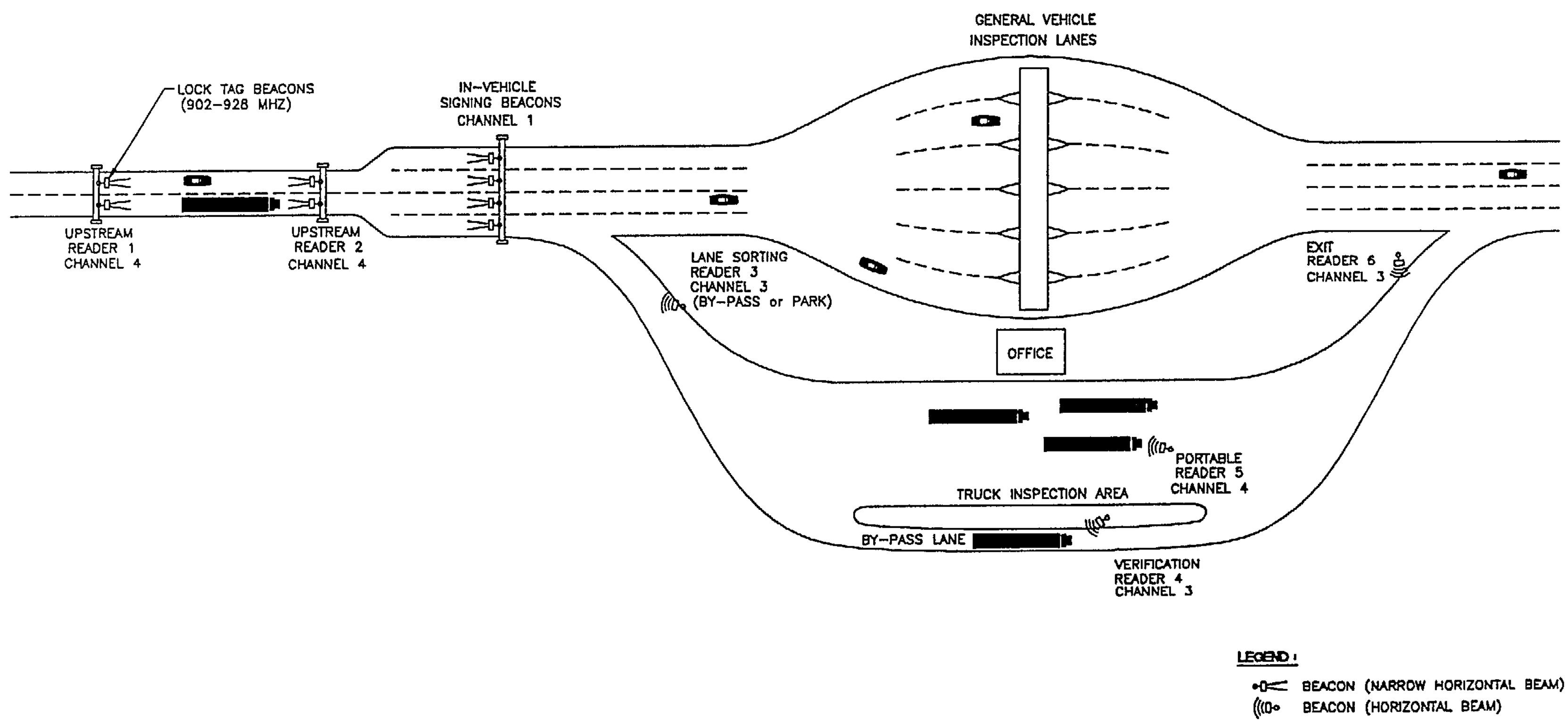

Figure 14. CVO Installation Group – International Border Clearance – with Channel Assignments

3.5.3 Intersection Installation Group

The applications in the intersection installation group (intersection collision avoidance, emergency vehicle signal preemption, and transit vehicle signal priority) are implemented by installing beacons in each direction of on-coming vehicles in the intersection as shown in Figure 15. Channels 1 and 2 are alternated between beacons to prevent cross-reads from intersecting lanes and interference from adjacent intersections. If no cooperating intersections are located upstream, at least two other sets of beacons should be employed on the alternate upstream channel: one at the range limit of the intersection beacon and another 2000 to 3000 feet away to implement collision avoidance and signal preemption. Intersection beacons are expected to use TDMA slotted aloha or similar protocol to communicate with multiple vehicles in the two or three approaching lanes. The transit vehicle data transfer is usually accomplished within the range of the intersection beacon but since it is operating on channel 3, and the vehicle is partially blocking the signal, this does not cause interference. Mobile location interrogation can also occur close to the intersection, but does not cause interference because it operates on channel 5. Four channels could be used in this application.

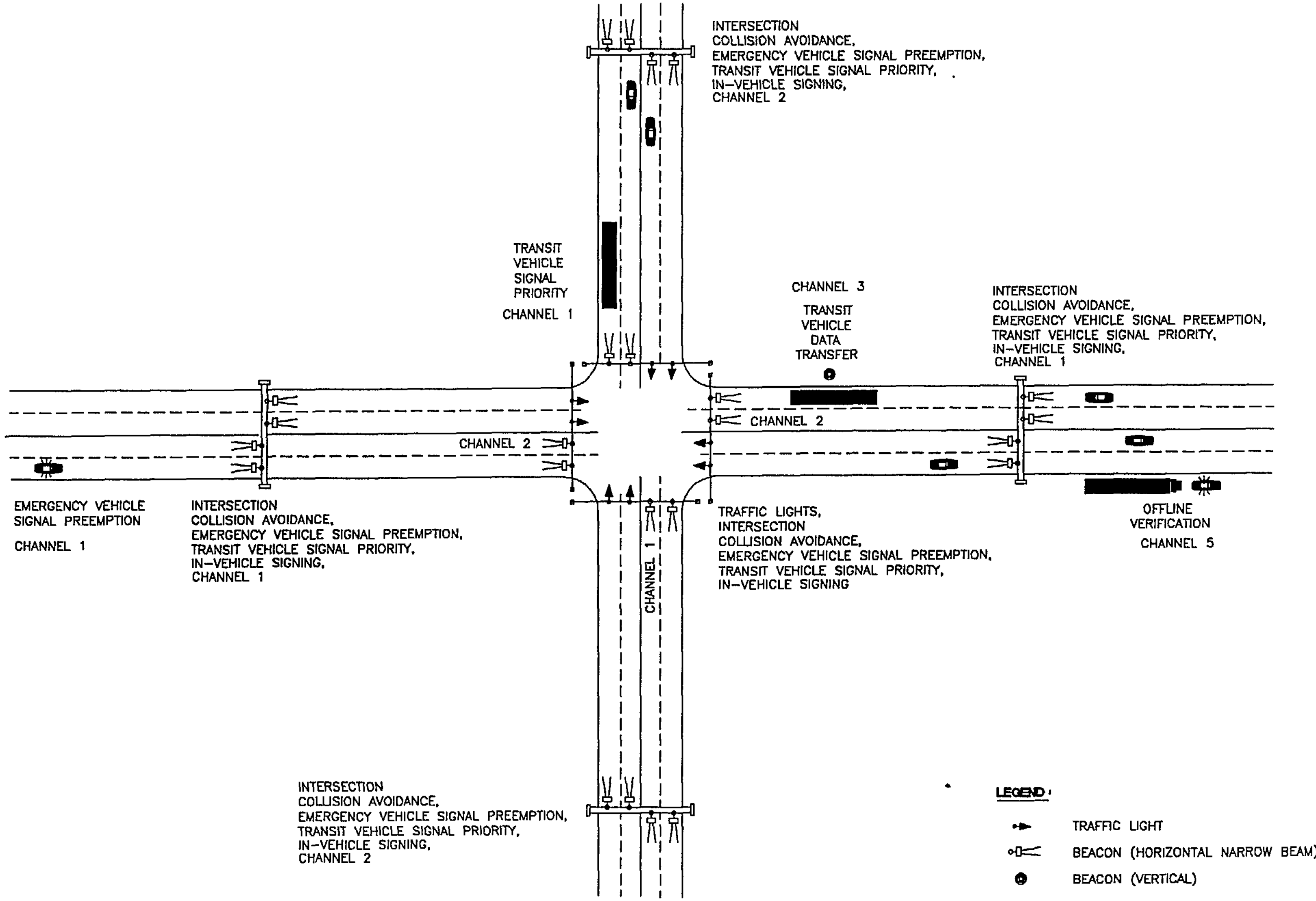

Figure 15. Intersection Installation Group (with channel assignments)

3.5.4 Automated Highway System-to-Vehicle Communications

Automated highway system-to-vehicle communications transfers data on the operational status and position of the AHS vehicle from the vehicle to the roadside, and transfers AHS operation instructions and AHS roadway status from the roadside to the vehicle (see Figure 16). AHS installations will operate on channel 6. Therefore, the location close to the in-vehicle signing or other applications does not cause interference.

3.5.5 Electronic Toll Collection (ETC)

In electronic toll collection, beacons are placed on gantries above toll lanes, and tags are attached to the windshield or license plate of vehicles (see Figure 17). Channels 3 and 4 are alternated between lanes to prevent cross lane interference because they are located close together. In addition, the manual toll collection area is also instrumented with antennas and readers that alternate between channels 3 and 4 to allow under-funded tags to have additional funds added. In-vehicle signing does not interfere because it operates on channel 1. AHS operations do not interfere because they operate on channel 6. Mobile location interrogation does not interfere because it operates on channel 5. In addition, if an intersection were nearby, it would not be interfered with because it would operate on channel 2 with channel 1 as its alternate.

3.5.6 Parking Payment / Access Control

The parking payment or access control application is implemented by placing antennas above the lanes entering the parking area and attaching tags to the windshield or front of vehicles (see Figure 18). Channels 3 and 4 are alternated between lanes to prevent cross lane interference because they are located close together. In addition, a low power setting is used because the capture zone is small and the vehicles are not moving fast. In this example, the transit vehicle data transfer would use channel 4, which is not the most proximate channel being used.

3.5.7 Drive-Thru Payment

In drive-thru payment, beacons are placed close to where the vehicle stops for service and tags are attached to the windshield or license plate of vehicles (see Figure 19). Channels 7 and 8 are alternated between lanes or between business locations to prevent interference. The reuse distance on each channel is small because a low power setting is used for the small capture zone.

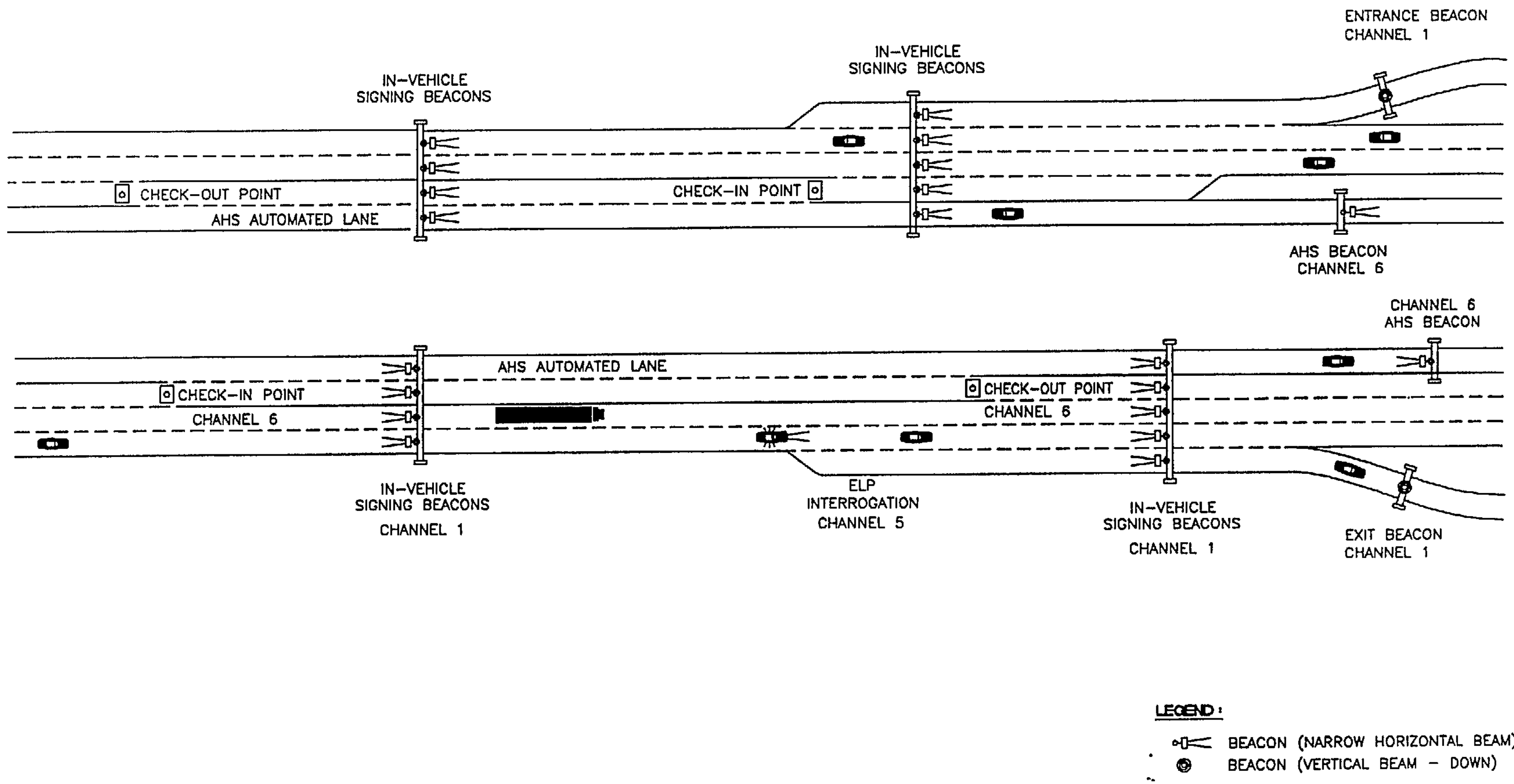

Figure 16. Automated Highway System to Vehicle Communications (with channel assignments)

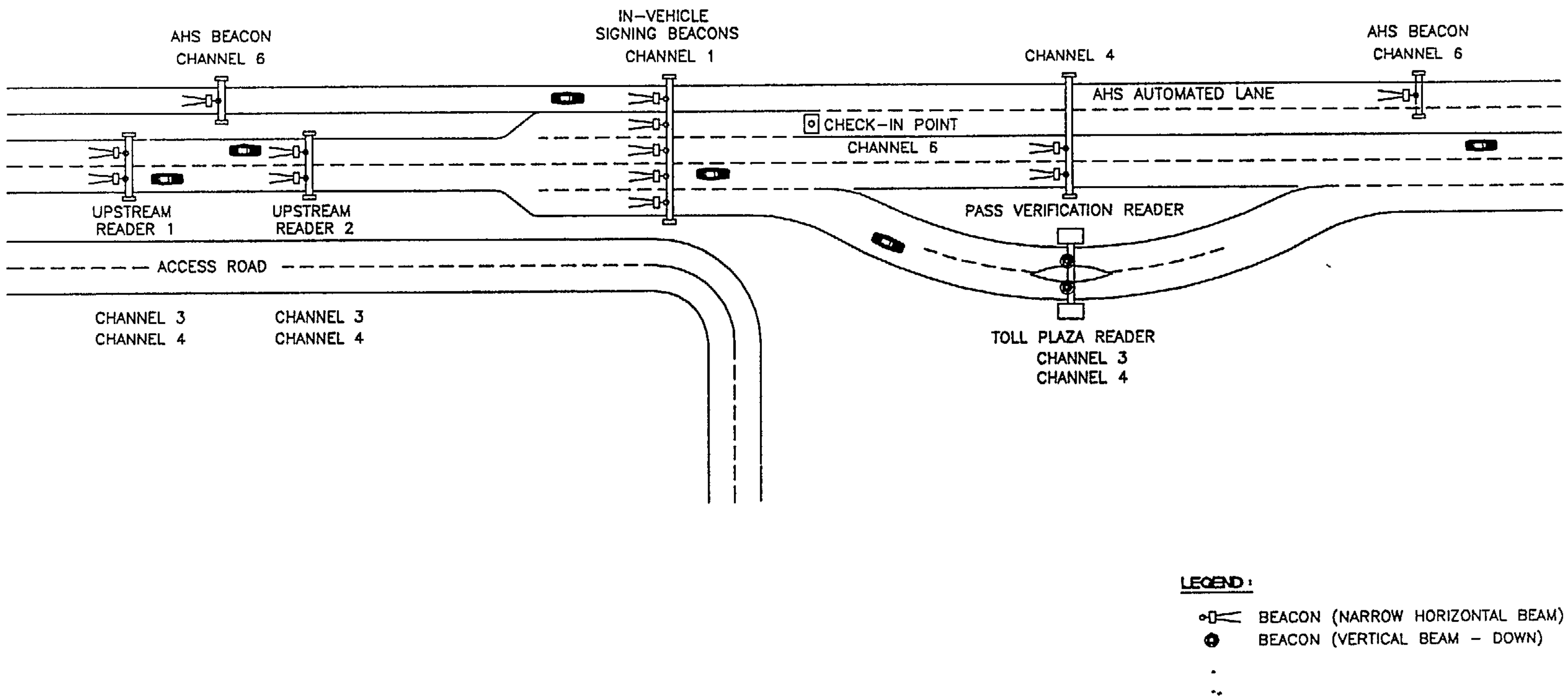

Figure 17. Electronic Toll Collection (with channel assignments)

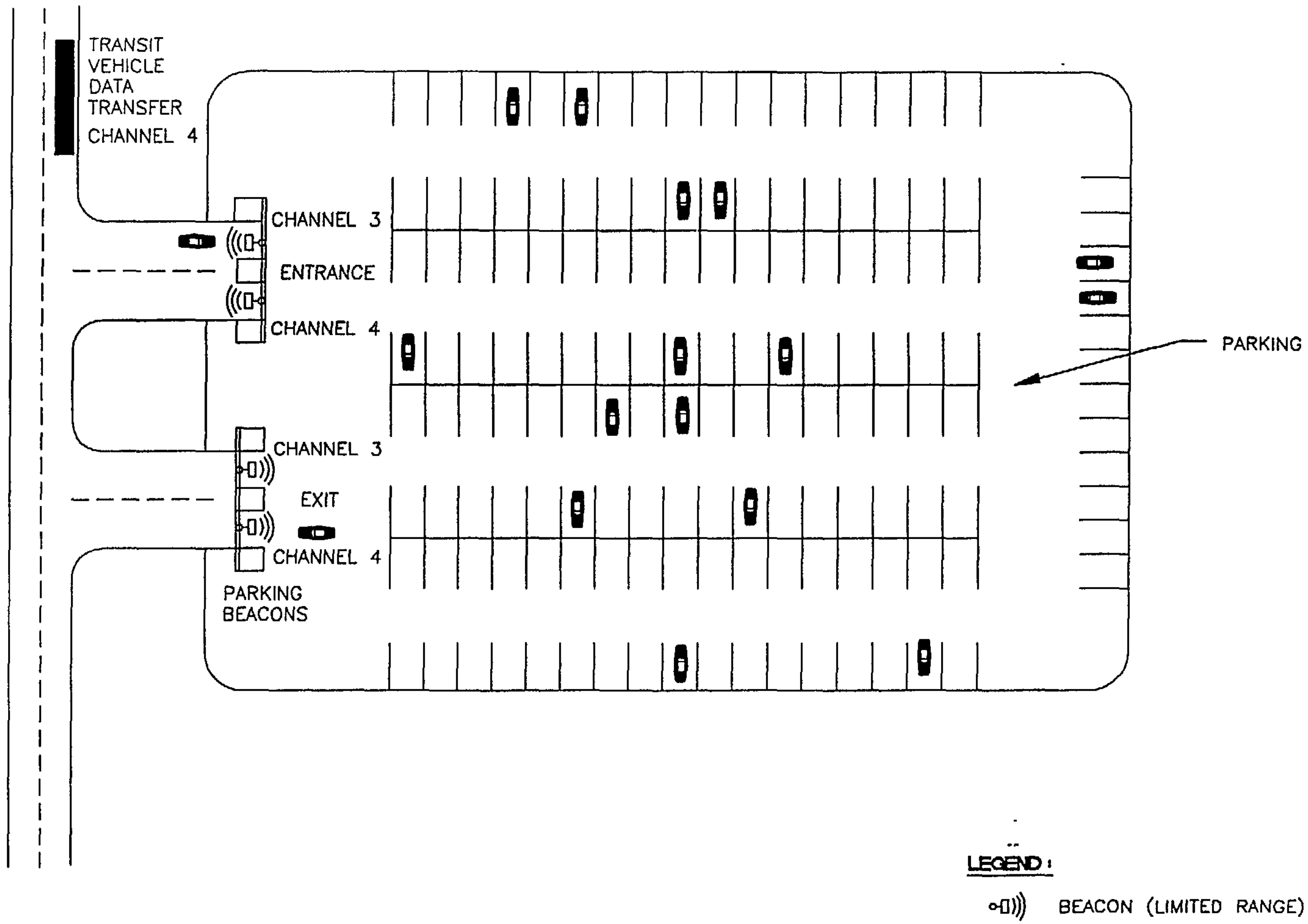

Figure 18. Parking Payment / Access Control Application (with channel assignments)

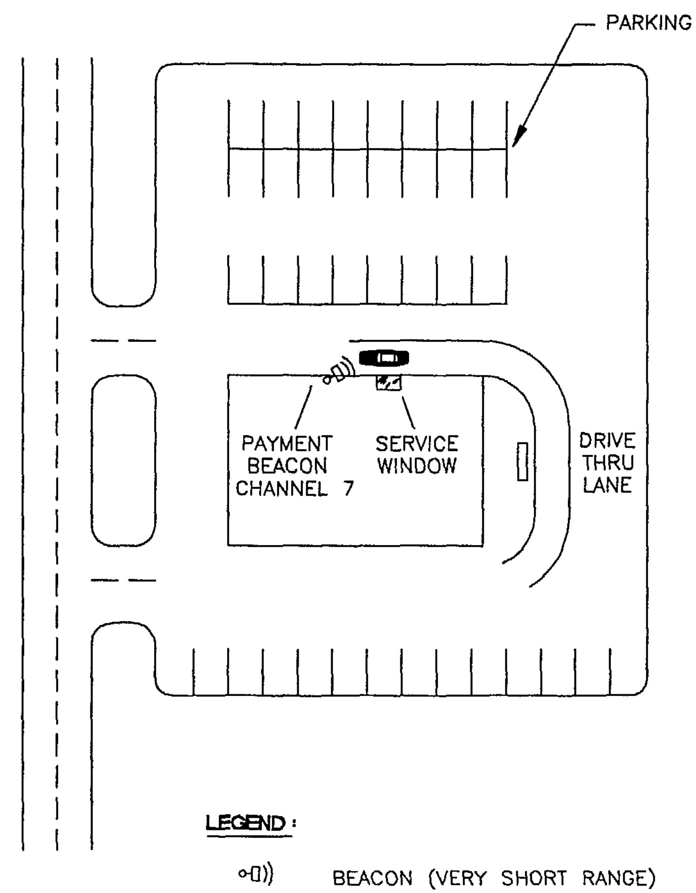

Figure 19. Drive–thru Business with channel assignment

3.5.8 Close Proximity Multiple Application Implementation

This subsection presents a worst-case scenario examining an exceptionally dense collection of applications in one location. In compiling this scenario, it was assumed that a set of routine techniques that allow channel sharing and channel reuse will be used to meet the number of channels allocated in the previous section. This implementation includes an intersection installation group, mobile location interrogation group, transit application, in-vehicle signing group, railroad crossing application, and parking application. Figure 20 shows an actual intersection with DSRC beacons added in several likely locations assuming a full DSRC system implementation. It is intended to be a dense environment of DSRC in order to assess interference mitigation schemes and channel assignment requirements. Beacons shown in Figure 18 include horizontal beacons intended for directional area coverage, and vertical beacons intended to cover a single lane and communicate with vehicles individually. Labels on individual beacons are explained in the following paragraphs.

Using the analyses presented in the earlier sections, the beacons shown in Figure 20 will be assigned channels and mitigation of interference between beacons will be discussed to explain the logic of the assignment. These assignments are listed in Table 3 below. Note that careful timing and coordination between the beacons is required to implement the installations using this channel assignment scheme.

Table 3. Final Suggested Assignment of Channels to Beacons in Example Intersection

Beacon	Channel	Beacon	Channel	Beacon	Channel	Beacon	Channel
A	1	K	2	U	1	EE	3
B	1	L	2	V	1	FF	4
C	2	M	2	W	5	GG	3
D	2	N	1	X	3		
E	2	O	1	Y	4		
F	2	P	1	Z	4		
G	1	Q	1	AA	4		
H	1	R	2	BB	3		
I	2	S	2	CC	4		
J	2	T	1	DD	3		

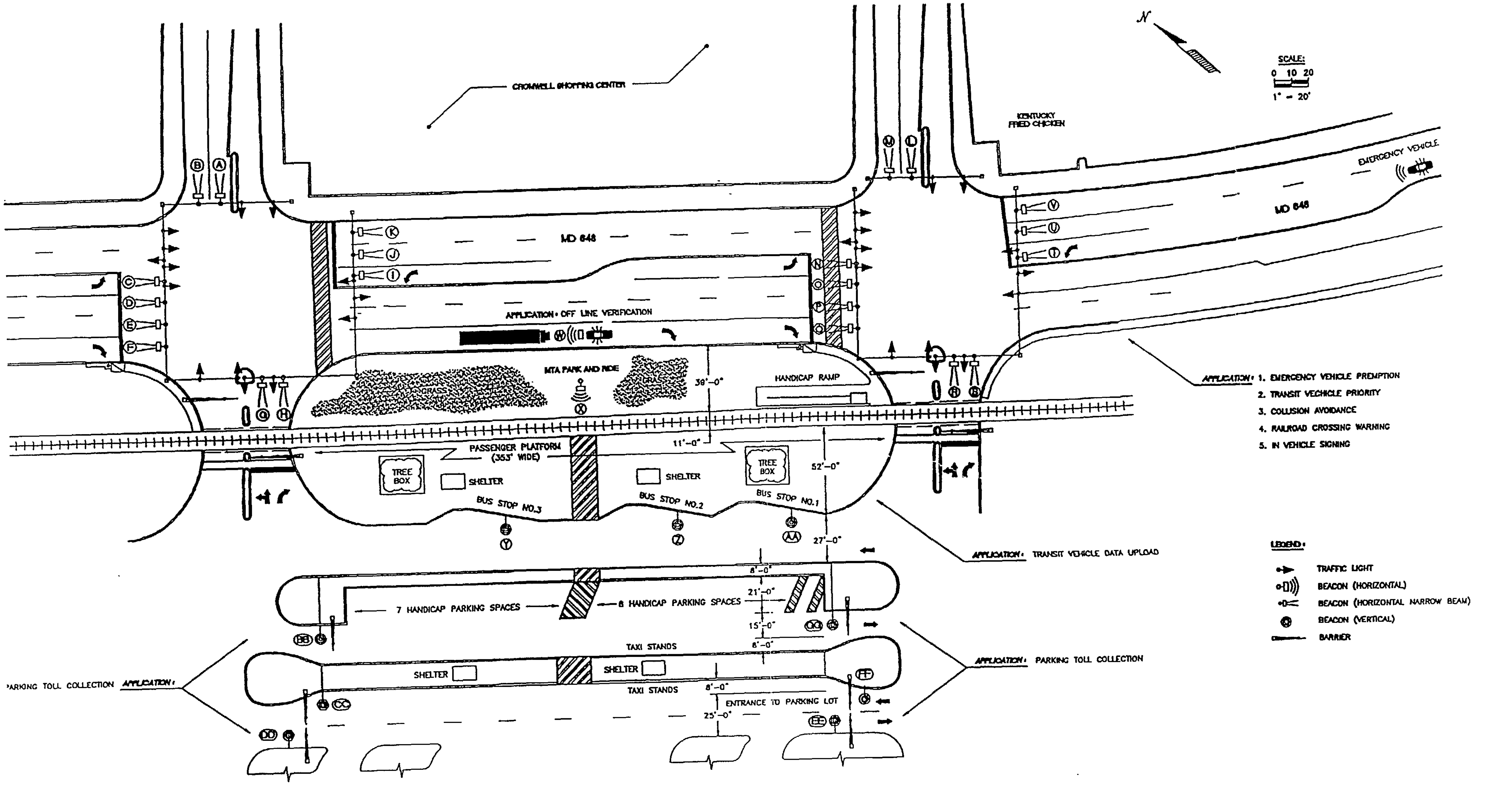

Figure 20. Multiple Group Installation

In this example, each direction of each intersection has one beacon in each lane for emergency vehicle preemption, transit vehicle priority, collision avoidance, railroad crossing warning and any in-vehicle signing required. No beacons are separately assigned to in-vehicle signing in this example, as intersection beacons are assumed to handle this function

Even with the number of channels used in the example intersection there is still a need for power control and spatial differentiation (antenna directivity) to mitigate interference between beacons. For example, the overhead parking beacons (BB - GG) must be carefully aimed and power controlled such that they do not communicate with tags of vehicles passing the parking zone on the roadway, or with the intersection beacons. Also, the power level of the beacon on the rail platform (X) that exchanges data with the Metro rail car (transit vehicle) must be kept as low as possible to avoid interfering with the three bus (transit vehicle) beacons (Y - AA). See Appendix D for sample calculations of channel reuse distances.

All three of the vertical beacons for bus (transit vehicle) data (Y - AA) are considered to be separated by enough distance to use a single channel at a very low power and small communication distances. The horizontal beacon on the rail platform is assigned another channel to mitigate any potential interference.

The mobile location interrogation beacon presents a unique scenario of interference between beacons. As described in Section 2.2, the reflected signal from the tag interrogated by the mobile location interrogation beacon includes a reflection of the intersection beacons that reach the tag. The interference caused by this reflection being received by the intersection beacon effectively reduces the range of the intersection beacon. Assume that the signal-to-interference ratio required for communications between the intersection beacon and another tag is 6 dB. The interference caused by the tag read by the off-line beacon reduces the operating range of the intersection beacon to 70 % of the distance from the intersection beacon to this tag. To mitigate the effects of this interference, the mobile location interrogation should reduce its operating time to the minimum required to complete data transfer. To minimize interference, the mobile location interrogation beacon should also synchronize with any in range stationary beacon, in an over the air link, and obtain an authorized slot sequence in which it can perform communications.

3.6 Summary of Channel Requirements

By using these mitigation techniques, the number of channels required to implement the DSRC systems can be reduced to 8 channels. Several special case situations were considered. Two channels were established for commercial operations so that they could be allocated under different rules, if necessary, and so that there would be no chance of interference with safety critical operations. The AHS function was assigned a single channel to provide an unmistakable and secure channel in which to operate AHS DSRC functions. The same rationale was used to enable a second intersection channel.

4.0 DSRC DATA RATE REQUIREMENTS

4.1 Data Rate Requirement

The required data rate is determined by the amount of data to be transferred, the protocol used to package the data, the data processing time, the channel access scheme and the time segment in which data is being transmitted. This analysis estimates upper bound data rates by assuming worst-case overhead rates and maximum retransmissions for messages adapted from the ITS Architecture and CVO requirements documents. We have also assumed a frame-based (TDMA -like) protocol, as this appears to be the direction the industry is moving.

Since the publishing of the previous paper, much work has been done on refining message content estimates and forecasting operating parameters. The data rates computed in the previous paper have been revised using the latest information on current systems, user requirements and developing standards to establish assumed values for the following underlined parameters. The parameters that are not underlined were computed from the underlined parameters:

- <u>Capture Zone</u> - length of the roadway over which the beacon antenna can create the proper signal level to enable communications - in feet;
- <u>Speed</u> - maximum vehicle speed during which communication shall be possible - in feet/sec;
- <u>Message No.</u> - number of messages passed for each transaction;
- <u>Overhead</u> - fraction of the message protocol not used for carrying application data;
- <u>Processing Time</u> - time used to compute the response to the messages - in seconds;
- Read Time / Frame - time in which the message data of each frame must be read - in seconds;
- <u>Max Read Time</u> - time that the vehicle is in the capture zone or, if the vehicle speed is zero, maximum time allowed for the transaction to occur (values for moving vehicles were computed) - in seconds;
- Frames Used - number of communications units (frames) used to send the messages;
- <u>Slots/Frame</u> - number of message data sections in each frame;
- <u>Max Slot Data</u> - maximum number of bits sent in each frame - bits;
- <u>Msg 1 Size</u> - number of bits in the first message of a transaction (downlink) - bits;
- <u>Msg 2 Size</u> - number of bits in the second message of a transaction (uplink) - bits;
- <u>Msg 3 Size</u> - number of bits in the third message of a transaction (downlink) - bits;
- <u>Msg 4 Size</u> - number of bits in the fourth message of a transaction (uplink) - bits;
- Total Size - number of bits in all the messages - bits; and
- Data Rate - maximum rate needed to send any one message in a transaction.

Figure 21 shows the relationship of the communication components in a lane-based transaction scenario. The lane-based scenario involves a short capture zone and communication with only one vehicle at a time. Figure 22 shows the relationship of the communication components in an open-road-based transaction scenario.

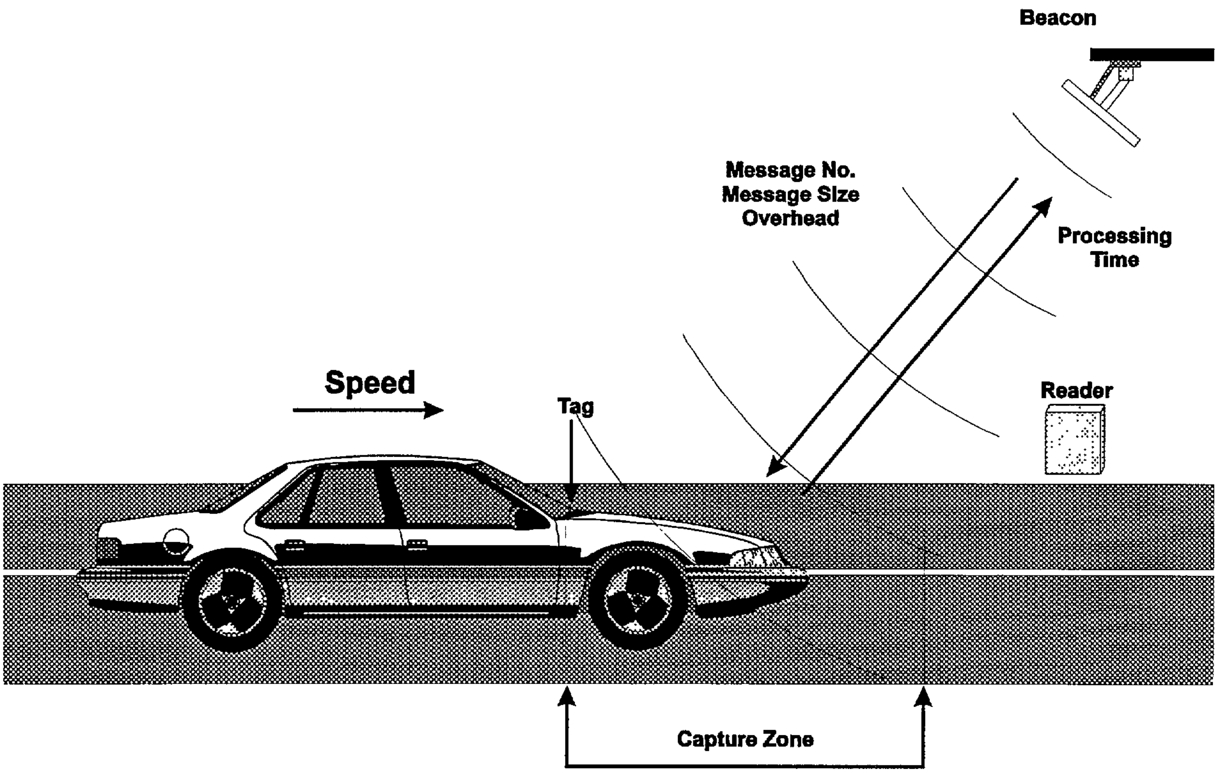

Figure 21. Lane Based Transaction Scenario (Single Communication Session)

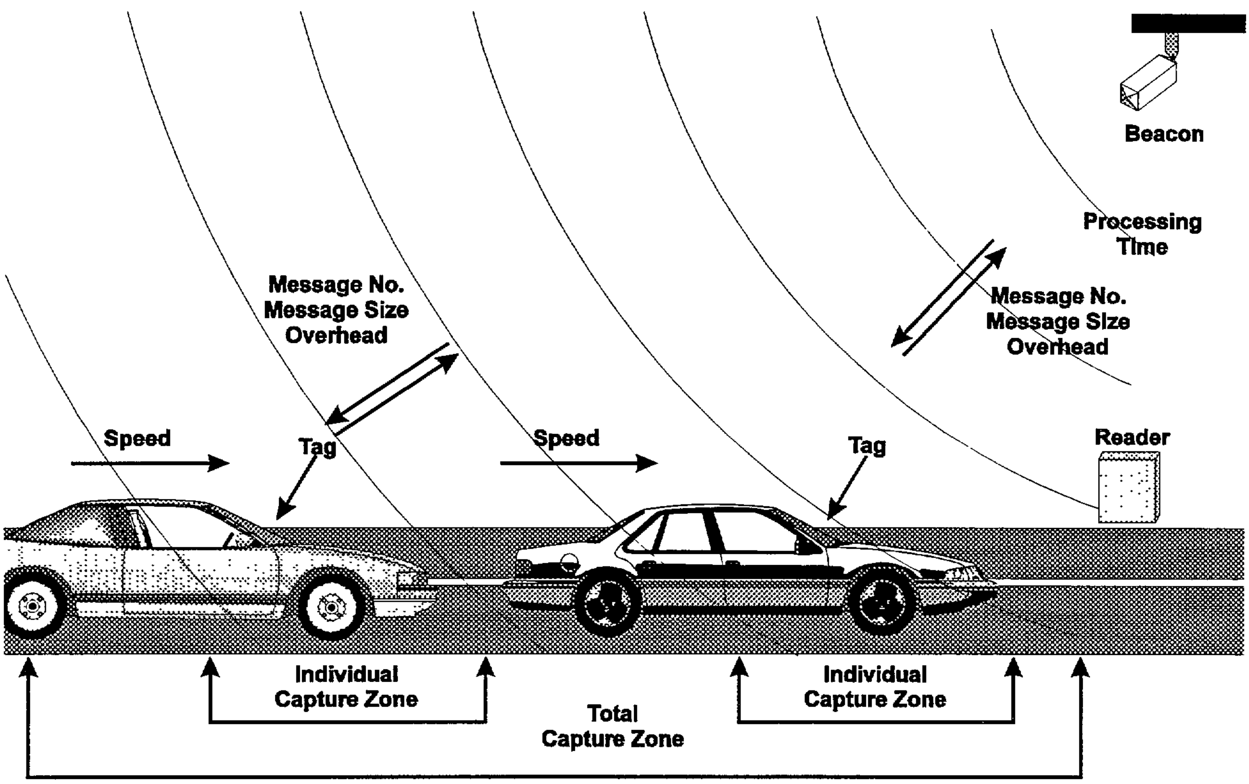

Figure 22. Open Road Transaction Scenario (Multiple Communication Sessions)

The open-road scenario includes a large capture zone in which it is possible to accomplish multiple transactions. The overhead is usually larger in this scenario than in the lane-based scenario because a significant amount of time is used to determine the access timing of the vehicles.

Table 4 lists the value of the parameters used for each transaction. The possible communication time was estimated by subtracting the processing time estimate from the time the vehicle would spend in the capture zone at maximum speed. For those transactions where the vehicle speed is expected to be zero, a default time limit, measured in seconds, was selected. The time actually spent transferring data (read time/frame) was then approximated by dividing the possible communication time by the number of frames and retransmissions needed to send the messages plus an extra net entry frame. The extra frame allowed the vehicle to enter the capture zone and receive the beacon signal until the beginning of a frame started. This allowed the tag to receive the all data in the starting frame correctly. The calculation always used two as the number of allowed retransmissions. Then the overhead was applied to the result. Each frame was assumed to be timed for a fixed data slot capacity in multiples of 560 bits. So, if the message data sent in a frame was 193 bits the frame would still take 560 bit time intervals to deliver the data. Therefore, the data rate was estimated from the number of message bits allocated in the timing of each frame and not the actual bits sent in the frame. The approximate data rate was computed by dividing the total number of bits allocated to each frame (Max Slot Data) by the available read time for each frame. The number of bits came from a hypothetical message set created for each transaction currently anticipated to be used for the ITS DSRC applications, see Appendix F. Messages from currently deployed applications were used as reference. However, the currently deployed applications use many different data sets, protocols and implementation procedures. Also, they do not represent all the functions that are expected to be deployed. Therefore, the message database represents an approximation of the data actually expected to be communicated.

Table 5 lists the transactions, applications, number of bits to be sent in the downlink (beacon to tag), number of bits to be sent in the uplink (tag to reader), the total number of bits to be sent (total size), and the data rate necessary to accomplish the transfer. The total number of bits to be sent includes both the downlink and uplink count of bits. The uplink bit count is smaller than the downlink bits for some transactions and larger than the downlink bits in other transactions. Therefore, the data rate is considered the highest rate required to send any of the messages in the transaction evaluated. The data rate must allow one transmission and up to two retransmissions, when necessary, in the time the vehicle is in the communication zone. The data to be transferred includes all ancillary characters like headers, transaction code, message length and Cyclic Redundancy Check (CRC) as well as the transaction data.

Table 4 – Transaction Parameters

ID	Transaction	Capture Zone (ft)	Speed (ft/sec)	Message No.	Overhead	Processing Time (seconds)	Read Time /Frame (seconds)	Max Read Time (seconds)	Frame s Used	Slots /Frame)	Max Slot Data (bits)	Msg 1 Size (bits)	Msg 2 Size (bits)	Msg 3 Size (bits)	Msg 4 Size (bits)	Total Size (bits)	Data Rate (bits/sec)
1	Toll Payment	10	182.3	3	0.69	0.020000	0.001201	0.055	3	1	560	72	240	124	0	436	466453
2	Obtain Parking Fee	10	0	3	0.69	0.040000	0.029760	1.000	4	1	560	72	80	124	0	276	18817
3	Parking Payment	10	0	3	0.69	0.020000	0.030380	1.000	4	1	560	72	240	124	0	436	18433
4	Drive-Thru Payment	10	0	3	0.69	0.020000	0.030380	1.000	4	1	560	232	232	276	0	740	18433
5	Sign Data	16	182.3	3	0.89	0.000100	0.000964	0.082	4	1	560	72	175	136	0	383	580707
6	Border Clearance	30	182.3	3	0.89	0.040000	0.001370	0.165	4	2	560	88	200	131	0	419	408699
7	Lock Tag Data	5	182.3	2	0.69	0.000100	0.001210	0.027	3	1	560	56	109	0	0	165	462730
8	Screening	30	182.3	3	0.77	0.040000	0.002865	0.165	4	2	1120	88	1042	310	0	1440	390929
9	Safety Inspection	10	0	3	0.69	0.001000	0.030969	1.000	4	1	560	88	151	156	0	395	18083
10	Safety Data Upload	30	182.3	2	0.89	0.000100	0.002584	0.165	3	1	560	56	162	0	0	218	216682
11	Access Control	10	0	3	0.69	0.010000	0.030690	1.000	4	1	560	72	175	72	0	319	18247
12	Driver's Daily Log Upload	10	0	2	0.69	0.000100	0.044281	1.000	3	1	560	72	180	0	0	252	12646
13	Registration Data Upload	10	0	3	0.77	0.010000	0.022770	1.000	4	2	1120	80	712	312	0	1104	49188
14	Signal Preemption	16	182.3	3	0.89	0.000100	0.000964	0.082	4	1	560	72	88	104	0	264	580707
15	Signal Priority Request	16	182.3	3	0.89	0.000100	0.000964	0.082	4	1	560	72	88	104	0	264	580707
16	Transit Fleet Status	10	0	3	0.69	0.100000	0.021462	1.000	5	1	560	64	72	696	0	832	26093
17	Traveler Information	10	0	2	0.54	0.100000	0.067231	2.000	5	4	2240	2456	2456	0	0	4912	18265
18	Fare Enforcement	10	0	4	0.54	0.000100	0.016880	4.000	37	4	2240	72	480	88	73784	74424	132699
19	Transit Vehicle Conditions	10	0	2	0.69	0.000100	0.044281	1.000	3	1	560	72	476	0	0	548	12646
20	Transit Vehicle Passenger And Use Data	10	0	2	0.69	0.000100	0.028180	2.000	8	1	560	72	2944	0	0	3016	19872
21	Driver Instructions	10	0	1	0.54	0.000100	0.057497	2.000	6	4	2240	9272	0	0	0	9272	32252
22	Advance Payment For Services	10	0	3	0.69	0.000100	0.019373	1.000	6	1	560	72	1288	376	0	1736	28906
23	Update The In-Vehicle Kiosk	10	0	1	0.54	0.000100	0.004191	60.000	2196	4	2240	4915808	0	0	0	4915808	534409
24	Fare Payment (Credit Card)	10	0	2	0.69	1.000000	0.031000	2.000	4	1	560	648	64	0	0	712	18065
25	Fare Payment (SMART Card)	10	0	3	0.69	0.040000	0.022892	1.000	5	1	560	648	72	64	0	784	24462
26	AHS Vehicle Data	10	0	2	0.69	0.001000	0.023822	1.000	5	1	560	72	1241	0	0	1313	23507
27	AHS Control Data Update	20	182.3	3	0.54	0.000100	0.003878	0.110	5	4	2240	72	205	4152	0	4429	577546
28	AHS Check Response	20	182.3	3	0.54	0.000100	0.003878	0.110	5	4	2240	72	205	4153	0	4430	577546
29	Speed and Headway	16	182.3	2	0.89	0.000100	0.001378	0.082	3	1	560	72	110	0	0	182	406495
30	Vehicle Probe Data	16	182.3	2	0.89	0.000100	0.001378	0.082	3	1	560	80	193	0	0	273	406495
31	Intersection Status	16	182.3	3	0.89	0.000100	0.000964	0.082	4	1	560	72	193	116	0	381	580707

Table 5. Transaction Summary

ID	Function	Transaction	Downlink (bits)	Uplink (bits)	Total Size (bits)	Data Rate (bits/sec)
1	Electronic Toll Collection	Toll Payment	196	240	436	466453
2	Parking Payments	Obtain Parking Fee	196	80	276	18817
3	Parking Payments	Parking Payment	196	240	436	18433
4	Drive-Thru Payments	Drive-Thru Payments	508	232	740	18433
5	In-Vehicle Signing & Traffic Information	Sign Data	208	175	383	580707
6	CVO International Border Clearance	Border Clearance	219	200	419	408699
7	CVO International Border Clearance	Lock Tag Data	56	109	165	462730
8	CVO Electronic Clearance	Screening	398	1042	1440	390929
9	CVO Safety Inspection	Safety Inspection	244	151	395	18083
10	CVO Fleet & Freight Management	Safety Data Upload	56	162	218	216682
11	CVO Fleet & Freight Management	Access Control	144	175	319	18247
12	CVO Fleet & Freight Management	Driver’s Daily Log Upload	72	180	252	12646
13	Off-Line Verification & Electronic License Plate	Registration Data Upload	392	712	1104	49188
14	Emergency Vehicle Signal Preemption	Signal Preemption	176	88	264	580707
15	Transit Vehicle Signal Priority	Signal Priority Request	176	88	264	580707
16	Transit Vehicle Data Transfer	Transit Fleet Status	760	72	832	26093
17	Transit Vehicle Data Transfer	Traveler Information	2456	2456	4912	18265
18	Transit Vehicle Data Transfer	Fare Enforcement	160	74264	74424	132699
19	Transit Vehicle Data Transfer	Transit Vehicle Conditions	72	476	548	12646
20	Transit Vehicle Data Transfer	Transit Vehicle Passenger And Use Data	72	2944	3016	19872
21	Transit Vehicle Data Transfer	Driver Instructions	9272	0	9272	32252
22	Transit Vehicle Data Transfer	Advance Payment for Services	448	1288	1736	28906
23	Transit Vehicle Data Transfer	Update The In-Vehicle Kiosk	4915808	0	4915808	534409
24	Transit Vehicle Data Transfer	Fare Payment (Credit Card)	648	64	712	18065
25	Transit Vehicle Data Transfer	Fare Payment (SMART Card)	712	72	784	24462
26	Automated Highway System to Vehicle Communications	AHS Vehicle Data	72	1241	1313	23507
27	Automated Highway System to Vehicle Communications	AHS Control Data Update	4224	205	4429	577546
28	Automated Highway System to Vehicle Communications	AHS Check Response	4225	205	4430	577546
29	Automated Highway System to Vehicle Communications	Speed and Headway	72	110	182	406495
30	Traffic Network Performance Monitoring	Vehicle Probe Data	80	193	273	406495
31	Intersection Collision Avoidance	Intersection Status	188	193	381	580707

The largest data rate estimated from the proposed requirements is 580707 bps. Typical upper level data rates supported by DSRC equipment currently manufactured ranges from 500 to 600 kbps. A data rate requirement of 600 kbps is selected because it will meet the estimated data rate forecast.

4.2 Channel Bandwidth Requirement

The bandwidth required for DSRC is affected by a number of factors including data rate, modulation type, modulation rate, encoding scheme, difference frequencies, output power, antenna separation (or installation density), propagation characteristics, system out-of-channel emissions requirements, and FCC out-of-band emissions requirements. The primary constituent of the total bandwidth needed is the necessary bandwidth, that amount used to transmit the signal with the quality required, and the secondary factor is the bandwidth needed to allow the amplitude of the harmonics to decrease below the system out-of-channel and FCC out-of-band emissions requirements. Having determined the data rate we can now compute the channel bandwidth required for the DSRC applications.

Currently, several different air interface specifications are used to perform DSRC communications in the 5.8 ISM band - mostly in European and Asian countries. The European Prestandard, CEN TC278, DSRC Physical Layer using Microwave at 5.8 GHz, is the 5.8 GHz air interface specification that contains the most detail at this time. However, the developing Draft ASTM Standard for Dedicated, Short Range, Two-Way Vehicle to Roadside Communications Equipment is adaptable to 5.8 GHz and has been tested in Asia operating in this mode. Neither, however, fully supports all the DSRC applications expected to be implemented. The European Prestandard supports multiple channels and up to 50-foot (15-meter) ranges, and equipment based on the draft ASTM standard supports one-channel operation and more than 100-foot (30-meter) ranges. Multiple channels and more than 100-foot (30-meter) ranges will be needed to encompass all the likely applications discussed here. Therefore, the bandwidth determination should be based on an expected combination of operating characteristics between the two specifications but mostly on the European Prestandard.

The required bandwidth was determined by performing an emulation of the expected transmission characteristics and plotting a spectral diagram of the results (See Appendix C, Spectrum Requirements for a Dedicated Short Range Communications (DSRC) Channel). The calculations included the European prestandard operating characteristics but the data rate was moved up to 600 kbps and the subcarrier frequencies were moved to 1800 kHz and 2400 kHz to accommodate the higher data rate. The emulation showed that the 600 kbps data rate could be transmitted within 6 MHz of bandwidth using baseband signal shaping and filtering. In addition, it is also possible to transmit the 600 kbps in 6 MHz using the ASTM draft standard. Since one option in the ASTM draft standard uses ASK for both the downlink and uplink the FCC formula below can be used to compute the minimum necessary bandwidth directly:

B_n = KB for two-level amplitude modulation [8]

In the above formula, K is a constant with value between 3 for a non-fading channel to 5 for a fading channel, and B is the modulation rate in baud. We use the downlink modulation method assumptions listed previously (ASK with Manchester encoding) and a data rate of 600 kbps. Manchester encoding causes the modulation rate to vary depending upon the exact sequence of information bits. The highest rate occurs when there is a contiguous sequence of “1” or “0” bits; during such a situation the modulation rate would be twice the data rate. Therefore, B = 1200 kbps. The channel characteristics for DSRC are closest to a non-fading channel, due to the short ranges involved. As a consequence of these assumptions, Bn = 3.6 MHz. However, we still need to account for the harmonics and out-of-channel emissions limits.

Of concern when allocating spectrum for DSRC systems are frequency separation and frequency reuse. The assigned channel bandwidth should allow multiple data transmissions with the desired accuracy at different frequencies so that the transmissions do not interfere with each other and do not violate the out-of-band emissions requirements. The bandwidth for current DSRC equipment is generally constrained by the FCC requirement on the LMS band to reduce out-of-band signal levels by 55 + 10 log(P) dB, where P is the effective power of the transmitter. Hence, the channel bandwidth would be set as twice the frequency offset at which the transmitted signal spectrum was 65 dB below that of the center frequency (assuming an Effective Isotropic Radiated Power (EIRP) of 10 Watts). In an ideal world, we would build a filter which completely eliminated everything outside the necessary bandwidth. Of course, that is not possible and we must compromise. For example, an 8 pole filter allowing 3 dB of passband ripple achieves a 65 dB isolation at a bandwidth which is 1.56 times the necessary bandwidth. Simpler (fewer pole) filters would require higher ratios, resulting in larger channel bandwidths. The 8 pole filter offers a reasonably good tradeoff between complexity (synonymous with cost) and bandwidth needed to achieve required isolation , and results in a channel bandwidth of 5.616 MHz. To allow for some drift of the center frequency and normal aging and degradation of components, it seems prudent that 6 MHz should be the bandwidth allowed for each channel.

Although the data rate required could be accomplished in less bandwidth with more complicated modulation schemes, the less complex schemes are used to maintain the lowest tag cost possible. Currently, tags cost between 20 and 100 dollars. Adding signal processing capability to the tag would significantly increase the cost. Because the tag will be distributed to hundreds of thousands or millions of vehicles, any increase in tag cost will have a large economic impact on the system deployment. Therefore, after careful evaluation of the implementation characteristics and deployment, the required bandwidth was determined to be 8 channels of 6 MHz each, or 48 MHz total. So, the LMS band, considering the bandwidth requirement and the other developing users, will be insufficient to support all of the DSRC applications previously discussed. Another band is needed to support the DSRC requirements.

5.0 ANALYSIS OF DSRC COMMUNICATION CHARACTERISTICS

5.1 Current and Proposed Radio Frequency Spectrum Allocation

Now we must determine the frequency range in which to request the allocation of the 48 MHz of bandwidth needed to implement all the functions of ITS DSRC. ETC installations make up most of the DSRC operations currently deployed and operate as Location and Monitoring Service (LMS) systems in the 902 to 928 MHz band under the Transportation Infrastructure Radio Services (TIRS) category-CFR, title 47, Part 90 [8]. However, the Federal Communications Commission (FCC) has allocated this frequency range for use by other types of equipment as well. The band in which LMS operates is assigned on a hierarchical basis as follows:

- Government radiolocation systems and industrial, scientific, and medical (ISM) equipment;
- Government fixed and mobile operations and LMS;
- Amateur radio service licensees; and
- Part 15 devices (e.g., remote meter readers, wireless local area networks, wireless security systems, portable telephones).

However, only two 6 MHz channels can be allocated to ITS functions in this band. In addition, many communications products are being developed for use in this band, and these may interfere with the operation of DSRC equipment at some point in the future. So, considering the bandwidth requirement and the developing other users, the 902 to 928 band may be insufficient to support the large number of DSRC applications to be implemented. To meet the projected need for increased bandwidth, other areas of the spectrum have been considered. Although it is not currently available for use, the band from 5.850 to 5.925 GHz is considered the primary candidate.

The band from 5.850 to 5.925 GHz may become available in the near future from the National Telecommunications and Information Administration (NTIA)[9]. This band is currently allocated to radiolocation (military only), fixed-satellite (earth-to-space), and amateur radio service licensees in the United States and internationally. In addition, it is allocated to fixed and mobile operations internationally. The proposed plan would open the band to non-government use.

Allocating the band from 5.850 to 5.925 GHz to DSRC applications would provide the following advantages:

- There are very few geographical areas where interference would occur while operating in this band;
- The European Standardization Committee CEN TC278 is creating a standard for DSRC from 5.795 to 5.805 GHz, with an alternate of 5.805 to 5.815 GHz [10,11]; and

- Manufacturers in both Europe and the United States are developing DSRC equipment that operates around 5.8 GHz. Expanding DSRC operations to frequencies ii-om 5.850 to 5.925 GHz would create a greater market for 5.8-GHz DSRC products, stimulating sales and research investment, and reducing costs.

To explore the suitability of the 5.850 to 5.925 GHz band in comparison to the 902 to 928 MHz band, the following sections will discuss the types of devices currently available, their signal characteristics, and the environmental effects on communications at these frequencies.

5.2 Device Types and Signal Characteristics

The existing DSRC systems [12][13] in the 902-928 and 5.850-5.925 ranges can be grouped according to their type of vehicle tag and their frequency. Five of the 5.8 GHz systems (including three developed in Europe and two from U.S manufacturers) employ a semi-active tag that modulates a continuous wave (CW) tone from the reader. One DSRC system (developed in the United States) has a 5.8 GHz and a 902 - 928 MHz downlink (roadside-to-vehicle) but uses an active uplink in the 40 - 70 MHz range. The 902 - 928 MHz systems are either completely active with a complete uplink transmitter, or use a reflective type technology in a semi-active or passive tag. The DSRC systems are listed according to frequency and tag type in Table 6.

Table 6. Classes of DSRC Systems

Frequency	In-Vehicle Tag Type	DSRC System
5.8 GHz	Semi-active	Amtech#
	Semi-active	Bosch: MobilPass
	Semi-active	GEC-Marconi: TRICS
	Semi-active	Saab-Combitech: PEMID
	Semi-active	Texas Instruments: EuroPassage#
	Active	AT/Comm*
902 - 928 MHz	Semi-active	Amtech: Intellitag
	Semi-active	Texas Instruments: TIRIS
	Passive	XCI RFID
	Active	Hughes
	Active	Mark IV: RoadCheck
	Active	AT/Comm

New systems - Data not available in appendix A.
* AT/Comm tags transmit in the 40 - 70 MHz band.

The four classes of DSRC systems listed in Table 6 are considered separately in the following environmental analysis. Grouping the systems according to these classes helps simplify the presentation of the results. Specific results from the individual systems will be presented where they differ from the results of the general class of DSRC systems being discussed.

The readers operate with an output power between **20** mW and 10 W EIRP with communications ranges from 15 feet to 1 mile (see Appendix A). The nominal power for operations in the 902 to 928 band is less than 1 W with ranges usually less than 100 feet. However, the Hughes system operates at 10 W EIRP with a two-way range up to 200 feet. AT/Comm uses the broadcast option for its 1 mile range. The power currently in use for operations in the 5.850 to 5.925 GHz band is 2 W with up to a 98 foot (30 meter) range. The range would be slightly extended if 10 W were used. The bandwidth for current DSRC equipment is generally constrained by the FCC requirement on the LMS band to reduce out-of-band signal levels by 55 + 10 log(P) dB, where P is the power of the transmitter. Appendix A of this paper contains updated templates on most of the DSRC systems discussed here.

The following subsections address the relative performance of communications systems for the 902 to 928 MHz band and the 5.850 to 5.925 GHz band.

5.3 Comparative Properties of the Current and Potential DSRC Bands

5.3.1 Antenna Characteristics

Antennas developed for use in the 5.8 to 5.9 GHz band have some advantages over those developed for use in the 902 to 928 MHz band. The primary advantage of the higher frequency antennas is size which is inversely proportional to the frequency. A 5.8 to 5.9 GHz antenna is roughly l/6 the size of an antenna with similar characteristics in the 902 to 928 MHz band. By giving up some of the size advantage, the higher frequency antennas can be designed to have more narrowly focused beams, reduced sidelobe levels, or both. Therefore, antennas operating in the 5.8 to 5.9 GHz band enhance the ability of the DSRC systems to spatially isolate individual beacons.

A disadvantage of higher frequency antennas is cost. The antennas must be designed and constructed to tighter tolerances in the 5.8 to 5.9 GHz band and are thus more expensive. However, the cost of antennas is a small fraction of the overall cost of the DSRC systems and the additional cost will be almost insignificant.

5.3.2 Propagation Loss

In free space, propagation loss increases as the square of the frequency. Because the ratio of the two bands is about 6, the free space loss at the higher frequency will be approximately 16 dB larger for the same path length. However, for the path lengths encountered in typical DSRC applications, where distances are no more than about 200 meters, the loss at 5.8 GHz is about 94 dB compared with about 78 dB at 915 MHz. Systems can be easily built to function in either band if an ERP of about 40 dBm (10 W) is available.

5.3.3 Active Device Cost

Because of low production quantities and low foundry yields, gallium arsenide (GaAs) devices are currently much more expensive than silicon. However, two factors will reduce the cost of 5.8 GHz devices for ITS. Fist, the huge market will result in investments in improved foundry processes (as happened with silicon 20 years ago), which will greatly increase the device yield per wafer. Second, at least one microelectronics company has been experimenting with a high-quality "super silicon," which can operate at frequencies up to 6 GHz in the 1 W power range. Assuming that 5.8 GHz transceivers become standard ITS equipment on most vehicles, the cost of the hardware will fall to consumer levels fairly rapidly. Europe has already adopted this band and has initiated experiments in which U.S. manufacturers are participating, so we can expect some cost data to be forthcoming in the near future that will support this opinion.

5.4 Environmental Effects Analysis

5.4.1 Weather Propagation Effects

The Environmental Analysis Framework and Methodology report [14] (Appendix E) considered the attenuation of fog, rain, snow, dust, and hail at 902-928 MHz and 5.8 GHz. The worst case proved to be heavy rainfall. Viewing several models for atmospheric attenuation due to rainfall demonstrated that the attenuation even for very heavy (100 mm/hr) rainfall produced less than 1 dB/km attenuation. This result was true for both 902-928 MHz and 5.8 GHz frequency bands. Therefore, weather propagation effects will have negligible effects on any of the DSRC systems' propagation.

5.4.1.1 Standing Water

While weather has negligible effect on the atmospheric propagation of the DSRC systems, there is one ancillary effect of rainfall that must be considered. At least one of the DSRC systems (Mark IV) operating at 902-928 MHz uses in-pavement antennas for reading the vehicle tags. During rainfall, the antenna can be covered with standing or running water. This water can cause significant attenuation, especially if the systems were to migrate to the 5.8 GHz band. At 902-928 MHz, the attenuation due to pure water is approximately 15 dB/m and at 5.8 GHz the attenuation is approximately 600 dB/m [15]. Table 7 demonstrates the attenuation of standing water on in-pavement antennas.

Table 7. Attenuation Due to Water on an In-Pavement Antenna

Depth of Water	902-928 MHz	5.8 GHz
0.25 inches	0.1 dB	3.8 dB
0.5 inches	0.2 dB	7.6 dB
1 .O inches	0.4 dB	15 dB
2.0 inches	0.8 dB	30 dB

From Table 7 it can be seen that using an in-pavement antenna at 5.8 GHz would result in significant power losses if water were on the antenna. Excellent drainage would be required to ensure that significant power loss did not occur during heavy rainfall. It would be better to avoid in-pavement antennas at 5.8 GHz in favor of overhead antennas. If in-pavement antennas were required in a 5.8 GHz DSRC system, significant attention would have to be given to power budget in rainfall and drainage around the antenna.

5.4.1.2 Accumulation of Snow on Roadside Antennas

In northern climates, it is possible and often likely that snow will accumulate on or stick to the radomes of the roadside antennas used for DSRC systems. Slick radome materials, heated radomes and antenna designs with vertical faces can reduce or eliminate the accumulation of ice and snow on radomes. If these measures are not implemented, then a layer of snow can accumulate on the face of a radome.

It is assumed that the roadside antennas are either pointing in a downward angle or directly horizontal given the anticipated beacon configuration. It is also assumed that the antenna has a smooth radome such that there are no pockets or cavities in which snow or ice can accumulate. Therefore, the ice on the antenna will be a crust of snow that has partially melted and re-frozen.

Only one example of measurements of attenuation due to crusted snow has been discovered thus far. The Engineering Experiment Station (now known as the Georgia Tech Research Institute) performed measurements on 2 inches of crusted snow at 3 5 and 95 GHz. [16] The measurements were conducted on dry snow as well as wet snow as the crust began to melt. By extrapolating these measurements and making a few assumptions on the relationship between attenuation and frequency, a rough estimate of the attenuations at 915 MHz and 5.9 GHz can be made.

Wet, crusted snow was found to cause the greatest attenuations in the tests by the Engineering Experiment Station. Extrapolating these measurements results in an estimated attenuation due to 2 inches of crusted snow of about 0.5 dB at 915 MHz and approximately 5 dB at 5.9 GHz. There is a fair margin of error in extrapolating the attenuation based on only two frequency measurements, but the results are fairly obvious. In the 902-928 MHz band, crusted snow on the antenna will not cause and appreciable degradation of the DSRC system's performance. In the 5.850-5.925 GHz band, crusted snow can reduce reflected signal power by about 10 dB (2-way signal loss in reflective tag system). This loss will reduce the maximum operating range of the DSRC system by about 44%. Note that this estimate is crude and further investigation of attenuation due to crusted snow is under way to produce a more reliable estimate of attenuation at the frequencies of interest.

Mitigating snow accumulation can be accomplished using any one or combination of several simple techniques. Since the antennas and radomes are relatively small, a heater can be used to melt the snow. "Slick" materials such as Teflon@ can be used to coat the radome to prevent the snow from adhering to the radome. A shield can be placed over the face of the radome to reduce snow accumulation on the face. Also, the antenna can be designed such that the radome face is angled downward. For in-road antennas, the only mitigation method is to keep compacted snow away from the antenna; this may be difficult in some circumstances.

5.4.2 Electromagnetic Environment Effects

The electromagnetic environment effects analysis considered the effects of unintentional emitters, non-DSRC emitters and other DSRC emitters.

5.4.2.1 Unintentional Emitters

The Environmental Analysis Framework and Methodology report [14] demonstrated that the primary unintentional emitter in the DSRC environment was automotive ignition noise. The automotive ignition noise in a typical 6 MHz bandwidth transceiver is well below the sensitivity of the DSRC receivers studied here. Thus, the unintentional emitters are not a significant interference threat to most DSRC systems operating at 902-928 MHz or at 5.8 GHz.

5.4.2.2 Non-DSRC Emitters

Interference sources vary by operational location and frequency. In Denver, CO, non-DSRC emitters in the 902-928 MHz band and the 5.850 to 5.925 GHz band were measured with an omnidirectional antenna. The received signal levels in the 902-928 MHz band were about -88 dBm (adjusted for a 600 kHz bandwidth and an isotropic antenna). Other measurements made at 5.250-5.925 GHz also in the Denver area show a received signal level of about -92 dBm (adjusted for a 600 kHz bandwidth and an isotropic antenna). However, the signal level would have been much lower if a directional antenna had been used. This type of measurement was done for non-DSRC emitters in the 902-928 MHz band and the 5.850 to 5.925 GHz band in the Frequency Spectrum Survey conducted for the Florida Department of Transportation, dated 1994. This survey was conducted with log-periodic directional antennas which have characteristics similar to some DSRC antennas. It was found that most of the measured sites had strong signals near or in the 902-928 MHz band and none had strong signals in or near the 5.850 to 5.925 GHz band. The average peak signal strength among the locations measured in the 902-928 MHz band was -58.56 dBm. The strongest of these signals in the 902-928 MHz band was -41dbm at 908.37 MHz. Many of the DSRC systems use the range between -30 and -60 dBm as the receiver sensitivity for the tag or reader or both. Most of the sites measured in the 5.850 to 5.925 GHz band had readings better than -100 dBm and only 16 of the 30 sites had a measurable signal in the band. This data means that 5.850 to 5.925 GHz band is a much better operating environment than the 902-928 MHz band.

5.4.2.2.1 Interference Sources in the 902-928 MHz Band

The DSRC systems operating in the 902-928 MHz band include both licensed and unlicensed (Part 15) roadside readers (all tags are unlicensed). Figure 23 shows the currently licensed operations in the 902-928 MHz band. Those systems operating in an unlicensed mode are not protected at all against other interference sources. The short range nature of the DSRC systems do offer some protection and some of the systems even use a squelch to reduce interference from other emitters operating in the band. Unfortunately, the 902-928 MHz band is quickly becoming popular for a number of unlicensed emitters including new cordless telephones.

The only DSRC system that boasts an unlicensed (Part 15) roadside reader is the XCI Radio Frequency Identification (RFID) system. This system uses a distinctive RF chirp signal to help differentiate valid in-vehicle tag responses from background noise.

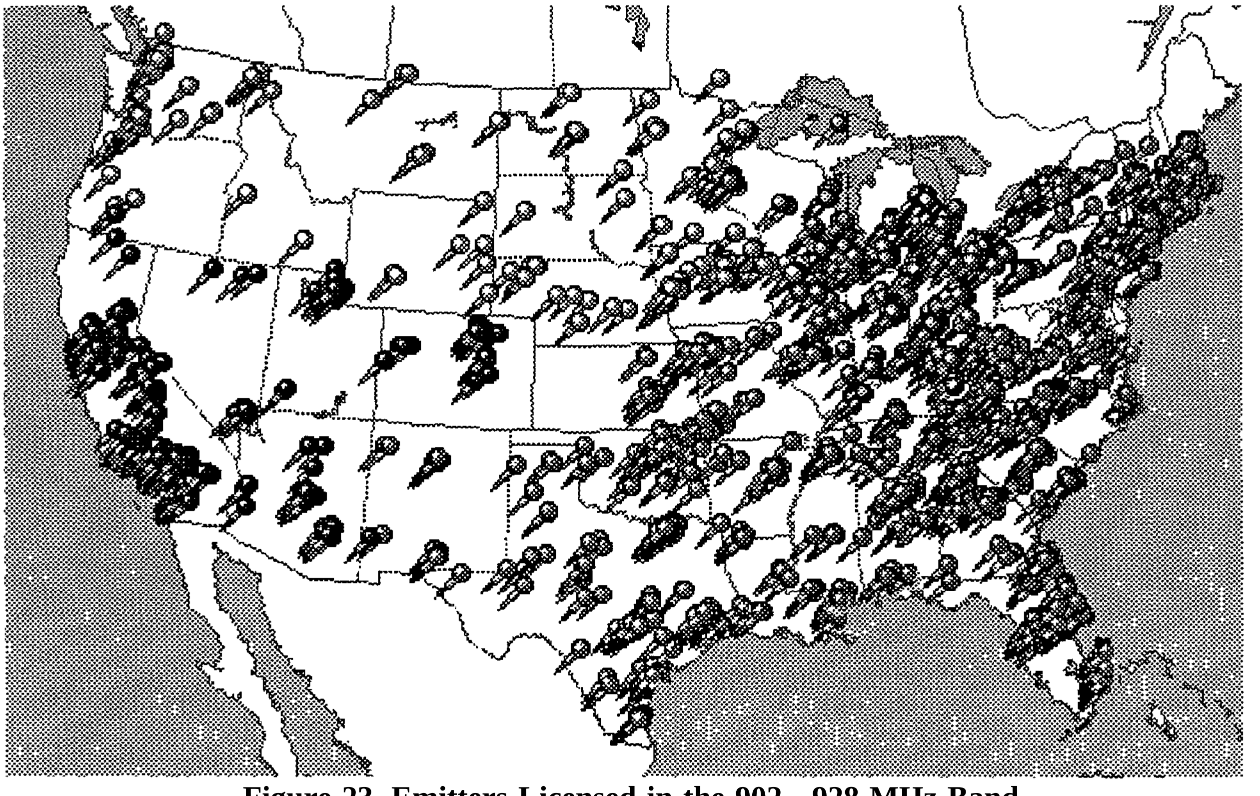

Figure 23. Emitters Licensed in the 902 - 928 MHz Band

The remaining 902-928 MHz DSRC systems require licensing of the roadside readers under FCC Part 90. This offers some protection against interference sources. Other licensed systems are required to coordinate with the DSRC system to avoid interference. Part 15 devices, however, can still operate in and around the operating band of the licensed DSRC system. These can affect the in-vehicle tag and the roadside reader if operated in close proximity. Fortunately, most Part 15 devices are not operated in a mobile environment, but are instead operated in the home or business environment.

5.4.2.2.2 Interference Sources Outside the 902-928 MHz Band

A major source of interference for DSRC systems operating in the 902-928 MHz band comes from emitters outside the band itself Figure 24 shows the currently licensed operators in and around the 902-928 MHz band.

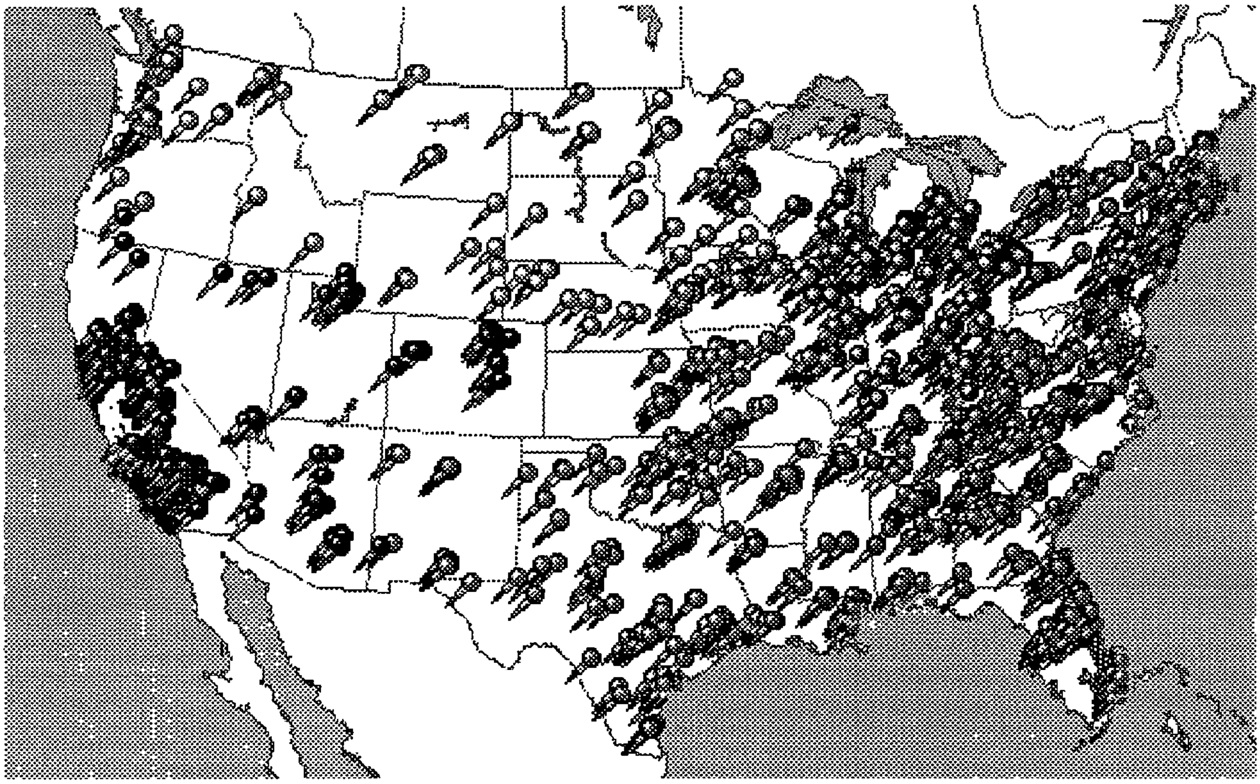
Figure 24. Emitters Licensed In and Around the 902 - 928 MHz Band

In-vehicle tags are typically inexpensive devices that often operate on small batteries. These inexpensive devices have a fairly wide bandwidth and simple front end filtering which leaves them vulnerable to strong emitters in nearby frequency bands. The interference typically does not interrupt communications, but rather causes the tag to activate unnecessarily and waste energy. Repeated activation of the tag can reduce battery life. [17]

Field testing has shown that the emitters which can cause the tag to activate include passing mobile telephones, AMPS cellular phone base stations, fixed pager base stations and UHF television stations. When tags are near these sources, the field strength can exceed the threshold and activate the tag and waste energy. In its inactive or sleep mode, the tag uses only 1 to 2 microamperes. When activated or awakened the tag uses several milliamperes of current. Therefore the incidental activation of the tags due to other non-DSRC emitters can cause a serious drain on the batteries.[17]

To mitigate the effects of the non-DSRC emitters near the band of operation of the tags, some tags use a 3-stage system. Normally the tag is in the sleep mode, drawing 1 to 2 microamperes, and monitors a simple passive field strength detector. When the detector output exceeds a pre-set threshold, the tag enters a “lookaround” mode wherein it examines the field for the characteristics of a beacon while only drawing a few more microamperes. The wakeup mode, which draws several milliamperes, is only entered if the tag has determined that the signal is from a beacon. This strategy conserves considerable battery life that would otherwise be lost to the out-of-band emitters. [17]

5.4.2.2.3 Interference Source In and Near the 5.850 to 5.925 GHz Bands

In this section, the potential source of interference in and near the 5.850 - 5.925 GHz band will be assessed. Measurement of background emission in the Denver, Colorado area showed a noise level in the 5.250-5.925 GHz band of less than -92 dBm (adjusted for a 600 kHz bandwidth and an isotropic antenna). In the 5.795-5.805 GHz, band used by the European systems (Bosch and GEC-Marconi), a signal with a -75 dBm power level was detected. In the 5.850-5.925 GHz band being considered for U.S. DSRC systems, no strong signals were detected. These background noise levels measured in Denver pose little or no threat to the DSRC systems studied in this effort. If licensing for U.S. DSRC systems in the 5.850-5.925 GHz band is approved (co-primary status with earth-to-satellite links), considerable protection for the operation of the DSRC systems can be achieved. Coordination with the earth-to-satellite links does not appear to be a problem at this time. [18]

It is assumed that the DSRC systems operating in the 5.8 GHz band will be wide bandwidth devices using a reflective or backscatter technology. They will likely be fairly inexpensive devices. Therefore, it is likely that these tags will also be vulnerable to activation and interference from source outside its operating band as well as those inside the band.

The primary non-governmental use of the 5.850-5.925 GHz band is for fixed satellite earth-to-space links. Figure 25 shows the current licensed earth-to-satellite fixed stations in the 5.850-5.935 GHz band. There are currently only 8 licenses in the contiguous United States in this band.

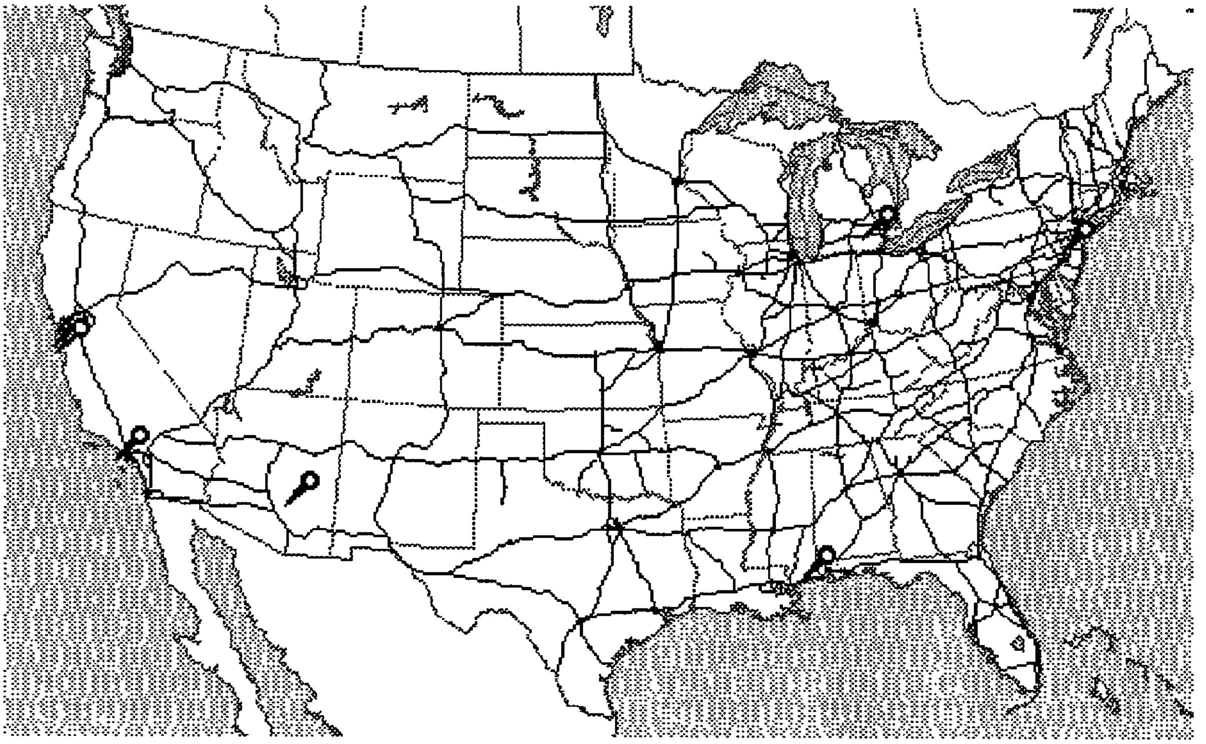

Figure 25. Emitters Licensed In the 5.850 - 5.925 GHz Band

There are two primary reasons to conclude that in-band emitters will not be a problem for DSRC systems operating in the 5.850 - 5.925 GHz bands. First, there are very few of these emitters, and thus mitigation would simply consist of avoiding beacon installations close to one of these emitters. Second, these are all earth-to-space satellite links using high-gain, low sidelobe antennas that point up, away from Earth. These emitters use low sidelobe antennas to avoid interference with other satellites, and thus will also reduce drastically the interference with DSRC systems. Conversely, DSRC systems will also not interfere with the satellite communications since these are uplinks to the satellites and the radiated power levels of DSRC systems will not significantly impact a satellite receiver.

The interference potential rises dramatically when emitters in bands adjacent to the 5.850-5.925 GHz bands are also considered. The 5.650-5.850 GHz band is a Radio Location and Amateur band. Some high power weather and tracking radars exist in this band. But, generally transmitted power levels are typically low to moderate. There is also a 5.725-5.875 GHz ISM band which overlaps with the 5.850-5.925 GHz band. Note, however, that the current 902-928 MHz systems operate in an ISM band with currently manageable interference problems.

The 5.925-7.075 GHz band is the potentially most serious source of interference problems. This band is used for earth-to-space fixed communications, but is also used for public and private fixed communications links. These fixed communications links can operate at high powers and over considerably long distances. A quick scan of the current licenses in this band reveal transmitter power levels exceeding 3 kW.

The scope of the interference problems from emitters in and near the 5.850-5.925 GHz band is demonstrated in Figure 24, which depicts the locations of all emitters whose license includes frequencies in or up to the edges of the 5.850-5.925 GHz bands. There are a large number of these emitters, mostly concentrated around urban areas where most DSRC emitters will be deployed.

Several mitigating techniques will be required to reduce the effects of the emitters in bands adjacent to the 5.850-5.925 GHz band on in-vehicle tags. A multi-stage tag wake-up scheme will likely be required to reduce the drain on battery life from activation due to these emitters. The implementation of this technique can be similar to those currently employed in tags in the 902-928 MHz band. Despite the number of emitters shown in Figure 26, the problem of battery drain is less significant when operating near 5.8 Ghz, because there are fewer potential interfering emitters operating near 5.8 GHz than there are cellular telephone and pager base stations in the 902-928 MHz band.

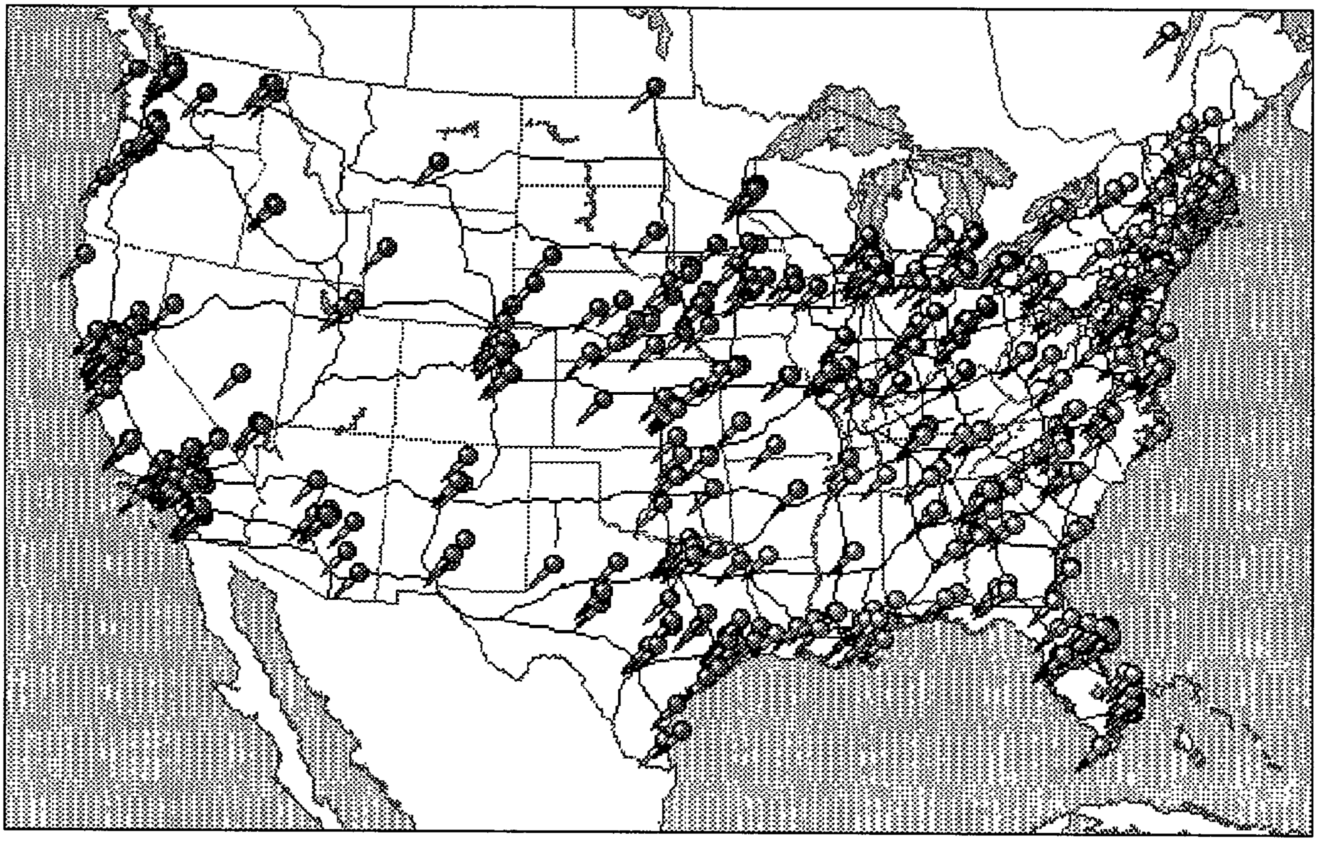

Figure 26. All Licensed Emitters In or Adjacent to the 5.850-5.925 GHz Band

A multi-stage wake-up scheme will conserve battery life, but may not completely solve the interference problems. Given the high transmit power levels of some of the fixed links, they may be capable of blocking communications between the beacon and the in-vehicle tag. The wide-band, simple detector front ends can be saturated by any strong signal that is not filtered out. Therefore, increased filtering is required to reduce the impact of the strong out-of-band signals. To provide this sharp filtering, a guard band near 5.925 GHz can be used. Providing 1 to 6 MHz of bandwidth to implement a sharp, deep filter can virtually eliminate the interference from emitters above 5.925 GHz. The bandwidth of the guard band and the depth of the filtering required to mitigate interference from the emitters above 5.925 GHz depends on cost and the power levels of the interference. Simple tests of field intensities around the interfering emitters are needed to determine the extent of filtering requirements to mitigate interference.

Potential interference sources below 5.850 GHz typically transmit at much lower power levels than those above 5.925 GHz. Therefore, filtering these signals out of the input to the tag receiver is not as difficult. A smaller guard band or a less complex filter is needed to mitigate interference from emitters below 5.850 GHz.

5.4.2.2.4 Other DSRC System Emitters

The potential for interference from other DSRC emitters is a recognized problem. The manufacturers of DSRC systems, particularly Electronic Toll Collection (ETC) systems, have had to implement solutions to interference problems between adjacent lanes. These techniques require cooperation or coordination between the roadside readers; some require discrimination by the in-vehicle tag. The following are examples of the techniques to avoid lane-to-lane interference used by the DSRC systems studied:

- The AT/Comm system uses an FM capture technique, and claims to provide orderly sequencing of multiple messages from the vehicle tags. The FM capture technique differentiates by the power levels of the received signals, communicating with the tag with the highest power level first.

- The Bosch MobilPass and Saab-Combitech systems use TDMA for multiple access. The typical configuration uses one reader per lane with tight antenna beams and low power levels to avoid interference.

- The Hughes DSRC system coordinates the communications times of adjacent or nearby readers to avoid cross-talk between communications zones.

- The Intellitag system uses directive antennas and power control to avoid cross-talk between lanes or communications zones. Time division is also used to reduce cross-talk between adjacent lanes in an ETC application. Furthermore, the system has the capability of employing frequency discrimination between lanes, varying the reader frequency between lanes, to augment the reduction in interference.

- The GEC-Marconi TRICS system also uses directive antennas and power control to avoid interference between lanes or communication zones.

- The Mark IV system also uses directive antennas and power control to avoid interference between lanes or communication zones. In addition, time division is used to reduce cross-talk between adjacent lanes in an ETC application.

- The Texas Instruments TIRIS system uses time delayed pulses from the individual lane readers to allow the in-vehicle tag to determine the lane it is in. The amplitudes of the pulses are compared at the tag and the highest amplitude pulse is determined. The tag then only responds to queries from the lane whose pulse had the highest amplitude.

- The XCI RFID system uses extremely low power levels and directive antennas to discriminate between lanes. They claim very little problem with cross-talk that the programmable readers cannot correct.

Along with the interference rejection methods described above, many of the single-lane implementations of the DSRC systems also use vehicle detectors to determine the presence of a vehicle. Only when a vehicle is present will the reader attempt to communicate with the in-vehicle tag. This reduces the amount of cross-talk between lanes and improves the enforcement capabilities of the toll and access control systems.

Given that the designs of the DSRC systems have included measures to reduce cross-talk between adjacent roadside readers in the same DSRC system, it is obvious that adjacent DSRC systems would require similar coordination in order to avoid interference between the DSRC systems. For example, a DSRC system employed to collect tolls at the exit of a toll road may get interference from a nearby DSRC system set up for parking access control or automatic fee payment.

Frequency separation between nearby DSRC systems is not sufficient to control interference. The reflective and backscatter techniques used by most of these systems are designed to automatically adjust their response to the frequency of the reader. If two reader signals at the same or different frequencies are received from different DSRC systems, the response of the tag may be unpredictable and unreliable. Time division or spatial techniques must be employed to reduce the interference problems between nearby DSRC systems.

Active in-vehicle tags can be used to respond to individual reader frequencies, The cost of producing active systems capable of responding to multiple frequencies (channelized receivers) may be prohibitive. Therefore, the solution to interference between adjacent DSRC systems is time or spatial differentiation. Active systems can, however, be used to differentiate a particular frequency. An example of this would be a dedicated emergency or safety channel.

The problem of interference from other nearby DSRC systems is perhaps the most significant problem yet to be completely solved. The problems get worse if DSRC systems are employed using multi-lane beacons instead of the single lane readers currently used by ETC systems. Mitigation analysis is required to resolve this problem.

5.4.3 Physical Effects

The physical effects on the DSRC systems include blockage (or diffraction) and multipath. The Environmental Analysis Framework and Methodology report [14] considered each of these effects and presented theoretical results for analyzing particular geometries associated with DSRC communications. These effects are discussed below to determine the extent to which the physical effects cause degradation of the DSRC systems.

5.4.3.1 Blockage / Diffraction

The diffraction analysis in the methodology report demonstrated that blockage causes significant losses in received signal power. Using a knife-edge approximation for a blockage, the analysis also showed that the effects were significantly greater at 5.8 GHz than at 915 MHz. Both frequency bands basically require line-of-sight between the roadside reader antenna and the in-vehicle tag.

A typical ETC application where individual antennas are used in each lane of traffic virtually eliminates blockage problems. A standard ETC installation uses an antenna mounted 16 feet off the roadway and pointed 30 degrees from vertical toward oncoming traffic. In this configuration, a car (tag 3 feet off the ground) would have to follow a 12 foot tall truck such that the tag is less than 5.5 feet from the back of the truck to be affected by blockage. This is an unlikely scenario. Another analysis [19] showed that blockage from roadside-mounted DSRC antennas can be significantly reduced by using multiple antennas (one on each side of the road).

Diffraction or blockage must be considered in the design and layout of DSRC systems. Antenna positioning and direction must be carefully designed to reduce the likelihood that blockage could occur. Blockage would prevent communications between the roadside reader and the in-vehicle tag in many cases.

Blockage is a site-specific and implementation-dependent problem. It has been considered in the design of existing DSRC systems, and, for the most part, has been resolved. Therefore, further consideration of this problem is not warranted for the current environmental analysis of DSRC systems.

5.4.3.2 Multipath

Multipath is a problem that has generally been addressed in the design of the DSRC systems tested. Most of the ETC applications use a protocol that includes acknowledgment to ensure the reliability of the link. Also, all of the systems generally communicate in short bursts, generally much shorter than the time between fades. At 5.8 GHz, the interval between fades is 0.158 the interval between fades at 915 MHz. [14] This means that fades occur more often and thus there is a greater chance that a fade will occur during a transmission. The other side of the coin is that the duration of the fades at 5.8 GHz is also 0.158 as long as at 915 MHz. Thus fewer bits are disrupted per fade at 5.8 GHz.

For ETC and access applications, the acknowledgment protocols currently implemented are sufficient to ensure very good reliability on the communications channel. Most of the systems are designed to allow for three chances to communicate with each passing vehicle in case a fade occurs, For other DSRC applications requiring longer messages, a TDMA system with acknowledgments can ensure nearly the same accuracy as the ETC systems.

Some design techniques can and have been used to minimize the effects of multipath on DSRC systems. High gain, low sidelobe roadside antennas minimize the reflection problem. The roadside reader antenna angle can also be adjusted to minimize the reflectivity of the environment. The high dynamic range front end can be designed into the roadside reader to minimize the effects of fading by allowing the receiver to track through most fades. Also, transmitter power levels can be adjusted to swamp the nulls, but consideration of cross-talk between lanes must be considered. [17]

Multipath is a problem with any mobile communications system. It has, however, been addressed in the design of most DSRC systems. While some problems do exist in multipath, most can be addressed using design and implementation strategies. The acknowledgment protocols currently being used can prevent a great percentage of the errors introduced by multipath. Therefore, further consideration of the multipath environment is not necessary at this time.

5.4.4 Environmental Effects Summary

A review of the environmental effects on DSRC systems has shown that the most significant problem is likely to be interference from other DSRC systems. This problem has already been addressed to resolve lane-to-lane interference issues within a single DSRC system. It has not been strongly addressed for the case of multiple DSRC systems operating in close proximity.

Interference from non-DSRC systems is currently not a significant problem. The growth of unlicensed (Part 15) devices may, however, be a problem in the 902-928 MHz band in the near future. If co-primary status with earth-to-satellite transmitters is granted to DSRC systems in the 5.850-5.925 GHz band by the FCC, greater protection of the DSRC communications can be provided. Interference between the very localized DSRC transmissions and the very directive earth-to-satellite links should pose little problem. It must, however, be considered in the granting of licenses as DSRC systems are deployed.

6.0 ANALYSIS OF THE 5.850 TO 5.925 GElit BAND USE

6.1 Other Users of the Band

As stated previously, the 5.850 to 5.925 GHz band is currently allocated to radiolocation (military), fixed-satellite (earth-to-space), and amateur in the United States and internationally. However, when the band is released to commercial use, primary status will probably be assigned to users other than military radiolocation. Furthermore, reports and studies of the radiators in and around this band indicate that the band is generally low in background emissions with the main source of possible interference to DSRC systems being out-of-band radar emissions. Most of the information in this section comes from the study, "Technical Evaluation of the 2.45 and 5.8 GHz ISM Bands for Intelligent Vehicle Highway Systems," A.D. Spaulding [18] and the report, "NTIA REPORT 93-294 Federal Government Spectrum Usage in the 902-928, 2400-2500 and 5725-5875 MHz Bands," U.S. Department of Commerce/NT& February 1993 [20]. Some of the possible sources, mentioned in the reference documents, include the following radars, which operate just below the band, but whose emissions may impinge on the band:

RADAR MODEL	FREQUENCY (MHz)	PEAK POWER (kW)
WSR-74C and AN/FPQ-21	5450-5825	250
DWSR-88C,-88TVand-90CTV	5450-5825	250
AN/FPQ-10	5725-5875	285
AN/FPS-16	5400-5900	5000
AN/FPS-105	5725-5875	1000
AN/FPS-105	5725-5875	1000
AN/MPS-25	5725-5875	1000
AN/MPS-26	5725-5875	250
AN/MPS-36	5725-5875	1000
AN/TPQ-18	5725-5875	2800
AN/TPQ-39	5450-5825	250
MOT MRS 111	5725-5875	0.4
VEGA 6571	5725-5875	1000
VEGA 6572	5725-5875	1.5
VEGA 6104	5725-5875	3.5
VIVRIR778	5725-5875	1000

Also included in the possible interference sources for this band is the INTELSAT satellite uplink transmission system. Twelve assignments relative to the INTELSAT system are currently registered. This equipment has the following characteristics:

TRANSMITTER	FREQUENCY (MHz)	AVG POWER (kW)
INTELSAT VI Earth station	5850-5875	1

The INTELSAT ground station transmitters radiate upward at relatively low power levels compared to most of the radars. Little interference is expected except in the immediate vicinity of the station.

Most of the transmitters in this range are government tracking radars or weather radars. The tracking radars operate mostly on remote ranges, and therefore have little influence on main highways. Weather radars are few in number but are scattered across the country at airports and other locations. Furthermore, the number of government meteorological radar stations in the vicinity of 5600-5650 MHz is expected to decline by approximately 60% by 1997 because the National Weather Service WSR-74S and WSR-74C radars are being replaced by the NEXRAD radar at 2700-2900 MHz. Measurements of the WSR-74S radar indicate a signal level of less than -90 dBm in the 5.850 to 5.950 GHz range, which is compatible with DSRC operations, at a distance of l/2 mile. However, measurements of the WSR-74C radar show between -40 and -60 dBm in the 5.850 to 5.950 GHz range, which is not compatible with DSRC operations, at l-1/2 miles distance. Fortunately, measurements of the NEXRAD radar show less than -80 dBm in the 5.850 to 5.950 GHz range, which is again compatible with DSRC operations, at l/2 mile. And synthesized spectrum analysis [18] of the Terminal Doppler Weather Radar (TDWR) shows less than -85 dBm in the 5.850 to 5.950 GHz range, which is also compatible with DSRC operations. Operating ranges and power levels of the radars compatible with DSRC are listed below:

RADAR MODEL	FREQUENCY (MHz)	PEAK POWER (kW)
WSR-74S	2700-2900	500
NEXRAD	2700-2900	250
TDWR	5600-5650	250

The DWSR-88TV and DWSR-90CTV Doppler radars, which are not directly compatible with DSRC operations, will be increasing in number from 1995 to 1997. Analysis of the DWSR-88TV radar potential interference indicates that, if the radar is operating at the proper frequency, a separation distance of seven miles is required to prevent interference to DSRC equipment in an ideal propagation environment. Fortunately, few of these radars are or will be deployed in comparison to the vast size of the national roadway structure, and the effect of hills, buildings and other obstacles will limit the interference of the ones that are within range of a road.

6.2 Coexistence Plan

Almost all of the nation’s roadways will be free of interference to DSRC in the 5.850 to 5.925 band. In those small pockets where either weather radars or satellite stations have the potential for interference, DSRC installation design adaptations should be implemented to compensate for the unwanted signals. These adaptations could include installing highly directional antennas, filters, and signal absorption or reflection devices. The DSRC operations are low power and pointed down toward the roadway or horizontal to the roadway. Therefore, the DSRC operations are not expected to interfere with weather radar operations. The INTELSAT operations are earth-to-space uplinks so they have no receiver for DSRC operations to influence. In the 5.850 to 5.925 band, individual installation frequency allocations for the eight DSRC channels can be moved around to avoid spurious out-of-band radar, INTELSAT operations, and other transmission peaks. The lower 25 MHz of the band contains some ISM band activity, INTELSAT and radar activity which could be avoided by using the middle part of the band for DSRC where necessary. Also, the upper 6 MHz of the band could be used as a guard band between the high-power operations just above 5.925. Therefore, since this room can be used to facilitate sharing the band with other services, the full 75 MHz in the band should be allocated to TIRS for the DSRC function in a co-primary status with earth-to-space satellite communications.

7.0 BAND UTILIZATION CONCLUSIONS

7.1 Protection of the Legacy Band at 902 to 928 MHz

As stated above, most DSRC and RFID equipment in the U.S. currently operate in the LMS band. The ETC, CVO, and inter-modal freight management applications are currently implemented in this band, and implementation of parking payments is underway.

The LMS band is important to the ETC and CVO applications because the investment of capital already made in deployment must be protected so that the industry can grow and provide the full benefit of these services. Some installations have been in operation for a few years. Many other installations are just coming on line or are in the planning stages. The public is just beginning to notice the benefit of this technology. A substantial effort is being made to sell the current systems and expand the market before spending more money to change the frequency of operation. Although, changing will bring the benefit of a more protected band and is planned to enable interoperability between applications some time will be needed for these applications to migrate to 5.850 to 5.925 GHz.

The LMS band is important to the AEI applications also, because an even more substantial amount of deployment has occurred. These tags are being manufactured in large numbers, representing a sizable base of effective equipment that will not need total replacement for many years. They are being used in the transportation industry to identify rail cars, shipping containers, trailers, shipping crates, boxes, and other objects whose handling is expedited by remote identification. In addition, a significant propagation advantage exists for AEI applications in the 902 to 928 MHz band that is difficult to achieve in the 5.850 to 5.925 MHz band. There is less attenuation from “shadowing,” or partial blockage of the propagation path between the reader and tag, in the lower frequency band than in the 5.850 to 5.925 band. Some AEI applications, unlike ETC applications, must identify objects that are always partially masked by other objects. The higher band is hence not an attractive option for AEI applications where such shadowing may occur.

For these reasons, the AEI applications are not expected to transition from 902 to 928 MHz to another frequency range. Therefore, this band must maintain its LMS allocation for the foreseeable future.

ETC, parking, and CVO users, also, need the option to operate in this band for a substantial time. It is expected that these users will migrate to the 5.850 to 5.925 band when they are economically ready.

7.2 Operations in the 5.850 to 5.925 GHz Band

The currently allocated LMS band does not have the bandwidth or authorization for operation that will allow all DSRC functions to be effectively implemented. The new applications (In-Vehicle Signing [Hazard Warning], Emergency Vehicle Signal Preemption, Transit Vehicle

Signal Priority, Transit Vehicle Data Transfer, Off-Line Verification, ELP, Intersection Collision Avoidance, and Automated Highway System-to-Vehicle Communications) must operate on interference-free frequencies. An allocation of bandwidth must also be made for those DSRC applications that migrate from the 902 to 928 MHz band to the 5.850 to 5.925 GHz band. The analysis of the characteristics of the 5.850 to 5.925 GHz band shows that DSRC operation is possible at these frequencies, sufficient bandwidth is available, few disadvantages exist, and that several significant advantages can be obtained. Therefore, to provide sufficient bandwidth to operate properly and to foster nationwide interoperability, the 5.850 to 5.925 GHz band should be allocated to DSRC services as co-primary with fixed-satellite services, which are already in the band.

8.0 SUMMARY

This paper has addressed three major questions in the debate about the use of beacons to support DSRC in the ITS National Architecture. These questions are summarized as issues of feasibility, capacity, and spectrum management.

On the question of feasibility, the analysis presented in this paper shows the following key points:

- Beacon - tag systems and RF beacon - tag systems in particular, have the underlying capability to support the ITS DSRC role. Our analysis indicates that the maximum data rate required to support ITS operations is less than the data rate supported by beacons.

- RF Beacons are not unduly affected by the normal environmental parameters encountered in highway situations, with the exception that standing water or compacted snow can reduce link operating margins in 5.8 GHz operations.

From the perspective of capacity, a careful consideration of deployment scenarios and functional groupings of ITS DSRC requirements has determined that eight channels will be needed to completely service foreseen requirements.

This is based upon the above eight channels, and a determination of the required channel bandwidth of 6 Mhz.

The channel bandwidth requirement value is based on:

- 600 Kbps data rate capability in the DSRC link.

- The path from Reader to Tag typically employs a simple modulation scheme to minimize the cost of the tag.

- Channel spacing required to prevent interference with adjacent channels and other services.

Reductions in the channel spacing can be achieved by trading spectrum for roadway efficiency or tag cost. More complicated and spectrally efficient modulation schemes will increase tag cost to the user, effectively “raising the entrance fee” into ITS. Restrictions on roadway operations, which would either increase the “read” zone or reduce the number of vehicles that could occupy the zone, could reduce the necessary data rate and hence spectrum. However, these restrictions would limit the overall highway efficiency, in direct opposition to the purpose of ITS.

DSRC applications, including In-Vehicle Signing, International Border Clearance, Electronic Clearance, Safety Inspection, Fleet Management, AEI, and Freight Management, Intersection Collision Avoidance, Emergency Vehicle Signal Preemption, Transit Vehicle Data Transfer, Traffic Network Performance Monitoring, Traffic Information Dissemination, Automated Highway System-to-Vehicle Communications, Electronic Toll Collection (ETC), and Parking Payments are being defined in the ITS architecture as functions to be implemented with RF beacon technology.

Even though installations of the applications were consolidated where possible, full implementation will require more bandwidth than is available in the current LMS 902 to 928 MHz band. Therefore, eight DSRC channels, 6 MHz each, should be allocated to the 5.850 to 5.925 GHz band. Intermodal Freight Management, which is already substantially deployed and involves equipment with different operating requirements, should continue to operate in the 902 to 928 MHz band. Electronic Toll Collection (ETC), Commercial Vehicle Operations (CVO), Traffic Network Performance Monitoring, Parking Payments and related activities which are already deployed in many areas, should continue to operate in the 902 to 928 MHz band until the user and manufacture communities decide to migrate to the 5.850 to 5.925 GHz band. New applications, such as In-Vehicle Signing (Hazard Warning), Emergency Vehicle Signal Preemption, Transit Vehicle Signal Priority, Transit Vehicle Data Transfer, Intersection Collision Avoidance, and Automated Highway System-to-Vehicle Communications should have the 5.850 to 5.925 band made available for use as soon as possible.

The 5.850 to 5.925 GHz band is generally free of interference and would provide a protected place for DSRC applications, many of which are safety-critical or safety-enhancing, to operate.

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Appendix A: DSRC Equipment Characteristics

1.0 Introduction

This appendix summarizes the literature search performed by GTRI and ARINC. The literature search was designed to collect technical, cost and market information on Vehicle-to-Roadside (DSRC) systems operating in the 902-928 MHz and 5.8 GHz frequency bands including:

- Frequency of Operation;
- Modulation Technique;
- Multi-Access Technique;
- Message Transfer Capacity;
- Permissible Operating Environment;
- Physical Deployment / Set-Up Constraints;
- Coverage Zone;
- Cost of Infrastructure (Deployment and NRE);
- Cost of Vehicle Equipment;
- Targeted Market; and
- Market Share.

Section 2.0 presents a summary of the DSRC systems. A basic categorization of the systems is presented. Section 3.0 contains more detailed descriptions of the DSRC systems studied in template form.

2.0 Summary and Categorization of the DSRC Systems

A total of eight operational DSRC system manufacturers were discovered in the literature search. Five of the systems are produced in the United States, one in the United Kingdom, one in Sweden, and one in Germany.

Table 1 lists the DSRC systems investigated in this search, their country of origin and their operating frequencies. All of the currently deployed U.S. systems operate in the 902-928 MHz frequency band. Three U.S. companies currently offer systems that operate in the 5.8 GIIz band. However, no data is available on the Amtech and Texas Instruments 5.8 GHz systems. All of the European systems operate in the 5.8 GHz or 2.45 GHz band. Since this effort focuses on the 902-928 MHz and 5.8 GHz bands, the 2.45 GHz systems are not presented here.

Table 1. DSRC Systems

DSRC System	Country	Operating Band
AT/Comm	United States	904.5 MHz, 2.45 GHz or 5.8 GHz
Bosch (MobilPass)	Germany	5.8 GHz
Hughes	United States	902-915 MHz
Amtech: Intellitag	United States	902-928 MHz 5.8 GHz
GEC-Marconi	United Kingdom	5.8 GHz
Nippondenso	Japan-U.S.	2.45 GHz
Mark IV (RoadCheck)	United States	902-928 MHz
Saab-Combitech	Sweden	2.45 GHz 5.8 GHz
Texas Instuments (TIRIS)	United States	902-928 MHz 5.8 GHz
XCI	United States	915 MHz

Most of the DSRC systems looked at in the effort were developed primarily for electronic toll collection (ETC). As such, they were first developed to communicate with vehicles in a single lane. Four of the DSRC system manufacturers also boast multiple access schemes that make the systems capable of communications with several vehicles simultaneously. Table 2 lists the four multiple access DSRC systems and their respective access scheme.

Table 2. Multiple Access Schemes Used by DSRC Systems

DSRC System	Multiple Access Technique
AT/Comm	FM Capture
Hughes	TDMA with Slotted ALOHA
Intellitag	“Flex-Frame” TDMA
Mark IV	TDMA with Slotted ALOHA
Saab-Combitech	TDMA with Slotted ALOHA

The Bosch MobilPass system made no mention of multiple access techniques, but only discussed single-lane/vehicle implementations. The XCI and GEC-Marconi DSRC systems also claim only single-vehicle communications, primarily ETC.

3.0 Templates of DSRC Systems

The following pages contain templates of the information gathered on the DSRC systems operating in the 902-928 MHz and 5.8 GHz frequency bands.

Name of System: **AT/Comm**

Manufacturer: AT/Comm Incorporated
America's Cup Building
30 Doaks Lane
Marblehead, Massachusetts 0 1945

Contact Person: Dave McLaughlin
Phone: (617) 631 - 1721
Fax: (617) 631 - 9721

System Description: AT/Comm produces DSRC equipment operating on dual frequencies, The roadside-to-vehicle link can operate at 904.5 MHz, 2.45 GHz or 5.86 GHz (licensed). The vehicle-to-roadside link operates in the 40 - 70 MHz band (unlicensed). The flexible architecture allows bi-directional communication, simultaneous multiple applications (up to 18 accounts), and includes location measurement (accuracy < 4 feet).

Detailed Specifications:

Operating Frequency:
Roadside-to-Vehicle: 904.5 MHz, 2.45 GHz or 5.86 GHz (site licensed)
Vehicle-to-Roadside: 40 - 70 MHz (unlicensed).

Modulation Technique:
Roadside-to-Vehicle: AM, balanced Manchester encoded
Vehicle-to-Roadside: FM, balanced Manchester encoded

Necessary Bandwidth:
Roadside-to-Vehicle: 40 kHz (estimated)
Vehicle-to-Roadside: 40 kHz (estimated)

Occupied Bandwidth:
Roadside-to-Vehicle:Not Provided
Vehicle-to-Roadside:Not Provided

Antenna Parameters:
Roadside Unit: Multiple antennas are used depending on application and desired coverage zone. Highly directional antennas are used for single lane ETC applications and lower gain antennas are used for multi-lane and CVO applications.
In-Vehicle Unit: PCB etched antenna (low gain, nearly omni-directional)

Transmitted Power:
Roadside Units: Tl ≤ 600 mW; T2 ≤ 20 mW; Variable depending on installation requirements.
In-Vehicle Unit: ≤10mW

Receiver Sensitivity:

Roadside Unit: -106 dBm
In-Vehicle Unit: -65 dBm

Multi-Access technique: Vehicle-to-roadside multi-access is accomplished using an FM capture technique that differentiates by power received. The claim is that this provides a normal, orderly sequencing of multiple FM messages that reliably and predictably provides multiple access without extra processing or time delays.

Message Transfer Capacity:

Roadside-to-Vehicle: 19,200 Baud ≤32 byte packets (5 byte header, 25 bytes data, **2** byte checksum) - not specified, but assumed to be same as below.

Vehicle-to-Roadside: 19200 Baud, ≤32 byte packets (5 byte header, 25 bytes data, 2 byte checksum)

Permissible Operating Environment: All weather operation. Operating range could be reduced by interference (see Receiver Sensitivity above).

Physical Deployment / Set-Up Constraints: Typically uses a roadside or over-the-road installation of the fixed antennas. In-vehicle unit is installed on the vehicle dash. Works in all weather.

Coverage Zone: This system is designed for longer range operation from roadside-to-vehicle. The actual coverage zone can be small (ETC applications) or larger (CVO applications) depending on the physical set-up.

Roadside-to-Vehicle: Up to 1 mile.
Vehicle-to-Roadside: Up to l/4 mile

Cost of Infrastructure:

Deployment: Claims an ETC station (single reader) can be installed for little as $500.
NRE:

Cost of In-Vehicle Equipment: $35 - $45, depending on volume

Targeted Market: Electronic Toll Collection (ETC), airport ground transportation management, electronic parking, Commercial Vehicle Operations (CVO) including HAZMAT, and Advanced Traffic Management Systems (ATMS).

Market Share: Currently in use in ETC (Illinois Tollway, Maine Turnpike, UK, Australia), airport ground transportation (Dulles International Airport), and electronic parking.

References

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Name of System: **MobilPass**

Manufacturer: Bosch ANT Telecom
Gerberstrasse 33
7 1522 Backnang
Germany

Contact Person: W. Detlefsen
Phone: 01 l-49-5121-49-3903
FAX: 011-49-5121-49-2538
Email: detlefsen@hic334.decnet.bosch.de

System Description: The MobilPass system is an electronic toll collection (ETC) system designed to operate in a multilane, free-flow environment. It features 100% recognition and identification of incorrectly paying or non-paying users. It includes vehicle type/class detection for variable tolls. It uses prepaid electronic cards ("chipcards" or "smartcards") that carry the toll account information. The communications between the vehicle tag and the roadside unit can also be used to transfer traffic information.

Detailed Specifications:

Operating Frequency: 5.8 GHz±5 MHz

Modulation Technique:
Roadside to Vehicle: ASK
Vehicle to Roadside: Subcarrier with PSK

Necessary Bandwidth:
Roadside to Vehicle: 1 MHz (500 kbaud)
Vehicle to Roadside: 500 kHz on subcarrier (250 kbaud)

Occupied Bandwidth: 2 channels, each 5 MHz
Roadside-to-Vehicle:Not Provided
Vehicle-to-Roadside: Not Provided

Antenna Parameters:
Roadside Unit: 12 dB gain
In-Vehicle Unit: 6 dB gain

Transmitted Power:
Roadside Unit: +33 dBm
In-Vehicle Unit: N/A, passive transponder

Receiver Sensitivity:

Roadside Unit: -110 dBm
In-Vehicle Unit: -45 dBm

Multi-Access technique: TDMA using the ALOHA protocol (probably slotted).

Message Transfer Capacity: 256 bytes per frame, probably Manchester encoded.
Roadside to Vehicle: 250 kbit/s (estimate)
Vehicle to Roadside: 125 kbit/s (estimate)

Permissible Operating Environment: All weather operation. Can be installed for single or multi-lane environments.

Physical Deployment / Set-Up Constraints: Overhead installation of roadside reader antennas is the typical deployment. In-vehicle equipment consists of a transceiver with a “smartcard” slot.

Coverage Zone: Single lane or multi-lane configurations. Multi-lane configurations use multiple readers, each covering a single lane.

Cost of Infrastructure: Not provided.
Deployment:
NRE:

Cost of In-Vehicle Equipment: Depends heavily on functionality required.

Targeted Market: Electronic Toll Collection (ETC), Access Control, Electronic Toll and Traffic Management (ETTM)

Market Share: The first demonstration or test of the MobilPass system was near Stuttgart, Germany; and a second system was installed on the A555 Federal motorway as part of the German field trial for automatic motorway charging.

References:

"MobilPass: The Flexible System for Automatic Debiting and Access Control,” System Description, Chapters I and II, March 27, 1995.

Email information received from Dr. Wolfgang Detlefsen of Bosch on January 25, 1996.

Name of System: Hughes VRC (MACS - Advantage I-75)

Manufacturer: Hughes Aircraft Company
Transportation Management Systems
Bldg. 675, MS DD3 11
190 1 W. Malvern Avenue
Fullerton, CA 92634
Phone: (800) 494 - 5509
(714) 732 - 0848
Fax: (714) 732 - 1606

Contact Person: Dave Weingartner
Phone: (714) 446 - 2355
Fax: (714) 441 - 8246

System Description: The Hughes VRC (DSRC) is an open-road, multi-lane system using TDMA access, two-way packetized messaging and internal security to support a large number of IVHS applications. The Hughes VRC system is currently being used in the Advantage I-75 Mainline Automated Clearance System (MACS). The current implementation consists of a single-lane reader and in-vehicle transponder. The MACS is designed to allow trucks to bypass weigh stations. The Hughes VRC system is designed to identify the trucks, verify their credentials, and provide the truck drivers with indications as to whether or not they need to pull into a weigh station.

Detailed Specifications:

Operating Frequency: 902-915 MHz

Modulation Technique:
Roadside to Vehicle: Manchester encoded ASK.
Vehicle to Roadside: Manchester encoded ASK.

Necessary Bandwidth:
Roadside to Vehicle: Not Provided
Vehicle to Roadside: Not Provided

Occupied Bandwidth: (912-918 MHz Adv I-75)) (-55 dBm (c?))
Vehicle-to-Roadside: 6 MHz
Roadside-to-Vehicle: same

Antenna Parameters:
Roadside Unit: 12.04 dBi
In-Vehicle Unit: Compact antenna, probably very low gain.

Transmitted Power:

Roadside Unit: 30 dBm peak (Adv. I-75), 40 dBm EIRP incl. all losses

In-Vehicle Unit: 10 mW

Receiver Sensitivity:

Roadside Unit: Squelch: -46 dBm to -52 dBm, Sensitivity: -60 dBm

In-Vehicle Unit: -30 dBm (squelch) used in Advantage I-75

Multi-Access technique: Frame-oriented TDMA. Each frame is 10 msec long consists of a reader message, four message slots and 16 activation slots (similar to slotted ALOHA), The in-vehicle unit can transmit 512-bit packets that are typically addressed and acknowledged.

Message Transfer Capacity:

Roadside to Vehicle: 500 kbps

Vehicle to Roadside: 500 kbps

Permissible Operating Environment: All weather. Receiver squelch settings typically -30 dBm for the in-vehicle unit and -46 to -52 dBm for the roadside reader, thus reducing its vulnerability to interference. The roadside reader typically uses a directional antenna, further reducing its vulnerability to interference.

Physical Deployment / Set-Up Constraints: Overhead or roadside installation of the roadside antennas. The roadside antenna can be designed to cover 1 or more lanes of traffic. The in-vehicle equipment is typically mounted on the dashboard of the vehicle.

Coverage Zone: 100 to 200 feet free space range typical (Adv. I-75). Can be used in single lanes or multiple lanes.

Cost of Infrastructure:

Deployment: $10,000 for a standard Model 200 roadside reader capable of multiplexing 4 antennas. This reader is similar to that used in Advantage I-75; only one reader per antenna was used on Advantage I-75.

NRE:

Cost of In-Vehicle Equipment: Approximately $75 for a Type III, externally powered tag with serial output. $20 - $40 for a Type II (ETC) tag that is battery powered without an external interface.

Targeted Market: Electronic Toll and Traffic Management (ETTM), Advanced Traveler Information Systems (ATIS), Commercial Vehicle Operations (CVO)

Market Share: The installation of the MACS along I-75 is one of the largest operational field tests of DSRC equipment to date. MACS are currently being installed in the HELP Pre-Pass System; installations already include California and New Mexico. Currently performing a demonstration on the Ohio Turnpike. Various trucking companies use the system for access monitoring. Being used in a demonstration for Mexico border crossing. Currently being installed on Highway 407 in Canada for automated toll collection.

References:

Notes and specification received from Dave Weingartner, November 29, 1995.

Promotional literature, ‘Weigh Station Bypass System,” Hughes Transportation Management Systems.

Parkany, A. E., and Bernstein, D., ‘Using VRC Data for Incident Detection,” Pacific Rim TransTech Conference Proceedings, July 25 - 28, 1993, Vol. 1, pp. 63-68.

Deacon, J. A., Pigman, J. G., and Jacobs, T. H., ‘Implementing IVHS Technology: ADVANTAGE I-75 Approach,” Proceedings of the Vehicular Navigation and Information System Conference 199 1 (VNIS ‘9 l), Part 1, pp. 3 5 5-363.

Crabtree, J., “Advantage I-75 Prepares to Cut Ribbon on Electronic Clearance,” Public Roads, Autumn 1995, pp. 16-21.

Telephone conversation with Dave Weingartner on January 18, 1996.

Name of System: **Intellitag**

Manufacturer: Intellitag Products
A Motorola/Amtech Technology Partnership
17304 Preston Road, Bldg. El 00
Dallas, Texas 75252

Contact Person: R. Rand Brown, Amtech Gary Butz, Amtech
Phone: (214) 733 - 6622 (214) 753 - 6441
Fax: (214) 733 - 6699

System Description: Intellitag products form a vehicle-to-roadside communications system capable of supporting ETC or ETTM applications. Intellitag is capable of providing ‘gateway” communications at high vehicle speeds when the vehicle passes within tens of meters of the reader. The system consists of IT2001 Reader (roadside), IT2410 tag programmer, and either the IT2 10 1 tag mounted on inside of windshield or the IT2 111 tag mounted to an exterior flat surface of the vehicle. The tags have 2564 bits of memory, which can be programmed using a wireless programmer (IT2410). The system is designed to meet or exceed all the CALTRANS specifications.

Detailed Specifications:

Operating Frequency: 902-928 MHz, programmable in 1 MHz steps.
In-vehicle tag frequency set by the roadside reader.

Modulation Technique:
Roadside to Vehicle: Manchester encoded ASK
Vehicle to Roadside: FSK Encoded (over the reflected signal from the reader)

Necessary Bandwidth:
Roadside to Vehicle: Not Provided
Vehicle to Roadside: Not Provided

Occupied Bandwidth:
Vehicle-to-Roadside: 6 MHz, -50 dBc
Roadside-to-Vehicle:6 MHz, -50 dBc

Antenna Parameters:
Roadside Unit: Variable, Spec. sheets use 6 - 14 dBi as examples.
In-Vehicle Unit: Compact internal antennas, probably with low gain. Options include antennas designed for tag mounted directly on a metal surface and designed for installation at least one inch from a metal surface.

Transmitted Power:

Roadside Unit: 40 - 1000 mW, programmable in 1 dB increments

In-Vehicle Unit: N/A, uses backscatter technique

Receiver Sensitivity:

Roadside Unit: Not provided. See Coverage Zone for information on maximum operating ranges.

In-Vehicle Unit: Not provided.

Multi-Access technique: Uses a TDMA protocol called flex-frame TDMA. The user selects the activation and transaction slots in the frame. Fewer slots for sites requiring large data transfers in a short period of time and more slots to increase the number of simultaneous in-vehicle tags in the reader's field of view. Can be used for single lane coverage or multiple lane coverage.

Message Transfer Capacity:

Roadside to Vehicle: 600 kbps encoded, 300 kbps decoded

Vehicle to Roadside: 2400 kbps encoded, 600 kbps decoded.

Permissible Operating Environment:

Roadside Unit: Temperature: -40°C to +85°C
Humidity: 95% noncondensing
Vibration: lg, 10 to 500 Hz RMS

In-Vehicle Unit: Temperature: -40°C to +85°C
Humidity: 100% condensing
Vibration: 2.0g, 5 to 2000 Hz RMS
Shock: 20g, l/2 sine pulse, 6 ms duration, 3 axis

Physical Deployment / Set-Up Constraints: In-vehicle tags can be mounted inside the vehicle (typically hanging from the rear-view mirror) or mounted on the outside of the vehicle. The roadside reader is typically mounted above the roadway (or lane for single lane operation), or on the side of the road. Antenna gain and beamwidth determine the physical deployment necessary to achieve desired performance.

Coverage Zone: Either single lane coverage or multiple lane coverage with multiple access (TDMA) protocols. Operating range varies according to the gain of the antenna used with the reader (roadside unit). The typical maximum range is about 35 A with 300 mW of reader output power measured at the input to the antenna.

Cost of Infrastructure:

Deployment: Standard reader unit $8,100 (single lane ETC), high power beacon reader $8,800, and reader with ATA $16,500 (essentially 2 readers in one).

NRE: Mean Time between repairs is 20,000 hours and typically the units are replaced rather than repaired. Also recommend that 10% reader spares are kept on hand at all times.

Cost of In-Vehicle Equipment: The following are list costs. Internal (dash) units list for $45.75 for the standard configuration and $50.75 with LED displays. External (license plate mount) units cost $55.50. Currently under development is a tag with an RS-232 serial interface for CVO applications, no cost available.

Targeted Market: Toll Collection, Traffic Monitoring, Vehicle-to-Roadside Communication (VRC), Commercial Vehicle Operations (CVO), and Advanced Traffic Management Systems (ATMS).

Market Share: Currently used by the Kansas Turnpike Authority, and older versions used on Oklahoma turnpike tolls. AmTech older tags also in use in GA 400 (Atlanta, Ga.), Crescent City Connection Bridge (Louisiana), Lake Pontchartrain Causeway (Louisiana), the New York Lincoln Tunnel, Oklahoma Turnpike, Texas Turnpike, the Sam Houston Tollway and Hardy Toll Road (Texas), and the Houston (Texas) Freeway Monitoring System.

References:

Sales and advertising brochures.

Majdi, S., 'Houston ETTM Project: Use of AVI Technology for Freeway Traffic Management," Proceedings of the 1st World Congress on Applications of Transport Telematics & Intelligent Vehicle-Highway Systems, 1994, Vol. 2, pp. 7 12-7 18.

Tetsusaki, K., 'High Security Electronic Toll and Traffic Management and Road Pricing System Using Encrypted Messages and Personal Identification Number," 1994 Vehicle Navigation & Information Systems Conference Proceedings, pp. 695-698.

Koelle, A. R., "Advances in Practical Implementation of AVI Systems," 1991 Vehicle Navigation & Information Systems Conference Proceedings, Part 2, pp. 969-975.

'Radio Frequency Identification (RFID)," Market Study, Air Force Automatic Identification Technology (AIT)) Program Management Office, May 1995.

Telephone conversation with Gary Butz on January 19, 1996.

Name of System: **GEC-Marconi : Traffic and Road Information Communications System (TRICS)**

Manufacturer: Marconi Communications
GEC-Marconi Research Centre
West Hanningfield Road
Great Baddow, Chelmsford
Essex. CM2 8HN

Contact Person: Richard (Dick) Baker
Marconi Communications, Inc.
11800 Sunrise Valley Drive, Tenth Floor
Reston Virginia 2209 1
Phone: (703) 620 - 0333
Fax: (703) 620 - 04 15

Paul Kimber
GEC-Marconi
UK
011-44-1245-24-2856

System Description: TRICS was developed as part of the PROMETHEUS Short Range Communications Task Force (SRCTF). It is a 5.8 GHz, bi-directional vehicle-to-roadside communications (DSRC) system. The in-vehicle tags use a semi-passive technology that modulates a CW tone from the roadside reader by varying the reflectivity of the tag's antenna. The system is designed for use with smart cards. A variation of this system was used in the operational TELEPASS systems in Italy.

Detailed Specifications:

Operating Frequency: 5.8 GHz ± 5MHz

Modulation Technique:
Roadside to Vehicle: ASK - On/Off Keying (OOK)
Vehicle to Roadside: Binary FSK (750 kHz and 1 MHz)

Necessary Bandwidth:
Roadside to Vehicle: 1 - 2 MHz (estimated)
Vehicle to Roadside: 2 MHz (estimated)

Occupied Bandwidth: Two channels - 5 Mhz each
Roadside-to-Vehicle: **Not** Provided
Vehicle-to-Roadside: **Not** Provided

Antenna Parameters:
Roadside Unit: Transmit: Horizontal BW &40°
Vertical BW ±6°
Receive: 13 dB nominal gain
In-Vehicle Unit: 5 dB nominal gain, BW ±40° both axes

Transmitted Power:
Roadside Unit: 33 dBm EIRP
In-Vehicle Unit: Subcarrier level approx. - 10 dBm at 1 meter

Receiver Sensitivity:
Roadside Unit: < -95 dBm (5 dB Noise Figure)
In-Vehicle Unit: < -40 dBm at 250 kbit/sec downlink

Multi-Access technique: Narrow receive beam width of receiver provides separation of individual vehicles.

Message Transfer Capacity:
Roadside to Vehicle: 250 and/or 500 kbit/sec
Vehicle to Roadside: 125 kbit/sec

Permissible Operating Environment: Developed in Europe, this system would almost surely require site licensing for readers in the United States. It is designed to operate in all weather.

Physical Deployment / Set-Up Constraints: Typically uses overhead installation for monitoring of individual lanes. Road- or lane-side installation also possible.

Coverage Zone: Coverage range is 30 meters maximum, 15 meters typical. Designed for a small footprint coverage in a single lane.

Cost of Infrastructure: Not provided
Deployment:
NRE:

Cost of In-Vehicle Equipment: Not provided

Targeted Market: Electronic Toll Collection (ETC), Electronic Toll and Traffic Management (ETTM), Commercial Vehicle Operation (CVO), including fleet management

Market Share: Used in the European PROMETHEUS project, the operational TELEPASS system, and has undergone extensive multi-lane system testing in Italy, Singapore, and Germany. Though not specifically identified by name, this is probably the system tested in the Australian Microwave Toll Debiting Pilot Project.

References:

Notes and specifications sent by Paul K. Kimber, Chief Scientist, Transportation Avionics Laboratory, GEC-Marconi, November 17, 1995. Includes: Protocol for the Air Interface for the BMM ‘94, April 25, 1994 - Data Specifications for the TRICS Applications, July 11, 1993

Sales and advertising literature.

Bhandal, A., et al., “Short-Range Communications Systems Used by the Prometheus Project,” Proceedings of the 1st World Conference on Applications of Transport Telematics & Intelligent Vehicle-Highway Systems, 1995, Vol. 5, pp. 2573-2580.

Name of System: **Mark IV - ROADCHECK**

Manufacturer: Mark IV IVHS, Inc.
2 12 Durham Avenue
Metuchen, New Jersey 08840
Phone: (908) 494 - 7720
Fax: (908) 484 - 8005

Contact Person: Paul Manuel (marketing) and Kelly Gravelle
Phone: (905) 624 - 3025
Fax: (905) 624 - 4572

System Description: The ROADCHECK systems provides two-way, short range communications between vehicles and host computer systems. Options include basic tags, which are simply read by the roadside reader; read/write vehicle tags with 5 12 bits of storage capacity; and read/write interfaces which allow the transfer of information to other in-vehicle systems (processors, ATIS, etc.). These are currently in use in field tests, and are due to become commercially available in the third quarter of 1996. They claim to have a dual protocol: one lane based, and one wide area.

Detailed Specifications:

Operating Frequency: 902 - 928 MHz, 915 MHz nominal, roadside reader requires licensing

Modulation Technique:
Roadside to Vehicle: AM, Manchester encoded
Vehicle to Roadside: AM, Manchester encoded

Necessary Bandwidth:
Roadside to Vehicle: Not Provided
Vehicle to Roadside: Not Provided

Occupied Bandwidth:
Roadside-to-Vehicle: Not Provided
Vehicle-to-Roadside: Not Provided

Antenna Parameters:
Roadside Unit: Multiple antenna choices including overhead flat panel antennas, in-pavement antennas and patch antennas (for fixed or mobile installations).
In-Vehicle Unit: Compact, probably etched printed circuit card, antennas with low gain and little or no directionality.

Transmitted Power: Specific to installation and application.
Roadside Unit:
In-Vehicle Unit: 1 mW

Receiver Sensitivity: Not published

Roadside Unit:

In-Vehicle Unit:

Multi-Access technique: Typically uses very short range communications in conjunction with time division access to cover multiple lanes. A single reader can cover eight lanes. It does have a wide area mode in which it interacts as a ‘tireless LAN.” The access mode used in the Highway 407 project (Canada) is based on the combination of Slotted Aloha and Time Division Multiple Access (TDMA) protocols.

Message Transfer Capacity: 500 kbps $\pm$10%

Permissible Operating Environment: The in-pavement antennas can operate through 6 inches of dry snow or 2 inches of debris (dirt, leaves, etc.).

Physical Deployment / Set-Up Constraints: Roadside antennas can be installed overhead for most applications. The system also includes the option of using in-pavement antennas.

Coverage Zone: The lane based (single-lane coverage for a single antenna) range is about 20 ft. Multiple lanes (up to 8) can be time multiplexed by a single reader. The open road operation (multiple-lane coverage for a single antenna) range is about 100 ft.

Cost of Infrastructure:

Deployment: These estimates assume that a single reader is multiplexed over 8 antennas:

$5,000 per lane for 1 antenna per lane (dual reader, 8 lanes per reader)

$10,000 per lane for dual antenna high reliability apps. such as ETC

$20,000 per lane for two-zone, Type III applications

Installation requires approximately l/2 day field labor per lane per antenna.

NRE: After warrantee maintenance agreements cost around 15-20% of the original equipment costs.

Cost of In-Vehicle Equipment: The Type II (IAG) transponder cost is less than $25 (based on the IAG deposit amount). The Type III multi-mode (IAG and TDMA protocols) externally powered transponders cost approximately $75 - $100 in large volumes. Actual cost depends on options.

Targeted Market: Electronic Toll Collection (ETC), Commercial Vehicle Operations (CVO)

Market Share: The Mark IV technology has been in use for many years on the Heavy Electronic License Plate (HELP) project, currently known as Pre-Pass. It is being made compatible with the Advantage I-75/Highway 407 (AVION) project. In planning for use in the Atlantic City Parkway and Garden State Parkway (E-ZPass) in New Jersey.

References:

Sales and advertising literature sent by Paul Manuel on October 2, 1995.

Telephone conversation with Paul Manuel on January 18, 1996.

Name of System: **PREMID™: Trans Tag™ TS3100**

Manufacturer: Saab-Scania Combitech Traffic Systems
Box 1063, S-551 10 Jonhoping, Sweden
Phone: **46 36** 19 43 00
Fax: 4636194301

Also/

2 1300 Ridgetop Circle
Sterling, Virginia 20 166
Phone: **(703) 406 - 7284**
Fax: **(703) 406 - 7224**

Contact Person: Ove Salomonsson, Vice President (Sterling, Virginia)

System Description: This is a semi-passive (backscatter) vehicle-to-roadside communications system. It operates at 2.45 GHz on both up- and down link with circular polarization. The communications link uses an active roadside reader and a reflective mode transponder in the vehicle. Size of transponder memory between 256 Bytes and 32 Kbytes. Wide product range available: portable reader/programmer broadcasting beacons, Type I and Type III tags (on-board electronics interface).

Detailed Specifications:

Operating Frequency: **2.45 GHz**

Modulation Technique:
Roadside to Vehicle: Manchester encoded ASK
Vehicle to Roadside: FSK

Necessary Bandwidth:
Roadside to Vehicle: +/- 2.0 MHz
Vehicle to Roadside: +/- 2.0 MHz

Occupied Bandwidth:
Roadside-to-Vehicle: Not Provided
Vehicle-to-Roadside: Not Provided

Antenna Parameters:
Roadside Unit: 8-patch antenna, 14 dB gain
In-Vehicle Unit: low-gain compact antenna

Transmitted Power:
Roadside Unit: less than 500 mW EIRP (FCC Part 15 and Part 90 approval available
In-Vehicle Unit: reflective backscatter

Receiver Sensitivity:

Roadside Unit: -65 dBm/m^2

In-Vehicle Unit: -5 to -11 dBm/m^2

Multi-Access Technique: Yes. Proprietary HDLC

Message Transfer Capacity:

Roadside to Vehicle: 167 kbit/sec

Vehicle to Roadside: 267 kbit/sec

Permissible Operating Environment:

Physical Deployment / Set-Up Constraints: both side pole and over head mount OK

Coverage Zone: in a toll environment 3 x 4 meters

Cost of Infrastructure:

Deployment: approximately USD10,000 per lane

NRE:

Cost of In-Vehicle Equipment: from USD30.00 to 150.00

Targeted Market: Two-way communications between the vehicle and the roadside, primarily for automatic debiting applications (ETC), but used also for commercial fleet management and public transit monitoring process.

Market Share: Installations include:

Toll Collection: ASF Toulouse, France; AREA, Open System, Lyon, France; SAPRR Gannat, France; AREA, Closed System, Lyon, France; SAPN Normandie, Normandy Bridge, Tancarville Bridge, France; SPN A29, France; SAPN A14, France; Dartford River Crossing London, England; Mersey Tunnels Liverpool, England; Alesund/Giske Bruselshap Alesund, Norway; Trygg Tunnel A.S. Tromso, Norway; Europistas, Spain; Tate /Es Cairn Tunnel, Hong Kong; DARS, Torovo, Slovenia; Penang Bridge, Malaysia; Shan Alam Expressway, Malaysia; Zhuhai, China; AUSOL Buenos Aires Argentina; Tauem Autobahn Austria.

Access Control: Direction General de Trafico, Madrid, Spain;

Border Crossing Shenzen Customs, China

Name of System: **PREMID™: EURO TAG™ TS3200**

Manufacturer: Saab-Scania Combitech Traffic Systems
Box 1063, S-55 1 10 Jonhoping, Sweden
Phone: 4636194300
Fax: 4636194301

Also/

2 1300 Ridgetop Circle
Sterling, Virginia 20 166
Phone: (703) 406 - 7284
Fax: (703) 406 - 7224

Contact Person: Ove Salomonsson, Vice President (Sterling, Virginia)

System Description: This is an open protocol vehicle-to-roadside communications (VRC) system developed in coherence with PAMELA/ADEPT project under the European DRIVE program. It operates at 5.8 GHz and uses circular polarization. The communications link uses an active roadside reader and a reflective (backscatter) transponder in the vehicle. The system is fully compatible with the preliminary European standard for DSRC (Dedicated Short Range Communications) developed under Cen TC 278. Real "electronic pulse" Smart Cart capability available (Type IV transponder).

Detailed Specifications:

Operating Frequency: 5.795 to 5.805 GHz

Modulation Technique:
Roadside to Vehicle: Manchester encoded ASK
Vehicle to Roadside: FSK

Necessary Bandwidth:
Roadside to Vehicle: +/- 1.25 MHz
Vehicle to Roadside: 0.5 MHz per sideband x 2

Occupied Bandwidth: Two 5 MHz channels
Roadside-to-Vehicle:Not Provided
Vehicle-to-Roadside:Not Provided

Antenna Parameters:
Roadside Unit: 12 dB
In-Vehicle Unit: low-gain compact patch antenna 7 dB

Transmitted Power:
Roadside Unit: 2.0 W EIRP
In-Vehicle Unit: reflective backscatter

Receiver Sensitivity:
Roadside Unit: -100 dBm
In-Vehicle Unit: -40 dBm

Multi-Access Technique: **Yes.** TDMA, slotted ALOHA

Message Transfer Capacity:
Roadside to Vehicle: 500 kbit/sec
Vehicle to Roadside: 250 kbit/sec

Permissible Operating Environment:

Physical Deployment / Set-Up Constraints:

Coverage Zone:

Cost of Infrastructure:
Deployment: USD 15,000 per lane (estimate
NRE:

Cost of In-Vehicle Equipment: USD 30.00 to USD 150.00

Targeted Market: Two-way communication between the vehicle and the roadside, primarily for automatic debiting applications (ETC)

Market Share: Installations include:

Toll Collection: ASF Toulouse, France; AREA, Open System, Lyon, France; SAPRR Gannat, France; AREA, Closed System, Lyon, France; SAPN Normandie, Normandy Bridge, Tancarville Bridge, France; SPN A29, France; SAPN A14, France; Dartford River Crossing London, England; Mersey Tunnels Liverpool, England; Alesund/Giske Bruselshap Alesund, Norway; Trygg Tunnel A. S. Tromso, Norway; Europistas, Spain; Tate /Es Cairn Tunnel, Hong Kong; DARS, Torovo, Slovenia; Penang Bridge, Malaysia; Shan Alam Expressway, Malaysia; Zhuhai, China; AUSOL Buenos Aires Argentina; Tauem Autobahn Austria.

Access Control: Direction General de Trafico, Madrid, Spain;

Border Crossing Shenzen Customs, China

Name of Svstem: **TIRIS**

Manufacturer: Texas Instruments
TIRIS Sales and Application Center
13020 Floyd Road
Dallas, Texas 75243
Phone: (214) 917 - 1462
Fax: (214) 917 - 1440

Contact Person: Dave Newman
(214) 917-1460

Svstem Description: TIRIS is a DSRC system based on backscatter technology. The AM modulated signal is imposed with an FM subcarrier at 900 kHz for the uplink (vehicle to roadside) channel. Tags are available in read-only or read/write versions. Versions are also available for dash mounting or exterior (license plate) mounting.

Detailed Specifications:

Operating Frequency: 915 MHz (902 - 928 MHz)

Modulation Technique:
Roadside to Vehicle: Manchester II Encoded ASK
Vehicle to Roadside: ASK with FSK subcarrier: Mark: 1200 kHz sq. wave
Space: 600 kHz sq. wave

Necessary Bandwidth:
Roadside to Vehicle: Not Provided
Vehicle to Roadside: Not Provided

Occupied Bandwidth:
Roadside-to-Vehicle: < 3 MHz
Vehicle-to-Roadside:< 3 MHz

Antenna Parameters:
Roadside Unit: Various options.
In-Vehicle Unit: 90 deg. field of view typical. Etched PC board antenna.

Transmitted Power:
Roadside Unit: 100 mW to > 1.0 W
In-Vehicle Unit: N/A (backscatter)

Receiver Sensitivity:
Roadside Unit: Proprietary

In-Vehicle Unit: 500 mv/m

Multi-Access technique: California Title 21 compliant / Access and Silence. No specific multi-access technique. It does use a pulse amplitude technique for lane discrimination.

Message Transfer Capacity:
Roadside to Vehicle: 300 kbps (including coding)
Vehicle to Roadside: 300 kbps (including coding)

Permissible Operating Environment: All weather operation.

Physical Deployment / Set-Up Constraints: Typically an overhead antenna is installed to monitor a single lane of traffic. Multiple lane coverage includes readers for each lane with synchronized pulse that the tag uses for lane discrimination (simple amplitude comparison).

Coverage Zone: Various antenna beamwidths and transmit power levels available. Typical single lane deployment has an antenna mounted 18 feet above the roadway with 22, 30, 3 5 and 40 degree beamwidths.

Cost of Infrastructure: Proprietary
Deployment:
NRE:

Cost of In-Vehicle Equipment: Proprietary

Targeted Market: Electronic Toll Collection (ETC), Electronic Traffic and Toll Management (ETTM), Parking / Access Control

Market Share: Proprietary

References:

Information received from Dave Newman (filled out above template) January 24, 1996.

Sales brochures on the TIRIS system,

Sharpe, C. A., ‘Wireless Automatic Vehicle Identification,” *Applied Microwave & Wireless,* Fall 1995, pp. 32-58.

Name of System: **XCI: RFID Systems for Toll Collection**

Manufacturer: XCI, Inc.
Automatic Identification
63 15 San Ignacio Ave.
San Jose, CA 95110
Phone: (408) 281-6612
Fax: (408) 578-4 102

Contact Person: Karen Vorster, Sales Manager

System Description: XCI produces a variety of passive automatic identification systems for the toll collection (ETTM), factory automation, access control and automatic vehicle identification (airports) markets. The products manufactured by XCI include RF readers, reader controllers, and transponders. The transponders are passive, using Surface Acoustic Wave (SAW) technology. The toll collection transponders are referred to as the Commute Tag (IWT-1) and the Commercial Tag (IDR00l). These transponders, in conjunction with the RF readers and read controllers, enable accurate identification at vehicle speeds up to 150 mph using very low power. The XCI system does not require FCC licensing due to the low power utilized by the reader.

Detailed Specifications:

Operating Frequency: 915 MHz

Modulation Technique:
Roadside to Vehicle: FM chirp
Vehicle to Roadside: Delay modulation

Necessary Bandwidth:
Roadside to Vehicle: 20 MHz
Vehicle to Roadside: 20 MHz

Occupied Bandwidth:
Roadside-to-Vehicle:Not Provided
Vehicle-to-Roadside:Not Provided

Antenna Parameters:
Roadside Unit: 8 dBi patch linear polarization
In-Vehicle Unit: 3 dBi dipole linear polarization

Transmitted Power:
Roadside Unit: 0.05 W, peak power
In-Vehicle Unit: passive, reflective

Receiver Sensitivity:

Roadside Unit: -115 dBm

In-Vehicle Unit: N/A

Multi-Access Technique: None. By spatial isolation only.

Message Transfer Capacity: Instantaneous data rate of 20 Mbps

Permissible Operating Environment: All weather operation.

Physical Deployment / Set-Up Constraints: The system is modular and easy to install. There are no set-up constraints, the reader is simply mounted in an overhead position. There is very little problem with 'cross-talk" as the readers are software programmable to correct.

Coverage Zone: Range from reader to tag is 15 feet typically, and 20 feet maximum.

Cost of Infrastructure: Not Provided.

Deployment:

NRE:

Cost of In-Vehicle Equipment: The Commute windshield transponder has a $25 list price. The Commercial rugged transponder has a $28 list price.

Targeted Market: Electronic Toll Collection (ETC), Electronic Toll and Traffic Management (ETTM), factory automation, access control and automatic revenue collection, and curbside control.

Market Share: Used in the San Francisco Bay Area Rapid Transit (BART) system to provide improved access for disabled persons. Also used in Chrysler automobile production to electronically tag each vehicle with its VIN number. Other sample installations include:

Toll Collection: E-470 Denver, Colorado

Factory Automation: Hyundai, Freightliner, Chrysler, Honda, Bethlehem Steel, and EDS

Access Control: Federal Reserve Bank, Stanford University, Park&Service, E-470 toll road, Bay Area Rapid Transit, and Maytag

Automatic Vehicle Identification: PG&E, San Jose International Airport, Sky Chefs Chicago O'Hare International Airport, Kennedy International Airport, and LaGuardia International Airport

References:

Sales and advertising literature.

'Radio Frequency Identification (RFID)," Market Study, Air Force Automatic Identification Technology (AIT) Program Management Office, May 1995.

Fax received from Karen Vorster, Sales Manager, XCI, Inc., on January 26, 1996.

Appendix B: AEI and CVO Tag Usage

As quoted from the CVO requirements document[1], "it is assumed that several types of tags will exist and that a vehicle may have to use more than one tag in order to participate in ITS. For example, a private vehicle will able to use a single tag for all appropriate and desired ITS applications (i.e., electronic toll collection, in-vehicle signing), However, a commercial vehicle will employ a more capable power unit tag that supports both private vehicle as well as commercial vehicle functionality. Furthermore, CVO will require the use of multiple types of tags. For example (as shown in Figure l), two classes of tags, a read/write and a read-only tag, would be used to support different functions. The read/write class would be used for the power unit. The read only tag supports fleet and freight management oriented applications such as automatic equipment identification (AEI) and freight tracking."

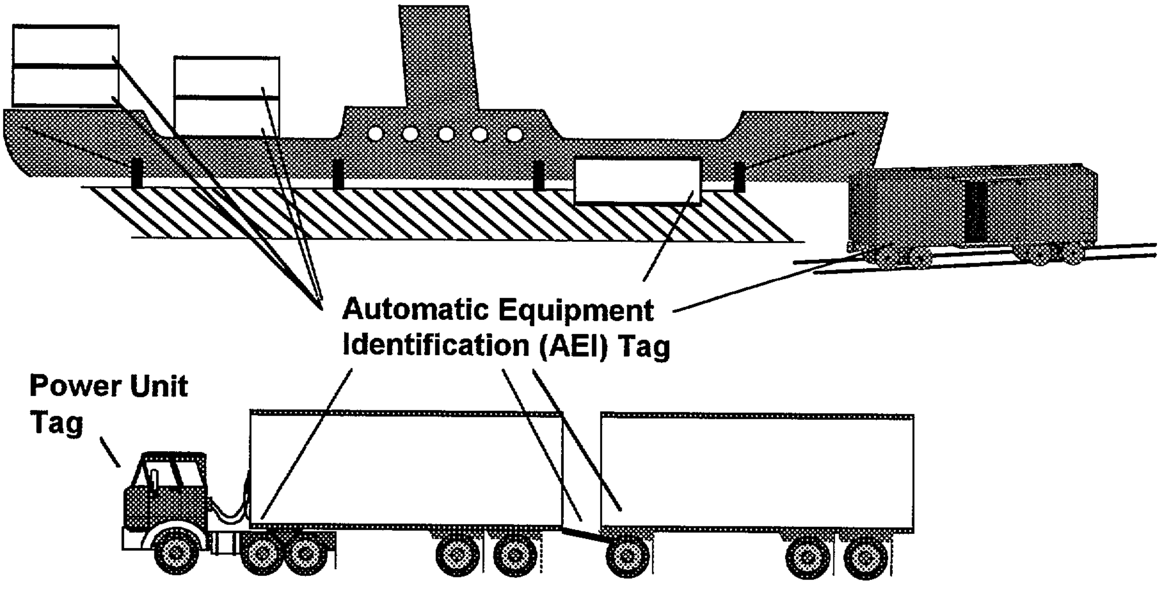

Figure 1 Use of Multiple DSRC Tag Types for CVO

References

[l] Yuan, R, Johns Hopkins University Applied Physics Laboratory, Draft CVO Dedicated Short Range Communications (DSRC) Requirements for ITS Version 2.0, April 1996.

APPENDIX C: SPECTRUM REQUIREMENTS FOR A DEDICATED SHORT RANGE COMMUNICATIONS (DSRC) CHANNEL

1.0 Introduction

This appendix presents an assessment of the spectrum required to support a single DSRC channel. There are still many options for the selection of the air interface specification and this section will describe the spectrum requirements for one of the most demanding of these options. The purpose of this section is not to support selection of a particular air interface, but rather to explore the spectrum needed by an example air interface.

The candidate air interfaces include the draft ASTM standard, the European DSRC prestandard using the default parameters, a modified European DSRC prestandard, and the European DSRC prestandard using higher optional data rates. The European DSRC prestandard modified to meet the estimated US data rate is the one that has the most demanding spectrum requirement. By basing the spectrum requirement calculation on the most demanding option, any of the options can be selected for use if compromises in reuse distance, transponder complexity, message content, or range are determined to be the best course of action.

The default parameters for the European DSRC prestandard [l] result in a 500 kBit/s downlink data rate and a 250 kBit/s uplink data rate. Currently, the US proposed rates are 600 kBit/s for downlink and uplink. If the European DSRC prestandard were used as a basis for a US standard, the US requirement could be met by scaling the frequency parameters of the European prestandard and employing an option in the standard to carry data in both subcarrier channels. In addition, the US standard could use a preamble (similar to the European standard) that establishes the parameters from a list of options (including the data rate) for each communications session. This would allow a vehicle to use the default parameters for an application that does not require the highest data rate and use the highest data rate for more demanding applications in other locations. This could allow initiation of DSRC operations using the default data rates for applications that need only modest data rates and the use of higher data rate options when more demanding applications are deployed. The default parameters can be implemented with various options in different communications sessions while using the same equipment in each session.

Section 2.0 describes the parameters in the European prestandard for DSRC and how it might be modified to meet the US requirements. Section 3.0 describes the parameters for the proposed US DSRC standard. Section 4.0 presents an analysis of the spectrum requirements for the proposed US DSRC standard derived from the European prestandard.

2.0 Modifying the European Prestandard for DSRC

The European prestandard for DSRC presents the requirements for a vehicle-to-roadside communications system. The European DSRC systems assume a half duplex communications scheme where the roadside unit (RSU) or beacon transmits the data to the vehicle and then provides a tone for the uplink. The onboard unit (OBU) in the vehicle modulates the tone from the beacon and reflects the signal back to the beacon for the uplink communications. This communications scheme minimizes the RF components in the OBU which in turn reduces the complexity and cost of the OBUs.

The primary source of information for spectral analysis of the European DSRC systems is the latest prestandard for the DSRC physical layer [1]. The downlink is defined in the European prestandard as an amplitude-shift-keyed (ASK) signal. The default encoding of the downlink data is FMO. FM0 encoding is defined as a transition in the signal at the beginning and end of each bit plus an additional transition in the middle of the “0” bit. An alternative data encoding for the downlink is NRZI. NRZI encoding is defined as no transition at the beginning of a “1” bit, a transition at the beginning of a “0” bit, and constant level within a bit. The default data rate for the downlink is 500 kBit/s. The primary downlink parameters from the prestandard that are required to assess the spectrum are listed in Table 1.

Table 1. European DSRC Downlink Parameters

Parameter	Default Value	Optional Values
Modulation	Two level amplitude modulation	None
Modulation Index	0.5 . . . 0.9	None
Data Coding	FM0	NRZI
Bit Rate	500 kBit/s	31.25 kBit/s 62.5 kBit/s 125 kBit/s 250 kBit/s 500 kBit/s 1000 kBit/s

The optional values listed allow applications that use lower data rates to use lower performance receivers; tolerate more noise, because they can use a smaller IF bandwidth; and obtain closer distances between adjacent channels, due to more signal attenuation between occupied spectra.

The uplink described in the European DSRC prestandard uses M-ary phase shift keying (M-PSK) on one or both of two subcarriers. The default uplink parameters specify that the data are to be transmitted on only the upper subcarrier or the same data are to be transmitted on both subcarriers simultaneously. The prestandard allows for different data to be transmitted on each subcarrier as an option. The subcarrier signals are synchronized with the data sequence such that the transitions of the data coincide with the transitions of the subcarrier. The data are encoded using the NRZI protocol and the default data rate is 250 kBit/s. Table 2 lists the primary uplink parameters from the European prestandard.

Table 2. European DSRC Uplink Parameters

Parameter	Default Value	Optional Values
Subcarrier Frequencies	1.5 MHz and 2.0 MHz	None.
Use of Subcarrier Bands	Same data on both bands or data only on upper band will be allowed for default	• Same data in both • Data only in upper • Different data in each
Subcarrier Modulation	M-PSK	None.
Data Modulation Order	M = 2	M=2 M=4 M=8
Modulation on Carrier	Multiplication of modulated subcarrier with carrier	None.
Data Coding	NRZI	None.
Symbol Rate (per subcarrier)	250 kBit/s	Bit Rate: 31.25 kBit/s 6.25 kBit/s 125 kBit/s 250 kBit/s 500 kBit/s 750 kBit/s

Simply scaling the European prestandard parameters results in a US DSRC system with a default downlink data rate of 600 kBit/s and a default uplink data rate of 300 kBit/s. To achieve a default uplink of 600 kBit/s, the default options for the uplink must be changed. The European DSRC default uplink either transmits the same data on both uplink subcarriers or transmits data only on the upper (2.0 MHz) subcarrier. The US DSRC system can have a default 600 kBit/s uplink by selecting the default option that different data is transmitted on each subcarrier. Since each subcarrier can transmit 300 kBit/s, the result is a total uplink data rate of 600 kBit/s.

There are other options for modifying the European DSRC prestandard to achieve 600 kBit/s on the uplink. The uplink default data modulation order could be changed to 4 (QPSK). Another option would be to combine the two uplink subcarrier into a single subcarrier and double the baud rate of the uplink Either of these options are feasible alternatives for doubling the uplink data rate. For this analysis, however, changing the default use of the two subcarrier bands was assumed.

3.0 Proposed US DSRC Based on European Prestandard

The data rate requirements for a US DSRC system are discussed in the main body of this report. These estimated data rates are required to support all the DSRC functions expected in the US lntelligent Transportation Systems (ITS) National Architecture. The uplink and downlink data rates estimated are both 600 kBit/s. This data rate is slightly higher than the European prestandard default downlink data rate and more than twice the default uplink data rate. However, the estimated US required data rate is within the limits of the optional parameters for the European prestandard.

For this analysis, the parameters for the US DSRC system are derived by simply scaling the European parameters by 6/5. For example, the European prestandard assumes a 5 MHz bandwidth and therefore the US DSRC bandwidth will be 5 MHz x 6/5 = 6 MHz. The US DSRC modulation formats and data encoding are assumed to be the same as those in the European prestandard. The resulting parameters for the US DSRC downlink and uplink are listed in Tables 3 and 4, respectively.

Table 3. Assumed US DSRC Downlink Parameters

Parameter	Default Value	Optional Values
Modulation	Two-level amplitude modulation	None
Modulation Index	0.5 . . . 0.9	None
Data Coding	FM0	NRZI
Bit Rate	600 kBit/s	37.5 kBit/s 75 kBit/s 150 kBit/s 300 kBit/s 600 kBit/s 1200 kBit/s

Table 4. Assumed US DSRC Uplink Parameters

Parameter	Default Value	Optional Values
Subcarrier Frequencies	1.8 MHz and 2.4 MHz	None.
Use of Subcarrier Bands	Different data transmitted on each subcarrier for default	• Same data in both • Data only in upper • Different data in each
Subcarrier Modulation	M-PSK	None.
Data Modulation Order	M=2	M=2 M=4 M=8
Modulation on Carrier	Multiplication of modulated subcarrier with carrier	None.
Data Coding	NRZI	None.
Symbol Rate (per subcarrier)	300 kBit/s	Bit Rate: 37.5 kBit/s 75 kBit/s 150 kBit/s 300 kBit/s 600 kBit/s 900 kBit/s

4.0 Spectrum of Proposed US DSRC: 600 kBit/s Downlink, 600 kBit/s Uplink

Each of the spectrum plots depicted in this section was generated by modeling the appropriate waveform in MathSoft's Matlab version 4.0. The data rate was modeled as a sequence at 1 Bit/s and then encoded as defined in Tables 3 and 4. The appropriate modulation was then applied. The spectrum was generated by calculating 20 times the log of the magnitude of the Fast Fourier Transform (FFT) of the modulated waveform. The plots were scaled in frequency to the appropriate data rate and then shifted such that the center frequency was 0 Hz. Any filtering that was used assumed an ideal bandpass filter.

The proposed US DSRC air interface is basically identical to the European DSRC prestandard system scaled to accommodate the higher data rates. The only significant difference assumed is that the uplink subcarriers carry different information and thus an uplink data rate of 600 kBit/s can be achieved. Note that the US system can operate in a default mode with 300 kBit/s uplink data being transmitted on both subcarriers or the upper subcarrier only, just like the European system. During a transaction between the RSU and OBU, the system can elect to switch to different data on each uplink subcarrier when necessary. This option is allowed in the European protocol and would thus maintain another similaritiy between the proposed US DSRC system and the European DSRC prestandard system.

Figures 1 - 3 depict the spectra of the proposed US DSRC system (with the carrier frequency normalized to 0 Hz). Each link assumes the 22-bit data sequence (0 1 0 1 0 0 1 1 0 0 0 1 11 0 0 0 0 1 1 1 1). Figure 1 depicts the ASK downlink which is 600 kBit/s data that is FM0 encoded and then binary ASK modulated with an 0.7 modulation index. Note that the mainlobe of the spectrum is contained within $\pm$ 1.2 MHz of the carrier. The bandwidth is determined primarily by the data rate and not the particular data sequence chosen. Figure 2 depicts the spectra of the uplink subcarriers at 1.8 MHz and 2.4 MHz. Each of the uplink subcarriers transmit data at 300 kBit/s with NRZI encoding and BPSK modulation. Note that the main lobes of the subcarrier spectra are 600 kHz wide and thus do not overlap with each other or the downlink main lobe.

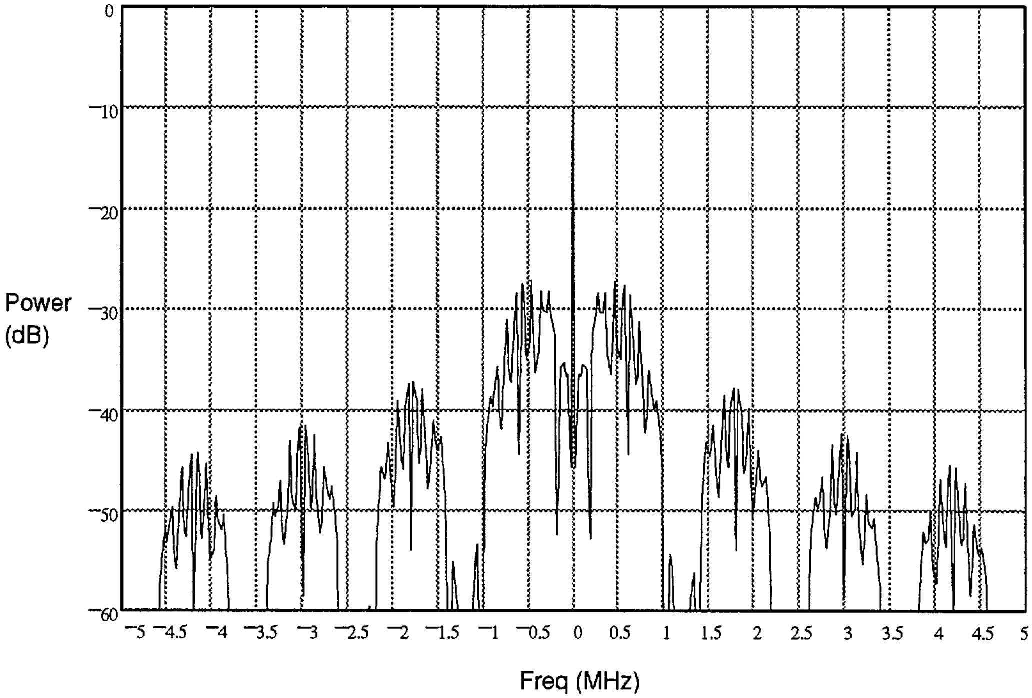

Figure 1. Spectrum of the Proposed US DSRC Downlink

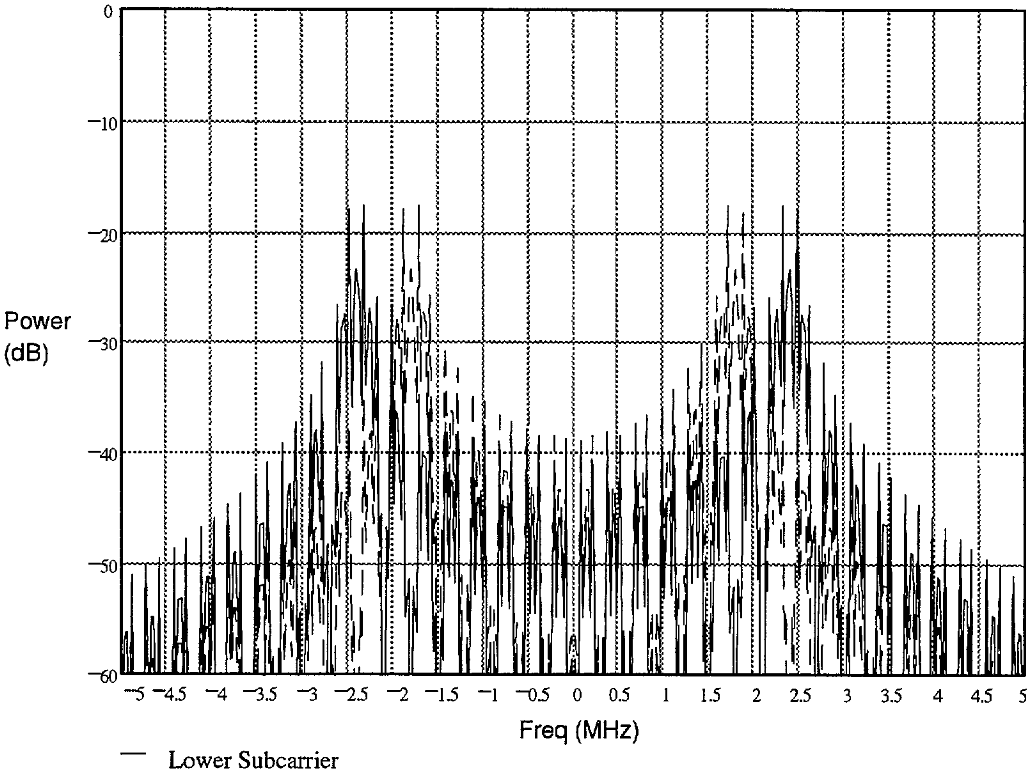

Figure 2. Spectrum of the Proposed US DSRC Uplink

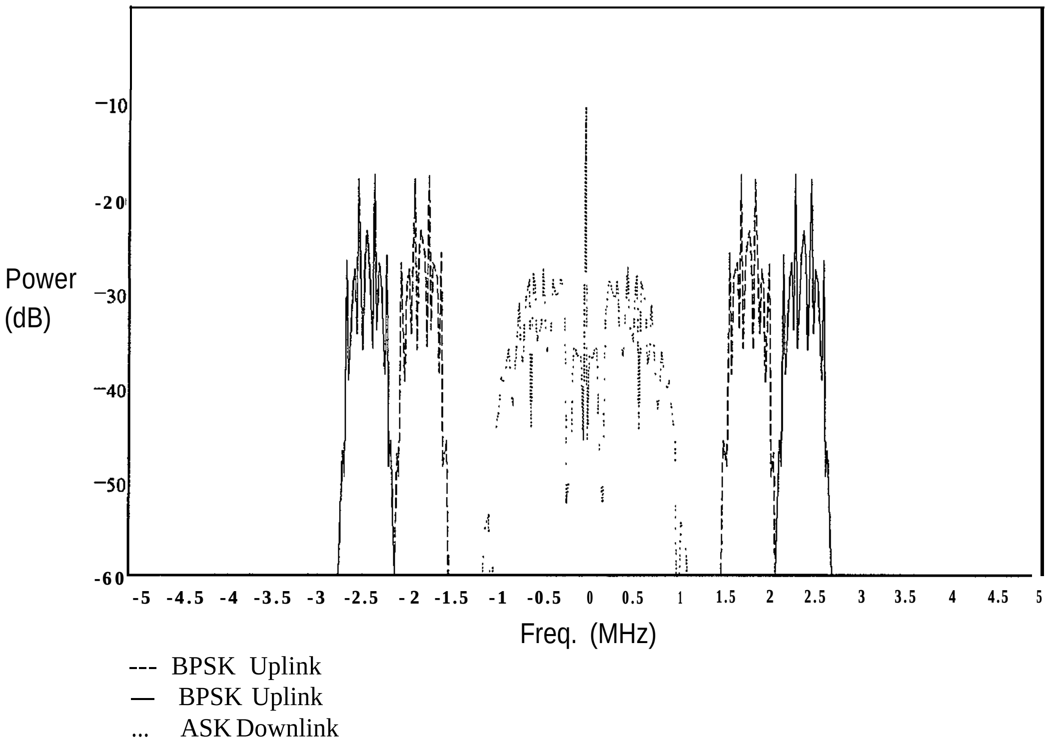

Figure 3. Composite Spectrum of the Proposed US DSRC Downlink and Uplink

Figure 3 was developed by filtering the uplink and downlink spectrums with bandpass filters such that only the mainlobes of the spectrums are transmitted. The downlink bandpass filter in the RSU allows only ± 1.2 MHz of the center frequency to pass through and be transmitted. Each of the subcarriers is filtered with a 600 kHz wide bandpass filter prior to being mixed with the RSU tone. The plot in Figure 3 assumes ideal filtering. The design of the actual filters used will determine the level of isolation between the communication bands.

Note that the entire spectrum of a US DSRC channel can be contained within the 6 MHz bandwidth. There is an approximately 300 kHz guard band on each side of the channel to allow for filtering to reduce adjacent channel interference. There is also a 300 kHz guard band between the downlink spectrum and the spectrum of the uplink lower subcarrier which again can be used to increase isolation (reduce interference).

5.0 Conclusions

The spectral analysis presented above demonstrates that the proposed US DSRC system with 600 kBit/s uplink and downlink data rates can be achieved within a 6 MHz bandwidth by scaling the European standard and using one of the uplink optional parameters. This result indicates that any of the less demanding air interfaces can be implemented within this 6 MHz bandwidth. These optional interface include the draft ASTM standard, the unmodified European DSRC prestandard, and the European DSRC prestandard using higher optional data rates.

However, in order to use another air interface, compromises would need to be made in reuse distance, transponder complexity, message content, or range.

References

[1] “European Prestandard: Road Traffic and Transport Telematics (RTTT) Dedicated Short-Range Communications (DSRC): DSRC Physical Layer using Microwave at 5.8 GHz,” Ref. No. prENV 278/9/#62 Version 4.0 1995, drawn up by CEN TC278 WG9 SG.Ll and Project Team MO1 8/PT06, October 1995.

APPENDIX D

DEDICATED SHORT RANGE COMMUNICATIONS (DSRC)

REUSE DISTANCE CALCULATIONS

DEDICATED SHORT RANGE COMMUNICATIONS (DSRC)

REUSE DISTANCE CALCULATIONS

June 1996

Prepared for

ARINC
255 1 Riva Road
Annapolis, Maryland 2 140 1

and

Federal Highway Administration
Turner-Fairbank Research Center
6300 Georgetown Pike
McLean, Virginia 22 10 1

Prepared by

Bruce A. Harvey, Ph.D.
Communications and Networking Division
Information Technology and Telecommunications Laboratory
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332-0821

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1.0 INTRODUCTION

This paper presents sample calculations of DSRC frequency reuse distances for some DSRC installations developed in reference [l]. In this document, the DSRC system parameters and characteristics assumed are similar to the latest draft European DSRC standards [2]. However, in many cases the power levels vary significantly from the European standard to achieve the ranges needed for the US applications.

The particular objectives of this paper are the following:

1. To provide the theoretical basis and formulas for computing same channel frequency reuse distances,

2. To provide the theoretical basis and formulas for computing power levels that will prevent interference between DSRC beacons operating on different channels,

3. To calculate specific examples of frequency reuse distances and power levels using the formulas in (1) and (2) by making reasonable assumptions about the characteristics of the equipment involved, and

The specific calculations of reuse distances and power levels will be based on example installations of DSRC beacons from the main body of the report. The modulation format, data encoding and other communication parameters assumed in this paper were derived from the most recent draft European DSRC standards [2]. The European DSRC standard is adjusted to meet the requirements of the US DSRC systems. The pertinent communications link parameters of the DSRC systems from the spectrum requirement report and the European draft DSRC standards are as follows:

Downlink:	Modulation:	FM0 Encoded, ASK (On-Off Keying) (FM0 has transition at the beginning of each bit with and additional transition in the middle of a “0” bit.)
	Data Rate:	600 kbps
Uplink:	Modulation:	Binary and Quadrature Phase-Shift Keying (PSK)
	Data Rate:	600 kbps

The theoretical formulas for computing same and different channel power levels and separation distances required are presented in Section 2. Section 3 presents generic power level requirements and separation distance calculations similar to those in the European DSRC standards at 5.8 GIIz [2]. The specific examples of frequency re-use distance calculations are presented in Section 4.

2.0 Theory and Formulas for Calculating Interference Power Levels and Separation Distances

The calculation of minimum separation distance for either same channel or different channels begins with the calculation of transmit powers and required (minimum) received signal levels for successful downlink and uplink communications. Next, thresholds must be determined for the power levels of interfering signals. Finally, the propagation equations must be used to calculate minimum ranges meeting the interference thresholds. The calculations in this paper solve the minimum separation distance for same and adjacent channel operations because these are the worst case separation distances.

2.1 Minimum Received Signal Level Calculations

The Minimum Received Signal Level (MRSL) for a receiver is a function of the modulation used, data rate of the transmission, the Noise Figure (NF) of the receiver, and the required Bit Error Rate (BER) for the communications link. The modulation type and the data rate transmitted determine the bandwidth required by the receiver. Similarly, the modulation type and the required BER determine the required Signal-to-Noise Ratio (SNR) at the receiver. The formula[1] for calculating the MRSL of a receiver, expressed in dBm, is as follows:

$$MRSL = 10 * \log(k * T) + 10 * \log(B) + NF + SNR_{Req} + M \tag{1}$$

where k = Boltzman's constant = 1.38 x 10^{-23} joule/K,
T = temperature in Kelvin = 290 K (typically),
B = receiver bandwidth in Hz,
NF = receiver noise figure in dB,
SNR_{Req} = required SNR in dB to achieve desired BER, and
M = communications link margin to allow for losses and multipath.

The maximum BER for the DSRC uplink and downlink is assumed to be 10^{-6} to match the European DSRC standard [2]. Assuming that a simple noncoherent detection scheme is used, the required SNR for the ASK downlink is 17.2 dB. The required SNR for coherent PSK on the uplink is 10.5 dB to achieve a BER of 10^{-6} [4].

The NF assumed for the DSRC systems to be evaluated here will be that of the GEC-Marconi TRICS system. The TRICS system operates at 5.8 GHz and its uplink receiver has a NF of 5 dB. No NF is quoted for the downlink. The IF (intermediate frequency) bandwidth of a PSK receiver is approximately twice the baud rate (rate at which the phase changes). The 250 kbps data rate uplink with NRZI encoding has a 250 kHz baud rate. Therefore, the PSK modulation at subcarrier frequencies of 1.5 kHz or 2 MHz, where each has a 250 kbps data rate, requires an lF bandwidth of approximately 500 kHz for a receiver tuned for either carrier. The quoted MRSL

1 The noise factor formula in reference [3] was used as a basis for deriving this MRSL formula.

for the TRICS uplink receiver is -95 dBm (-125 dBW). Inserting these values into the above equation and solving for the link margin shows that the assumed link margin (M) is 6.5 dB.

The MRSL for the DSRC investigated here can now be calculated by assuming the NF of the TRICS system and a similar link margin. The bandwidth of the DSRC uplink, calculated by assuming that the uplink data rate of each subcarrier is 300 kbps, is 600 kHz. Using the above equation, the MRSL of the uplink receiver in the Road Side Unit (RSU) is

$$MRSL = -204.0 + 57.8 + 5 + 105 + 6.5 = -124.2 \text{ dBW} = -94.2 \text{ dBm}$$

The MRSL for the DSRC downlink can be calculated similarly. However, the downlink receiver of the On-Board Unit (OBU) typically operates well above the MRSL. Thresholding is used to prevent the OBU from becoming active in the presence of very low signal levels. The European DSRC standard [2] set the MRSL of the downlink (OBU) at -40 dBm assuming a 0-dB-gain receive antenna. The threshold actually refers to the power density at the OBU rather than at the OBU receiver itself. If the OBU antenna has a gain, G, then the receiver's actual MRSL threshold must be -40 dBm + G. The threshold of -40 dBm will be used throughout this analysis. The MRSLs assumed for the DSRC for the remainder of this paper are listed in Table 1.

Table 1. DSRC Minimum Received Signal Levels

Receiver	Minimum Received Signal Level
Uplink Receiver (RSU)	-94 dBm
Downlink Receiver (OBU)	-40 dBm (0 dB receive antenna)

2.2 Downlink Transmit Power Requirements

The power received by any particular receiver, P_R, can be calculated using the following formula:

$$P_R = \frac{P_T * G_T * G_R * l^2}{(4*p)^2 * R^2} \qquad (2)$$

where: P_T = Transmit power in Watts,
G_T = Transmit antenna gain in the direction of the receiver,
G_R = Receive antenna gain in the direction of the receiver,
a = Wavelength of the transmitted signal, and
R = Range between the transmit and receive antennas.

The required transmit power, P_T, can be calculated by letting the received power equal to the MRSL of the receiver and solving the equation for P_T. The resulting equation is as follows:

$$P_T = \frac{MRSL*(4*p)^2*R^2}{G_T * G_R * l^2} \quad (3)$$

Note that it is often more efficient to calculate these values in dB, especially in spreadsheets. Most of the calculations done in this effort were accomplished using spreadsheets and thus were done in dB. The above equation expressed in dB is

$$P_T = MRSL + 20 \log(4 * p) + 20 \log(R) - G_T - G_R - 20 \log(l) \quad (4)$$

where P_T, G_T, G_R and $MRSL$ are all expressed in dB.

The DSRC downlink transmit power is calculated using the MRSL thresholds listed in Table 1. Assuming the receive antenna gain is 0 dB (GR = 0 dB). the required transmit power for a successful downlink in dBm is

$$Pt\_d = OBU\_min + 2*F\_PI + 2*Rmax\_dB - (RSU\_g - RSU\_gl) - 2 * Lambda\_dB \quad (5)$$

where:	*Pt_d*	=	Transmit power required for successful downlink in dBm,
	OBU_min	=	-40 dBm = MRSL of OBU assuming 0 dB antenna,
	F_PI	=	10log(4*π),
	Rmax_dB	=	10log(maximum range, Rmax, in feet),
	RSU_g	=	Peak Gain of RSU antenna in dB,
	RSU_gl	=	RSU antenna pattern shape loss (assumed to be 3 dB for edge of main lobe, and
	Lambda_dB	=	10log(*l*)where 1 is expressed in feet.

The variable names used in equation 5 are those used in the spreadsheets later in this paper.

2.3 DOWNLINK TRANSMIT POWER REQUIRED FOR SUCCESSFUL UPLINK

The DSRC OBU is assumed to be a semi-active transceiver. It simply modulates a carrier tone transmitted from the RSU by mixing the tone with a PSK modulated subcarrier at 1.8 MHz or 2.4 MHz. The resulting signal is then amplified with a 10 dB gain amplifier and retransmitted to the RSU. Since the uplink transmission is a modulated and amplified reflection of a downlink tone, then the received signal level of an uplink is a function of the downlink transmit power.

The signal power received by the OBU is modulated and reflected back to the RSU with some losses and gains inherent in the OBU. To determine the sum total of the losses and gains due to the OBU, the assumption used in the European DSRC standard [2] will be used in this analysis. The European DSRC standard assumes that the OBU antenna has a gain *(OBU_g)* of 4 dB up to 35 degrees off boresight, a one-way transmission loss through the windscreen *(L_w)* of 3 dB, a modulation loss *(L_m)* of 3 dB (due to on-off keying) and a realization loss *(L_r)* of 4 dB. The OBU also has a 10 dB RF amplifier *(OBU_rf)*. The transmitted signal level (including antenna gains) from the OBU relative to the received power level (assuming 0 dB antenna gain) is called the minimum conversion gain *(OBU Gain).* The minimum conversion gain is calculated: *OBU-Gain* = 2*OBU_g + OBU_rf - 2*L_w -L_m -L_r = +5 dB.

The power received by the OBU can be calculated using equation 2. The OBU antenna gain can be considered as 0 dB because the antenna gain is included in *OBU_Gain.* The power transmitted back to the RSU is calculated by adding *OBU_Gain* to the received signal level at the OBU. Finally, the received signal level at the RSU is calculated by again using equation 2 for the return link. The required transmit power for a successful uplink is that which results in a received signal level at the RSU equal to the MRSL. The transmit power required for a successful uplink, *Pt_u,* in dBm can be expressed as

$$\begin{gathered} Pt\_u = RSU\_mrsl + 4*F\_PI + 4*Rmax\_dB - OBU\_gain \\ -2*(RSU\_g - RSU\_gl) - 4*Lambda\_dB \end{gathered} \tag{6}$$

where: *RSU_mrsl = uplink MRSL in dBm.*

The required RSU transmit power for a given operating range, *Pt,* is the maximum of *Pt_d* and *Pt_U.*

2.4 Separation Distance Calculations

The required separation distance between transmitters and receivers is a function of the maximum allowable interference level at the receiver, the transmit and receive antenna gains in the direction of transmission, the transmit power levels, and the isolation between the transmitted signal and the received frequency bands.

The transmit power levels are determined by the required operating ranges and antennas for a given scenario. The equations for determining the required transmit power level were presented in Section 2.3. Each of the remaining parameters is discussed in the following sections, followed by derivation of the equations for calculating minimum required separation distances.

2.4.1 Maximum Allowable Received Interference Level

The maximum allowable received interference levels assumed in the analysis were derived from the European DSRC standard [2] and the MRSL of the GEC-Marconi TRICS system. The European DSRC standard quotes an RSU maximum interference level of -115 dBm (-135 dBm plus a 20 dB antenna gain). This level is 20 dB below the MRSL quoted for the TRICS system. Since the MRSL for the RSU of the DSRC system assumed for this analysis is -94 dBm, then the assumed maximum RSU interference level, *RSU_int,* is assumed to be 20 dB lower or -114 dBm.

The downlink MRSL is assumed to be the same as that quoted in the European DSRC standard (-40 dBm) and thus the maximum interference level is also assumed to be the same. The maximum received interference level at the OBU, *OBU_int,* is therefore assumed to be -60 dBm, assuming a 0 dB gain OBU antenna.

2.4.2 Antenna Gain and Sidelobe Levels

The RSU antenna gains assumed in each of the scenarios in Section 4 are calculated from the elevation and azimuth beamwidths required for the RSU to cover its intended area on the road. The geometry of the scenario determined the azimuth and elevation beamwidths of the antenna, which then were translated to antenna gain.

The gain of an RSU antenna, *RSU_g*, can be expressed in terms of the area of the aperture, A; the aperture efficiency, ρ_a; and the wavelength, *l*, as follows: [5]

$$RSU\_g = \frac{4*p*A*r_a}{G_T * G_R * l^2} \tag{7}$$

The area of the aperture (assumed rectangular) can be calculated

$$A = d_a * d_e, \tag{8}$$

where d_a and d_e are the dimensions of the aperture in the azimuth and elevation directions, respectively. The European DSRC standard [2] assumes that the gain of the RSU antenna sidelobes is 15 dB *(RSU_sl)* below the peak of the main lobe. A parabolic energy distribution across an antenna aperture can produce an antenna pattern with sidelobes 15.8 dB below the peak antenna gain. The aperture efficiency of this aperture distribution is 0.994 and the beamwidth of the antenna in degrees is

The DSRC downlink transmit power is calculated using the MRSL thresholds listed in Table 1. Assuming the receive antenna gain is 0 dB (GR = 0 dB), the required transmit power for a successful downlink in dBm is

$$RSU\_az, el = \frac{53* l}{d_{a,e}} \quad [4] \tag{9}$$

By substituting equation 8 and 9 into 7, an equation for antenn a gain as a function of antenna beamwidth becomes

$$RSU\_g = 10\log\left(\frac{4*p*0.944*2809}{RSU\_az*RSU\_el}\right) \tag{10}$$

For the purposes of this analysis, the OBU antenna is usually assumed to have a very wide beamwidth and unknown orientation. Therefore, unless otherwise stated, it is assumed that the interference from or to an OBU is assumed to be transmitted through the main lobe of the OBU antenna. The gain of the OBU antenna, *OBU_g*, is assumed to be 4 dB as in the European DSRC standard [4].

2.4.3 Isolation Specifications for Same and Adjacent Channels

The isolation described in this section is due to the frequency differences (spectral masking) between the various transmitted signals. They are derived from the European DSRC standard [2] and translated for use in the DSRC system assumed for use in the US.

The downlink (RSU) isolation or spectral masking listed in the European standard is presented in terms of total EIRP (Effective Isotropic Radiated Power) in a bandwidth and is based on an assumed maximum transmitted EIRP of +33 dBm. For use in this analysis, the spectral masking is used as an isolation between the transmitted signal and another signal frequency band. The European standard specifications for interference are listed as maximum allowable power in particular bands. The Isolation specifications used for the proposed US DSRC systems were calculated from the European specifications by subtracting the allowable power in each band from the peak in-band power allowed by the European specifications,

The RSU transmissions include a tone for the OBU to modulate and an ASK modulated downlink signal. The spectrum mask standards are divided into three classes (A, B and C) with increasing levels of isolation. No reason is stated for the three classes in the European standard, but their existence would allow short range low power systems to operate with less sophisticated equipment than longer range systems. The RSU downlink isolation for the tone and each class of modulated downlink are listed in Table 2.

Table 2. RSU Transmit Isolation Levels

Class	Description	Label	Isolation (dB)
Tone	To Lower Uplink Band	RSU_TL	**60**
	To Upper Uplink Band	RSU_TU	**60**
	To Adjacent Channel	RSU_TA	**80**
Class A	To Lower Uplink Band	RSU_AML	**40**
	To Upper Uplink Band	RSU_AMU	60
	To Adjacent Channel	RSU_AMA	63
Class B	To Lower Uplink Band	RSU_BML	**50**
	To Upper Uplink Band	RSU_BMU	**60**
	To Adjacent Channel	RSU_BMA	**70**
Class C	To Lower Uplink Band	RSU_CML	**60**
	To Upper Uplink Band	RSU_CMU	60
	To Adjacent Channel	RSU_CMA	80

There is little spectral masking that can be done to the OBU emission in order to reduce unwanted energy in other channels. A filter cannot be used since the frequency changes depending on the beacon frequency. Only shaping (smoothing) of the amplitude variations can reduce the unwanted images of the PSK signal produced by the amplitude modulation. Very little (3 dB) isolation is specified in the European standard between the uplink bands and the downlink bands in the same channel and thus no isolation is assumed for this analysis. The only isolation specification of significance is isolation between adjacent channels, *OBUAI*, which is specified at 18 dB (-24 dBm maximum EIRP and -42 dBm maximum emissions in adjacent channels).

2.4.4 Calculating Minimum Separation Distance

The formula required to calculated minimum separation distances is a modification of equation 4 to account for isolation, antenna sidelobe levels (where needed) and actual maximum transmit powers. The generic formula for calculating minimum separation distance is

$$R_{sep} = 10\text{^}[(Pt+Gt+Gr-Isol+2*Lambda\_dB-2*F\_PI-P_{int})/10] \qquad (11)$$

where: R_{sep} = Minimum required separation distance in feet,
Pt = RSU transmit power or maximum OBU transmit power in dBm,
Gt = Gain of the transmit antenna in dB, and
$Isol$ = Isolation between bands of interest in dB.

Note that the European specifications limit the EIRP transmitted by the OBU (including antenna gain and windshield losses) to -24 dBm. It is assumed in the separation distance calculations that the OBU limits its output EIRP to -24 dBm. This limiting or automatic gain control (AGC) is assumed to prevent OBU output EIRP from exceeding -24 dBm regardless of received signal power.

3.0 GENERIC CALCULATIONS OF TRANSMIT POWER AND SEPARATION DISTANCE

As an initial step to determining minimum separation distances between DSRC system, a generic or worst-case analysis is performed. For this analysis, it is assumed that all OBU and RSU transmitters are operating at maximum power.

Applying the specifications from the European standard [2] yields a maximum OBU transmit EIRP of -24 dBm. The maximum EIRP for the RSU is calculated by assuming a 20 dB antenna gain and a maximum operating range of 50 feet. This yields a maximum transmit power *(Pt)* of 14.44 dBm or an RSU EIRP *(RSU_Pmax)* of 34.4 dBm.

The calculations of the minimum separation distances are shown in the spreadsheet in Appendix A. The bold values in the spreadsheets are those manually entered into the spreadsheet while the normal values are those calculated by equations within the spreadsheet.

The separation distances are calculated between all antennas, for all classes of RSU transmitters, between all frequency bands in a channel, and between adjacent channels. The separation distances are calculated assuming interference through the mainlobes and sidelobes of the RSU antennas. The distances calculated are between two DSRC systems with the same characteristics.

The separation distances calculated in Appendix A are labeled according to their direction of transmission. Therefore an uplink on downlink separation distance is the separation distance between a transmitting OBU (uplink) from one DSRC system and an OBU receiving data (downlink) from another DSRC beacon. Similarly, the uplink on uplink separation distance is the required separation distance between a transmitting OBU (uplink) responding to one RSU and a different receiving RSU (uplink).

The calculated separation distances in Appendix A vary from almost 8,000 feet to less than 1 foot depending on which combination of transmitter and receivers are being analyzed, whether RSU antenna sidelobe or mainlobe is assumed, or whether same channel or different channels are assumed. The longest required separation distances are the downlink (RSU transmitter) on uplink (RSU receiver) distances, particularly those in the RSU antenna main lobe. The reduced isolation of the Class A RSU transmitter is evident in the longer required downlink on uplink separation distances.

The next longest separation distances calculated were in the uplink (OBU transmitter) on uplink (RSU receiver). The required separation between an RSU and an interfering OBU operating in the same channel and in its main lobe was calculated to be over 4000 feet. Even if the OBU was operating in the RSU antenna's sidelobes, the calculated separation distance required was over *750* feet.

This general analysis is useful determining basic guidelines on separation of DSRC systems. However, the specific implementation or deployment of the system could drastically affect the minimum required separation distance. Section 4 will demonstrate calculations of minimum separation distances for some specific same-channel and different-channel DSRC systems.

4.0 SPECIFIC SEPARATION DISTANCE CALCULATIONS

Further information on implementation and minimum required separation distances can be gleaned by investigating specific deployments of DSRC systems and determining required separation distances. In this section, five specific examples of separation distance calculations will be performed. These examples are all from example installation groups of DSRC systems in the updated study on DSRC spectrum requirements. main body of the report.

For each specific example, a spreadsheet was developed to calculate same channel and adjacent channel separation distances. The spreadsheets for each example are included in Appendices to this report. The RSU antenna gain and transmit power for each DSRC system were calculated to meet the coverage area requirements. Then it was determined whether or not the interference paths were through the mainlobe or the sidelobe of the RSU and OBU antennas. For cases where the two DSRC systems have different characteristics (coverage area, power, antenna gains, . . .), all combinations of interference between the two systems are assessed.

The first two example calculations in Section 4.1 and 4.2 are from the In-Vehicle Signing Installation Group explained in [I]. The In-Vehicle Signing Installation Group is shown in Figure 1. In Section 4.1, the minimum separation distances will be calculated to prevent interference between an in-vehicle signing beacon along the highway and an exit beacon. In Section 4.2, minimum separation distances between two identical in-vehicle signing beacons will be calculated.

The separation distance calculations in Section 4.3 to 4.5 refer to beacons in the Multiple Group Installation explained in [1]. The Multiple Group Installation is shown in Figure 2. The separation distance calculations between 2 identical intersection beacons (beacons J and P in Figure 2) are discussed in Section 4.3. In Section 4.4, the separation distance between identical bus stop beacons (beacons Y, Z and AA in Figure 2) are calculated. Lastly, in Section 4.5, the interference issues and separation distances between an off-line verification beacon (beacon W) and intersection beacon (such as beacon P) are evaluated.

In each of the examples below it is assumed that both DSRC systems are operating either at the same time or independently. In other words, there is no time multiplexing or coordination between the beacons that could reduce or eliminate the possibility of interference. In some cases, the communications requirements prohibit coordination while in other cases the separation distance calculation may indicate the need for time multiplexing or coordination. These issues will be discussed as needed in the analysis of the separation distance calculations. If time multiplexing is required, the capture zone can be lengthened so that the required date rate is not increased.

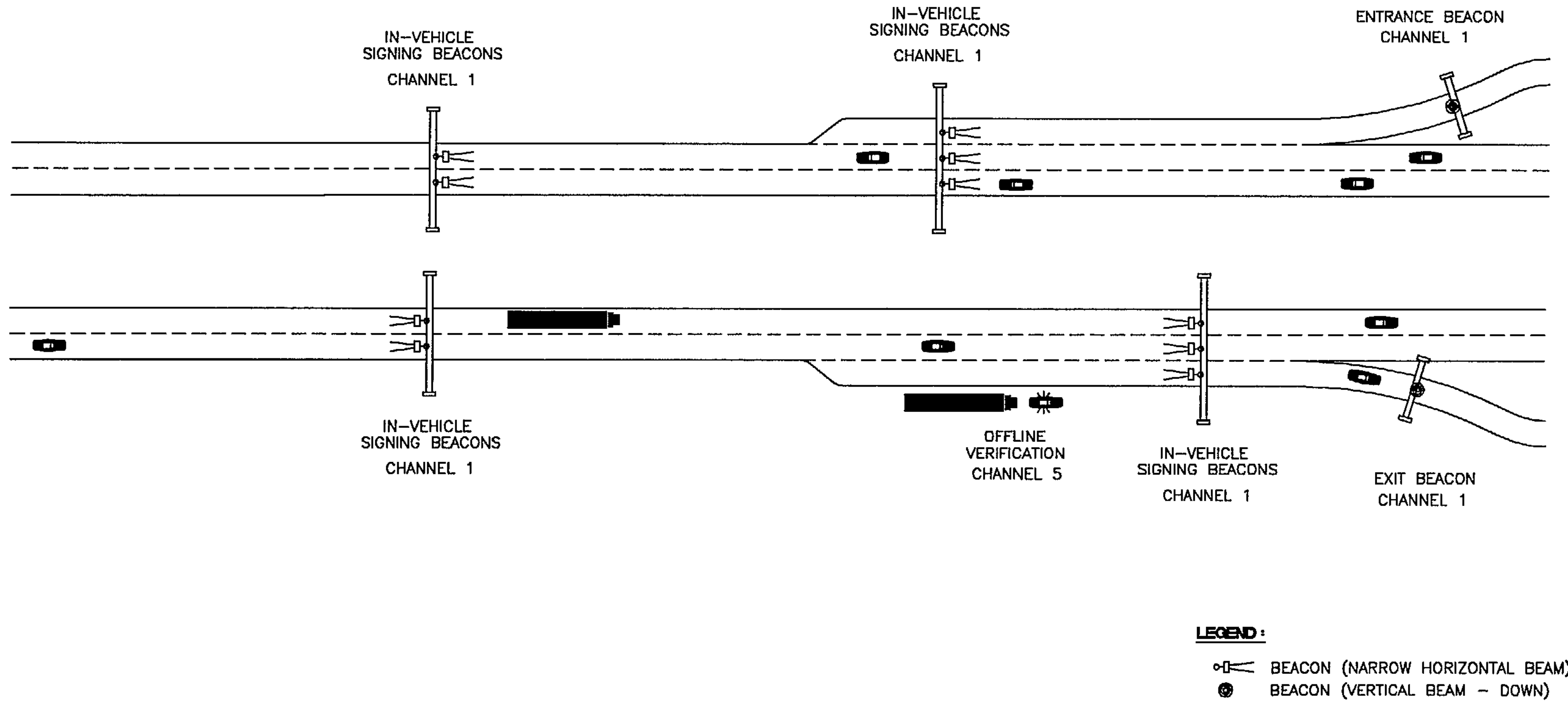

Figure 1. In–Vehicle Signing Installation Group (with channel assignments)

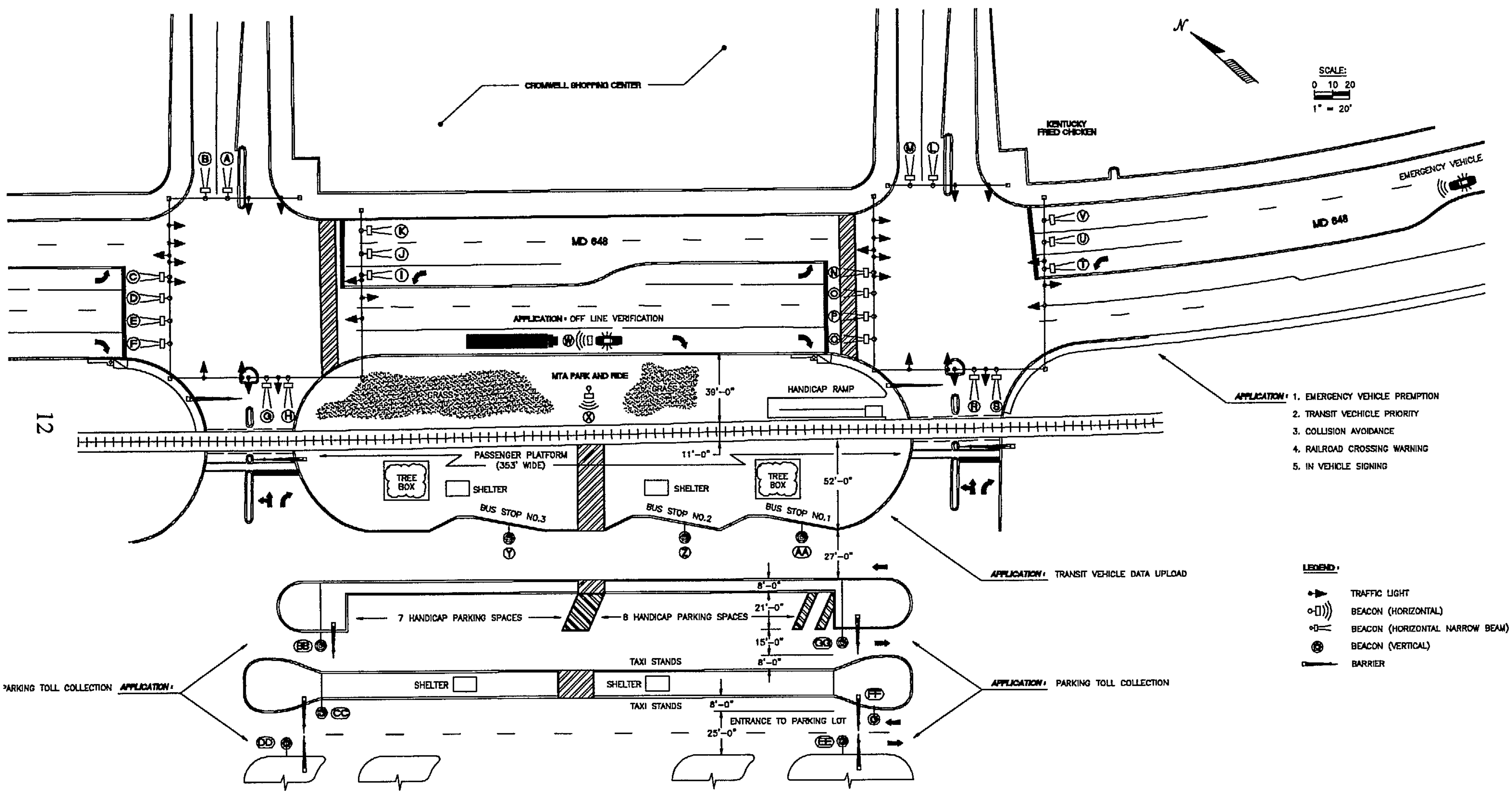

Figure 2. Multiple Group Installation

4.1 In-Vehicle Signing to Exit Beacons

The separation distances required between an in-vehicle signing beacon and an exit beacon in Figure 1 are evaluated in this section. Several assumptions have been made in determining the characteristics of the beacons. The assumptions for the in-vehicle signing beacon (Beacon 1) are as follows:

- The RSU beacon is mounted 20 feet off the road centered on a lane,
- The maximum distance down the road covered by the beacon is 50 or 100 feet,
- The minimum angle of the beam of the RSU antenna is 45 degrees from vertical,
- The 3 dB width of the RSU beacon's antenna beam at the longest range is 12 feet, and
- The height of the OBU is 5 feet.

The assumption for the exit beacon (Beacon 2) are as follows:

- The RSU beacon is mounted 20 feet off the road centered on an exit lane,
- The RSU antenna is pointed downward covering a 30 foot length of road 12 feet wide, and
- For purposes of determining maximum OBU transmit power, the minimum link range is assumed to be 12 feet.

The OBU is assumed to have an average height of 5 feet for both DSRC beacon systems.

4.1.1 Results Assuming a 50 Foot Range for the In-Vehicle Signing Beacon

The calculations of minimurn separation distances for this example assuming a 50 foot range on the in-vehicle signing beacon are shown in the spreadsheet in Appendix B-l. Beacon 1 is the in-vehicle signing beacon and Beacon 2 is the exit beacon. It is assumed that all interference from or to either RSU is through the RSU sidelobes since the intended coverage areas of each beacon are physically separated. The separation distances are calculated for each combination of transmitter and receiver. For example, an uplink on uplink calculation under the column labeled "2 on 1" is the separation distance required between the OBU transmitter operating with Beacon 2 and the RSU receiver of Beacon 1.

Figure 1 indicates that the in-vehicle signing beacons and the exit beacons will likely be operating on the same frequency. From the spreadsheet in Appendix B-l, the largest calculated same-channel separation distances are due to the Class A modulated downlink from the in-vehicle signing beacon on the uplink receiver of the exit beacon. The minimum separation distance is 629 feet for this case. Using a Class B or C RSU transmitter does not result in significantly lower separation distances because the minimum separation distance is limited by the same channel uplink on uplink. The separation distance required between an OBU responding to the exit beacon and an in-vehicle-signing RSU receiver operating at the same frequency is 5 15 feet. Therefore, the minimum separation distance for same channel operation is about 5 15 feet.

If the exit beacon must operate much closer than 515 feet, then different (possibly adjacent) channels must be used. The spreadsheets in Appendix B-l indicate that the minimum separation distance between the beacons is 65 feet (limited by uplink on uplink separation).

4.1.2 Results Assuming a 100 Foot Range for the In-Vehicle Signing Beacon

The calculations of minimum separation distances for this example assuming a 100 foot range on the in-vehicle signing beacon are shown in the spreadsheet in Appendix B-2. The results are very similar to those discussed in Section 4.1.1.

The largest same channel separation distance calculated in Appendix B-2 is 1226 feet for the Class A modulated downlink from the in-vehicle signing beacon on the exit beacon RSU receiver (downlink on uplink). If Class B or C RSU transmitters are used for the beacons, the limiting factor becomes the separation required between an OBU responding to the exit beacon and an in-vehicle signing beacon RSU (uplink on uplink). Therefore, the minimum separation distance required between an in-vehicle signing beacon (OBU or RSU) and an exit beacon operating in the same channel is 63 1 feet.

If different or adjacent channels are used, the separation distance can be reduced considerably. If Class A RSU transmitters are used for the in-vehicle signing beacon then the separation distance required is limited by downlink (in-vehicle beacon RSU) on uplink (exit beacon RSU) to about 87 feet. If Class B or C RSU transmitters are assumed, the minimum separation range is limited by uplink on uplink to about 79 feet.

4.2 IN-VEHICLE SIGNING BEACONS ALONG A HIGHWAY

In this section, the minimum separation distances between two in-vehicle signing beacons in Figure 1 are calculated. The assumptions used to define the beacons are the same as the in-vehicle signing beacon in Section 4.1. For this example it is assumed that the beacons have distinct coverage areas and thus all interference involving an RSU transmitter or receiver is through the sidelobes of the RSU antenna.

4.2.1 Results Assuming a 50 Foot Range In-Vehicle Signing Beacons

The results of the 50 foot range in-vehicle signing beacon same channel minimum separation distance calculations are shown in the spreadsheet in Appendix C-l. The minimum separation distance between in-vehicle signing beacons is again limited by the downlink (RSU transmitter) on uplink (RSU receiver) interference assuming Class A RSU transmitter specifications are assumed. The minimum separation distance calculated is 1,136 feet for the Class A RSU transmitters. If the Class B or C RSU transmitter isolation specifications are assumed the minimum separation distance is limited to 717 feet by the uplink (OBU transmitter) on uplink (RSU receiver) interference.

The same channel minimum separation distances calculated for in-vehicle signing beacons are not unreasonable to implement for most cases. However, if smaller separation distances are needed, then use of separate (or adjacent) frequencies can reduce the minimum separation distance to 114 feet assuming Class A transmitter parameters are used. If Class B or C RSU transmitters are used, then the adjacent channel separation distance is limited a minimum of 90 feet by the uplink on uplink separation requirements.

4.2.2 Results Assuming a 100 Foot Range In-Vehicle Signing Beacons

The results of the 100 foot range in-vehicle signing beacon same channel minimum separation distance calculations are shown in the spreadsheet in Appendix C-2. The minimum separation distance between in-vehicle signing beacons is again limited by the downlink (RSU transmitter) on uplink (RSU receiver) interference assuming Class A RSU transmitter specifications are assumed. The minimum separation distance calculated is 2,710 feet for the Class A RSU transmitters. If the Class B or C RSU transmitter isolation specifications are assumed the minimum separation distance is limited to 896 feet by the uplink (OBU transmitter) on uplink (RSU receiver) interference.

The same channel minimum separation distances calculated for in-vehicle signing beacons are again not unreasonable to implement for most cases. However, if smaller separation distances are needed, then use of separate (or adjacent) frequencies can reduce the minimum separation distance to 192 feet assuming Class A transmitter parameters are used. If Class B or C RSU transmitters are used, then the adjacent channel separation distance is limited a minimum of 113 feet by the uplink on uplink separation requirements,

4.3 INTERSECTION BEACONS

Beacons operating at intersections are similar in configuration to in-vehicle signing beacons. They generally do have to cover wider areas (more lanes) and in dense urban environments may have overlapping coverage areas. The minimum separation distance calculations for this example are based on the intersection beacons J and P in Figure 2. The assumptions for these beacons are as follows:

- The RSU beacon is mounted 20 feet off the road centered on a lane,
- The maximum distance down the road covered by the beacon is 50 or 100 feet,
- The maximum angle of the beam of the RSU antenna is 90 degrees from vertical (horizontal) to allow for the reception of longer range emergency vehicle OBUs,
- The minimum angle of the beam of the RSU antenna is 30 degrees from vertical,
- The width of the RSU beacon's antenna beam at the longest range is 12 feet with 1 antenna per lane approaching the intersection , and
- The height of the OBU is 5 feet.

The coverage area for the intersection beacons is very similar to in-vehicle signing beacons. The intersection beacons only differ in the fact that the minimum angle of the intersection beacon is 30 degrees from vertical (as opposed to 45 degrees for the in-vehicle signing beacons). For this example, the antenna pattern is assumed to be elliptical as one would expect from a rectangular aperture antenna.

4.3.1 Results Assuming 50 Foot Range Intersection Beacons

The results of the minimum distance calculations for intersection beacons with 50 foot maximum operating ranges are listed in the spreadsheets in Appendix D-l. The calculations in the spreadsheet included minimum separation distances assuming the interference was received or transmitted through the RSU antenna mainlobe and sidelobe. A quick check of the calculations shows that even assuming adjacent channel interference, the minimum separation distance between RSU antennas calculated for mainlobe interference is 356 feet (uplink on uplink assuming Class C RSU transmitters). This is almost the same as the separation distance between beacons J and P in Figure 2. Therefore, the implementation of intersection beacons must ensure that the RSU antennas do not include in their main lobe OBUs responding to another intersection beacon. This is consistent with the 50 foot range of the intersection beacons and the scenario shown in Figure 2.

Assuming that the RSU antennas of nearby beacons are not directed at one another (separated coverage areas), then the minimum separation distance between beacons operating in adjacent channels is 63 feet. The minimum separation distance is limited by the uplink (OBU transmitter) on uplink (RSU receiver). The separation distance between intersection beacons J and P in Figure 2 is over 300 feet. Therefore, the minimum separation distance is met between these beacons for adjacent channels. Beacons A and J in Figure 2 are only separated by 65-70 feet. These beacons barely meet the minimum separation requirements and it may be advisable to time multiplex these beacons to avoid interference, even if operating on different frequencies.

If the intersection beacons are operating in the same channel, then the minimum separation between RSU antennas is 780 feet for Class A RSU transmitters. Class B and C RSU transmitters must be separated by 503 feet (uplink on uplink). These results indicate clearly that any two intersection beacons operating at the same frequency from a single intersection must be time multiplexed in order to avoid interference. Also, closely spaced intersections with beacons using the same frequencies at both intersections must also be time multiplexed.

4.3.2 Results Assuming 100 Foot Range Intersection Beacons

The results of the minimum distance calculations for intersection beacons with 100 foot maximum operating ranges are listed in the spreadsheets in Appendix D-2. The calculations in the spreadsheet included minimum separation distances assuming the interference was received or transmitted through the RSU antenna mainlobe and sidelobe. A quick check of the calculations shows that even assuming adjacent channel interference, the minimum separation distance between RSU antennas calculated for mainlobe interference is 857 feet (downlink on uplink assuming Class C RSU transmitters). This is well over twice the separation distance between beacons J and P in Figure 2. Therefore, the implementation of intersection beacons must ensure that the RSU antennas do not include other RSU antennas in their main lobe. This is consistent with the 100 foot range of the intersection beacons and the scenario shown in Figure 2.

Assuming that the RSU antennas of nearby beacons are not directed at one another (separated coverage areas), then the minimum separation distance between beacons operating in adjacent channels is 88 feet assuming Class B or C RSU transmitters. The minimum separation distance is limited by the uplink (OBU transmitter) on uplink (RSU receiver). The separation distance between intersection beacons J and P in Figure 2 is over 300 feet. Therefore, the minimum separation distance is met between these beacons for adjacent channels. Beacons A and J in Figure 2 are only separated by 65-70 feet. The separation between these beacons does not meet the minimum separation requirements and therefore time multiplexing of these beacons is required to avoid interference, even if operating on different frequencies.

If the intersection beacons are operating in the same channel, then the minimum separation between RSU antennas is 2,710 and 857 feet for Class A and B RSU transmitters, respectively. Class C RSU transmitters must be separated by 699 feet (limited by uplink on uplink) These results indicate clearly that any two intersection beacons operating at the same frequency from a single intersection must be time multiplexed in order to avoid interference. Also, even moderately closely spaced intersections with beacons using the same frequencies at both intersections must also be time multiplexed.

4.4 BUS STOP BEACONS

Beacons Y, Z and AA in Figure 2 are bus stop beacons spaced fairly close together. The separation distances between the beacons are shown in Table 3. These beacons are assumed for this analysis to be operating independently and often communicating large amounts of information between the OBU on the bus and the RSU.

Table 3. Bus Stop Beacon Separation Distances in Feet

Beacon	Y	Z	AA
Y	N/A	100	167
Z	100	N/A	66
AA	167	66	N/A

The assumptions for the RSU and OBU in the Bus Stop scenario are as follows:

- The RSU beacon is mounted 20 feet off the road,
- The height of the OBU antenna is between 12 and 15 feet yielding a 5 to 8 foot operating range for the link,
- The RSU antenna is designed to cover a 8 x 8 foot area at a distance of 8 feet,
- The OBU antenna is mounted on the top of the bus directed vertically, and
- The sidelobes of the OBU antenna are 15 dB below the peak antenna gain (special shielding on the OBU antennas may be required, or a custom antenna).

In this scenario, the OBU antennas are assumed to have a known location and orientation on the vehicles (busses). The OBU antennas are directed straight upward and designed only to communicate with vertical beacons. Therefore, interference from other RSUs or OBUs is assumed to only be possible through the sidelobes of the OBU antennas.

The results of the minimum separation distance calculations are listed in the spreadsheet in Appendix E. The calculations include same channel and adjacent channel minimum separation distance calculations. The minimum same channel separation distance is 120 feet assuming Class A RSU transmitters. The distance is reduced to 57 feet for Class B or C RSU transmitters (limited by the uplink on uplink minimum separation distance). Therefore the separations between the bus stop beacons (Y, Z and AA) in Figure 2 are sufficient to support even same channel simultaneous operation using Class B or C RSU transmitters. If the separation between bus stop beacons is reduced below 57 feet, special RSU antenna or RF shielding will be required to operate using the same frequencies.

If adjacent channels are used, the minimum separation distance drops to less than 9 feet. This calculation assumes that all interference is transmitted and received through the sidelobes of the RSU and OBU antennas. At a range of 9 feet, this assumption is likely to be invalid.

4.5 Off Line Vefufication to Intersection Beacons

In this section an assessment of the impact of off line verification beacons will be presented. This analysis assumes a scenario similar to the off line verification beacon (Beacon W) shown in Figure 2. The minimum separation distances are calculated between the off line verification beacon and an intersection beacon. The assumptions for the intersection beacons are the same as those used in Section 4.3 with a 50 foot operating range. The assumptions for the off line verification beacon are as follows:

- The operating range of the off line verification beacon is between 6 and 30 feet,
- The RSU antenna has a 20 x 20 degree beamwidth,
- The off line verification beacon is mobile and may be used almost anywhere in or out of the main beam of another fixed beacon, and
- The RSU antenna is not pointed directly towards a fixed beacon.

The assumptions above indicate that the worst case minimum separation distance calculations assume that the interference to and from the off line verification beacon is through its antenna sidelobes. Also, the interference to and from the intersection RSU is through its antenna mainlobe.

The spreadsheets listing the minimum separation distance calculations are listed in Appendix F. Beacon 1 in these spreadsheets is the intersection beacon, and Beacon 2 is the off line verification beacon, The separation distances are calculated for each combination of transmitter and receiver. For example, an uplink on uplink calculation under the column labeled “2 on 1” is the separation distance required between the OBU transmitter operating with Beacon 2 and the RSU receiver of Beacon 1.

The results in Appendix F show clearly that if the same channel is used for both beacons, then the minimum separation distance must be greater than l/2 mile to eliminate uplink on uplink interference from the OBU responding to the off-line verification beacon on the intersection RSU receiver. Even if adjacent channels are used, the required separation distance due to off line uplink on intersection uplink interference is 356 feet which is greater than the operating range of either beacon.

The minimum separation distance results indicate that an off line beacon must coordinate its transmission with nearby fixed beacons. One method for doing this is to attach an OBU transceiver to the off-line beacon. The OBU transceiver would respond to any beacon within range and request a special time slot for off line verification reading. The fixed RSU could then transmit a response indicating a free communications time slot for the off-line verification beacon. The length of the time slot could be fixed or variable depending on the implementation. The off-line verification beacon would communicate with the desired OBU during the time slot allocated by the fixed RSU. If no nearby fixed RSU is detected by the off-line beacon's attached OBU, then the off-line reader's RSU would operate the same as any fixed beacon's RSU.

Coordination with the nearest fixed beacon does not however eliminate the need for a separate channel for the off-line verification beacon. The fixed beacons in a given area will be designed to avoid interference based on their transmit power levels and desired coverage areas. An off-line verification beacon operating close enough to detect one fixed RSU may still be close enough to interfere with another nearby beacon operating in the same channel as the off-line verification beacon. Therefore, the off-line verification beacon must operate on a channel guaranteed to be separate from any fixed beacon in order to take advantage of the adjacent channel isolation and reduce the possibility of interference.

One factor mentioned in earlier reports [6] is that the OBU responding to an off-line reader will also reflect any energy received from other RSUs operating within its range. This effect is not a problem if the off line verification reader coordinates communications with any fixed beacon within range.

If an off line verification beacon's attached OBU is actually out of range of a fixed beacon, but the OBU being read is within the range of the fixed beacon, then incidental interference may occur. The OBU being read by the off line beacon will reflect the energy received from the fixed beacon while it is responding to the off line verification beacon. From equation 6 it can be seen that the energy returned from an OBU is a function of the 4th power of the range between the OBU and the RSU. Therefore, if a 15 dB signal to interference ratio is required, then the fixed beacon will only be able to receive transmissions from OBUs that are within 42% of the range between the fixed RSU and the OBU responding to the off line reader. Note that no adjacent channel isolation can be applied since the interfering energy is a modulated reflection of the tone from the fixed beacon.

Interference between off line verification beacons and fixed beacons, and the need to coordinate transmissions with nearby fixed beacons, may impose some restrictions on the operation of off line verification beacons. The off line verification beacons should only be operated in short bursts that gather the intended information from the OBU and then discontinue operation. This will greatly limit the potential for interference with nearby fixed beacons.

5.0 EFFECTS OF QPSK UPLINK MODULATION ON DSRC OPERATING RANGES

The default uplink modulation defined in the European DSRC draft specifications is Binary PSK (BPSK). An alternative modulation which will double the uplink data rate on each subcarrier is Quadrature PSK (QPSK). [2] Using the QPSK modulation to double the data rate within the same operating bandwidth, however, requires greater received power to achieve the same bit error rate (BER) as BPSK.

The BER or probability of bit error, P_b, for BPSK at high signal to noise ratios (SNR) can be approximated [4]:

$$P_b \; / \; erfc \sqrt{2 * SNR}$$

where SNR = the received signal to noise ratio.

The BER for QPSK at high SNRs can likewise be approximated [4]:

$$P_b \; / \; erfc \sqrt{SNR.}$$

Therefore, a QPSK receiver requires twice the SNR of BPSK receiver to achieve the same BER (or P_b). The effects of this requirement on the operating range of DSRC beacons depend on whether the minimum required transmit power is limited by the downlink or the uplink (*Pt_d* or *Pt_u* in the spreadsheets, respectively).

If the required transmit power for successful downlink, *Pt_d*, is greater than the required transmit power for successful uplink, *Pt_u*, by 3 dB or more, then there is no effect in operating range by switching from BPSK to QPSK modulation. This is the case for many of the short to moderate range beacons. Beacons evaluated in Section 4 whose operating ranges are not affected by switching from BPSK to QPSK are the 50' range in-vehicle signing, exit, bus stop and off line verification beacons.

If *Pt_u* is greater than *Pt_d*, then the operating range of the beacon is reduced when the uplink modulation is switched from BPSK to QPSK. Essentially, the MRSL of the uplink is raised by 3 dB when QPSK is used instead of BPSK. From Equation 6 in Section 2.3, it can be shown that the operating range must be reduced by 3 dB / 4 = 0.75 dB in order to have a successful uplink if the transmit power remains the same. Therefore the operating range using QPSK is 84% of the operating range using BPSK. The beacons whose operating range will be reduced to 84% of their original operating range by switching to QPSK modulation are the in-vehicle signing and intersection beacons designed to operate up to 100' range. These beacons would now only be able to operate up to an 84' range.

The intersection beacon operating over a 50' range requires 18.33 dBm transmit power for a successful downlink and 17.65 dBm for a successful uplink. Therefore the designed transmit power for the beacon RSU is 18.33 dBm. If QPSK modulation were used on the uplink, then the transmit power required for a successful uplink at a 50' range would be 20.65 dBm which is

2.32 dB higher than the designed transmit power. Therefore, the operating range for the uplink (and thus the link itself) is reduced by 2.32 / 4 = 0.58 dB. The resulting operating range is reduced to 87.5% of its original operating range or about 44 feet.

The required transmit powers of most of the beacons analyzed in this report are driven primarily by the required downlink transmit power. Therefore, the operating range of most of these beacons is unaffected by switching the uplink modulation from BPSK to QPSK. Only the longer range beacons whose transmit powers are driven by the power required for a successful uplink are affected by the use of the QPSK uplink modulation. The uplink operating range is only reduced by l/4 of the change in required SNR (see Equation 6). Therefore the range of the affected beacons is reduced by at most 16% by switching the uplink modulation from BPSK to QPSK.

REFERENCES

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APPENDIX A

GENERIC CALCULATIONS OF MINIMUM SEPARATION DISTANCES

GENERIC CALCULATION OF RE-USE DISTANCES ASSUMING 50' MAXIMUM RANGE

General Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	**5.85**	GHz
	Speed of Light	Cf	984251969	feet/sec.
	Wavelength	Lambda	0.1682482	feet
	Wavelength in dB	Lambda_dB	-7.74	dB feet
	4*PI	F_PI	10.99	dB
	Maximum Operating Range	Rmax	**50.00**	feet
	Maximum Operating Range in dB	Rmax_dB	16.99	dB feet
RSU	Antenna Gain	RSU_g	**20.00**	dB
	Antenna Radiation Pattern Loss	RSU_gl	**3.00**	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	**15.00**	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	5.00	dB
	Minimum Received Signal Level (rcvr.)	RSU_mrsl	**-94.00**	dBm
	Maximum Interference Signal Level (rcvr.)	RSU_int	**-114.00**	dBm
	Maximum Transmit EIRP	RSU_Pmax	35	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	**60.00**	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	**60.00**	dB
	Isolation Tone to Adjacent Channel	RSU_TA	**80.00**	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	**40.00**	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	**60.00**	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	**63.00**	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	**50.00**	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	**60.00**	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	**70.00**	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	**60.00**	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	**60.00**	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	**80.00**	dB
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	**4.00**	dB
	Mimimum Received Signal Level (0 dB ant)	OBU_min	**-40.00**	dBm
	Maximum Received Signal Level (0 dB ant)	OBU_max	**-14.00**	dBm
	Maximum Transmit EIRP	OBU_Pmax	**-24.00**	dBm
	Maximum Interference Signal Level (0 dB ant)	OBU_int	**-60.00**	dBm
	Windscreen Loss, One-Way	L_w	**3.00**	dB
	Modulation Loss	L_m	**3.00**	dB
	Realization Margin	L_r	**4.00**	dB
	RF Amplifier Gain	OBU_rf	**10.00**	dB
	Minimum Conversion Gain	OBU_Gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	**18.00**	dB

GENERIC CALCULATION OF RE-USE DISTANCES ASSUMING 50' MAXIMUM RANGE EIRP (CONTINUED)

Uplink on Uplink Separation Distance OBU to RSU

RSU Antenna	Antennas SCENARIO	LABEL	VALUE	UNITS
Mainlobe	Same Channel		4,233.90	feet
	Adjacent Channel		533.02	feet
Sidelobe	Same Channel		752.91	feet
	Adjacent Channel		94.79	feet

Downlink on Uplink Separation Distance RSU to RSU

RSU Antenna	Antennas SCENARIO	LABEL	VALUE	UNITS
Mainlobe	Tone to Lower Uplink Band		671.03	feet
	Tone to Upper Uplink Band		671.03	feet
	Tone to Adjacent Channel		67.10	feet
	Class A: Modulated to Lower Uplink Band		6,710.28	feet
	Class A: Modulated to Upper Uplink Band		671.03	feet
	Class A: Modulated to Adjacent Channel		475.05	feet
	Class B: Modulated to Lower Uplink Band		2,121.98	feet
	Class B: Modulated to Upper Uplink Band		671.03	feet
	Class B: Modulated to Adjacent Channel		212.20	feet
	Class C: Modulated to Lower Uplink Band		671.03	feet
	Class C: Modulated to Upper Uplink Band		671.03	feet
	Class C: Modulated to Adjacent Channel		67.10	feet
Sidelobe	Tone to Lower Uplink Band		119.33	feet
	Tone to Upper Uplink Band		119.33	feet
	Tone to Adjacent Channel		11.93	feet
	Class A: Modulated to Lower Uplink Band		1,193.28	feet
	Class A: Modulated to Upper Uplink Band		119.33	feet
	Class A: Modulated to Adjacent Channel		84.48	feet
	Class B: Modulated to Lower Uplink Band		377.35	feet
	Class B: Modulated to Upper Uplink Band		119.33	feet
	Class B: Modulated to Adjacent Channel		37.73	feet
	Class C: Modulated to Lower Uplink Band		119.33	feet
	Class C: Modulated to Upper Uplink Band		119.33	feet
	Class C: Modulated to Adjacent Channel		11.93	feet

Downlink on Downlink Separation Distance RSU to OBU

RSU Antenna	Antennas SCENARIO	LABEL	VALUE	UNITS
Mainlobe	Same Channel		752.91	feet
	Tone - Adjacent Channel		0.08	feet
	Class A: Modulated - Adjacent Channel		0.53	feet
	Class B: Modulated - Adjacent Channel		0.24	feet
	Class C: Modulated - Adjacent Channel		0.08	feet
Sidelobe	Same Channel		133.89	feet
	Tone - Adjacent Channel		0.01	feet
	Class A: Modulated - Adjacent Channel		0.09	feet
	Class B: Modulated - Adjacent Channel		0.04	feet
	Class C: Modulated - Adjacent Channel		0.01	feet

Uplink on Downlink Separation Distance OBU to OBU

RSU Antenna	Antennas SCENARIO	LABEL	VALUE	UNITS
N/A	Same Channel		0.84	feet
	Adjacent Channel		0.11	feet

APPENDIX B-l

IN-VEHICLE SIGNING VERSUS EXIT BEACON

CALCULATIONS OF MINIMUM SEPARATION DISTANCES

ASSUMING 50′ RANGE IN-VEHICLE SIGNING BEACONS

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2)

Beacon Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	5.85	GHz
	Speed of Light	Cf	984251969	feet/sec.
	Wavelength	Lambda	0.1682482	feet
	Wavelength in dB	Lambda_dB	-7.74	dB feet
	4*PI	F_PI	10.99	dB
Beacon 1 (In-vehicle Signing Beacon)	Height of RSU Antenna	RSU_h	20.00	feet
	Height of OBU Antenna	OBU_h	5.00	feet
	Maximum Lateral Separation Distance	Sep_max	50.00	feet
	Minimum RSU Ant. Angle From Vertical	Ang_min	45.00	degrees
	Minimum Lateral Separation Distance	Sep_min	15.00	feet
	Maximum Operating Range	Rmax	52.20	feet
	Maximum Operating Range in dB	Rmax_dB	17.18	dB feet
	Minimum Operating Range	Rmin	21.21	feet
	Minimum Operating Range in dB	Rmin_dB	13.27	dB feet
	Width of Antenna Beam at Longest Range	Wmax	12.00	feet
	Antenna Elevation Beamwidth	RSU_el	28.30	degrees
	Antenna Azimuth Beamwidth	RSU_az	13.11	degrees
	Antenna Gain	RSU_g	19.76	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	4.76	dB
Beacon 2 (Exit Beacon)	Height of RSU Antenna	RSU2_h	20.00	feet
	Height of OBU Antenna	OBU2_h	5.00	feet
	Maximum Lateral Separation Distance	Spe2_max	15.00	feet
	Minimum RSU Ant. Angle From Vertical	Ang2_min	-45.00	degrees
	Minimum Lateral Separation Distance	Sep2_min	-15.00	feet
	Maximum Operating Range	Rmax2	21.21	feet
	Maximum Operating Range in dB	Rmax2_dB	13.27	dB feet
	Minimum Operating Range	Rmin2	12.00	feet
	Minimum Operating Range in dB	Rmin2_dB	10.79	dB feet
	Width of Antenna Beam at Longest Range	Wmax2	5.00	feet
	Antenna Elevation Beamwidth	RSU2_el	90.00	degrees
	Antenna Azimuth Beamwidth	RSU2_az	13.44	degrees
	Antenna Gain	RSU2_g	14.62	dB
	Maximum Antenna Gain Through Sidelobes	RSU2_gsl	-0.38	dB
RSU General	Antenna Radiation Pattern Loss	RSU_gl	3.00	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	15.00	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	-94.00	dBm
	Maximum Interference Signal Level	RSU_int	-114.00	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	60.00	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	60.00	dB
	Isolation Tone to Adjacent Channel	RSU_TA	80.00	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	40.00	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	60.00	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	63.00	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	50.00	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	60.00	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	70.00	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	60.00	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	60.00	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	80.00	dB

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

OBU Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	4.00	dB
	Minimum Received Signal Level (0 dB ant.)	OBU_min	-40.00	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	-14.00	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	-60.00	dBm
	Maximum Transmit EIRP	OBU_Pmax	-24.00	dBm
	Windscreen Loss, One Way	L_w	3.00	dB
	Modulation Loss	L_m	3.00	dB
	Realization Margin	L_r	4.00	dB
	RF Amplifier Gain	OBU_rf	10.00	dB
	Minimum Conversion Gain	OBU_gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	18.00	dB

Beacon 1 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	15.06	dBm
	Transmit Power for Successful Uplink	Pt_u	11.13	dBm
	Transmit Power for Up and Down Link	Pt	15.06	dBm
	Transmit EIRP	RSU_EIRP	34.82	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-29.18	dBm

Beacon 2 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt2_d	12.37	dBm
	Transmit Power for Successful Uplink	Pt2_u	5.75	dBm
	Transmit Power for Up and Down Link	Pt2	12.37	dBm
	Transmit EIRP	RSU2_EIRP	27.00	dBm
OBU	Max. Received Signal Level (0 dB ant.)	BU2_Rmax	-32.05	dBm

CALCULATION OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

Uplink on Uplink Separation Distance OBU to RSU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe	Same Channel	515.21	397.22	feet
	Adjacent Channel	64.86	50.01	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe	Tone To Lower Uplink Band	46.18	62.93	feet
	Tone To Upper Uplink Band	46.18	62.93	feet
	Tone To Adjacent Channel	4.62	6.29	feet
	Class A: Modulated to Lower Uplink Band	461.77	629.35	feet
	Class A: Modulated to Upper Uplink Band	46.18	62.93	feet
	Class A: Modulated to Adjacent Channel	32.69	44.55	feet
	Class B: Modulated to Lower Uplink Band	146.02	199.02	feet
	Class B: Modulated to Upper Uplink Band	46.18	62.93	feet
	Class B: Modulated to Adjacent Channel	14.60	19.90	feet
	Class C: Modulated to Lower Uplink Band	46.18	62.93	feet
	Class C: Modulated to Upper Uplink Band	46.18	62.93	feet
	Class C: Modulated to Adjacent Channel	4.62	6.29	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe	Same Channel	53.29	131.12	feet
	Tone - Adjacent Channel	0.01	0.01	feet
	Class A: Modulated - Adjacent Channel	0.04	0.09	feet
	Class B: Modulated - Adjacent Channel	0.02	0.04	feet
	Class C: Modulated - Adjacent Channel	0.01	0.01	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
N/A	Same Channel	0.59	0.83	feet
	Adjacent Channel	0.07	0.10	feet

APPENDIX B-2

IN-VEHICLE SIGNING VERSUS EXIT BEACON
CALCULATIONS OF MINIMUM SEPARATION DISTANCES
ASSUMING 100' RANGE IN-VEHICLE SIGNING BEACONS

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2)

Beacon Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	5.85	GHz
	Speed of Light	Cf	984251969	feet/sec.
	Wavelength	Lambda	0.1682482	feet
	Wavelength in dB	Lambda_dB	-7.74	dB feet
	4*PI	F_PI	10.99	dB
Beacon 1 (In-vehicle Signing Beacon)	Height of RSU Antenna	RSU_h	20.00	feet
	Height of OBU Antenna	OBU_h	5.00	feet
	Maximum Lateral Separation Distance	Sep_max	50.00	feet
	Minimum RSU Ant. Angle From Vertical	Ang_min	45.00	degrees
	Minimum Lateral Separation Distance	Sep_min	15.00	feet
	Maximum Operating Range	Rmax	52.20	feet
	Maximum Operating Range in dB	Rmax_dB	17.18	dB feet
	Minimum Operating Range	Rmin	21.21	feet
	Minimum Operating Range in dB	Rmin_dB	13.27	dB feet
	Width of Antenna Beam at Longest Range	Wmax	12.00	feet
	Antenna Elevation Beamwidth	RSU_el	28.30	degrees
	Antenna Azimuth Beamwidth	RSU_az	13.11	degrees
	Antenna Gain	RSU_g	19.76	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	4.76	dB
Beacon 2 (Exit Beacon)	Height of RSU Antenna	RSU2_h	20.00	feet
	Height of OBU Antenna	OBU2_h	5.00	feet
	Maximum Lateral Separation Distance	Spe2_max	15.00	feet
	Minimum RSU Ant. Angle From Vertical	Ang2_min	-45.00	degrees
	Minimum Lateral Separation Distance	Sep2_min	-15.00	feet
	Maximum Operating Range	Rmax2	21.21	feet
	Maximum Operating Range in dB	Rmax2_dB	13.27	dB feet
	Minimum Operating Range	Rmin2	12.00	feet
	Minimum Operating Range in dB	Rmin2_dB	10.79	dB feet
	Width of Antenna Beam at Longest Range	Wmax2	5.00	feet
	Antenna Elevation Beamwidth	RSU2_el	90.00	degrees
	Antenna Azimuth Beamwidth	RSU2_az	13.44	degrees
	Antenna Gain	RSU2_g	14.62	dB
	Maximum Antenna Gain Through Sidelobes	RSU2_gsl	-0.38	dB
RSU General	Antenna Radiation Pattern Loss	RSU_gl	3.00	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	15.00	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	-94.00	dBm
	Maximum Interference Signal Level	RSU_int	-114.00	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	60.00	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	60.00	dB
	Isolation Tone to Adjacent Channel	RSU_TA	80.00	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	40.00	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	60.00	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	63.00	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	50.00	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	60.00	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	70.00	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	60.00	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	60.00	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	80.00	dB

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

OBU Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	4.00	dB
	Minimum Received Signal Level (0 dB ant.)	OBU_min	-40.00	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	-14.00	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	-60.00	dBm
	Maximum Transmit EIRP	OBU_Pmax	-24.00	dBm
	Windscreen Loss, One Way	L_w	3.00	dB
	Modulation Loss	L_m	3.00	dB
	Realization Margin	L_r	4.00	dB
	RF Amplifier Gain	OBU_rf	10.00	dB
	Minimum Conversion Gain	OBU_gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	18.00	dB

Beacon 1 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	19.05	dBm
	Transmit Power for Successful Uplink	Pt_u	19.10	dBm
	Transmit Power for Up and Down Link	Pt	19.10	dBm
	Transmit EIRP	RSU_EIRP	40.61	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-23.39	dBm

Beacon 2 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt2_d	12.37	dBm
	Transmit Power for Successful Uplink	Pt2_u	5.75	dBm
	Transmit Power for Up and Down Link	Pt2	12.37	dBm
	Transmit EIRP	RSU2_EIRP	27.00	dBm
OBU	Max. Received Signal Level (0 dB ant.)	BU2_Rmax	-32.05	dBm

CALCULATION OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

Uplink on Uplink Separation Distance OBU to RSU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe	Same Channel	630.66	405.46	feet
	Adjacent Channel	79.40	51.04	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe	Tone To Lower Uplink Band	56.52	122.60	feet
	Tone To Upper Uplink Band	56.52	122.60	feet
	Tone To Adjacent Channel	5.65	12.26	feet
	Class A: Modulated to Lower Uplink Band	565.24	1226.03	feet
	Class A: Modulated to Upper Uplink Band	56.52	122.60	feet
	Class A: Modulated to Adjacent Channel	40.02	86.80	feet
	Class B: Modulated to Lower Uplink Band	178.75	387.71	feet
	Class B: Modulated to Upper Uplink Band	56.52	122.60	feet
	Class B: Modulated to Adjacent Channel	17.87	38.77	feet
	Class C: Modulated to Lower Uplink Band	56.52	122.60	feet
	Class C: Modulated to Upper Uplink Band	56.52	122.60	feet
	Class C: Modulated to Adjacent Channel	5.65	12.26	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe	Same Channel	53.29	255.44	feet
	Tone - Adjacent Channel	0.01	0.03	feet
	Class A: Modulated - Adjacent Channel	0.04	0.18	feet
	Class B: Modulated - Adjacent Channel	0.02	0.08	feet
	Class C: Modulated - Adjacent Channel	0.01	0.03	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
N/A	Same Channel	0.59	0.84	feet
	Adjacent Channel	0.07	0.11	feet

APPENDIX C-l

In-Vehicle Signing Beacons with 50′ Operating Range

Calculations of Minimum Separation Distances

CALCULATION OF RE-USE DISTANCES BETWEEN IN-VEHICLE SIGNING

General Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	**5.85**	GHz
	Height of RSU Antenna	RSU_h	**20.00**	feet
	Height of OBU Antenna	OBU_h	**5.00**	feet
	Maximum Lateral Separation Distance	Sep_max	**50.00**	feet
	Minimum RSU Ant. Angle From Vertical	Ang_min	**45.00**	degrees
	Minimum Lateral Separation Distance	Sep_min	15.00	feet
	Maximum Operating Range	Rmax	52.20	feet
	Maximum Operating Range in dB	Rmax_dB	17.18	dB feet
	Minimum Operating Range	Rmin	21.21	feet
	Minimum Operating Range in dB	Rmin_dB	13.27	dB feet
	Width of Antenna Beam at Longest Range	Wmax	**12.00**	feet
	Speed of Light	Cf	9.84E+08	feet/sec.
	Wavelength	Lambda	**0.168248**	feet
	Wavelength in dB	Lambda_dB	**-7.74**	dB feet
	4*PI	F_PI	10.99	dB
RSU	Antenna Elevation Beamwidth	RSU_el	28.30	degrees
	Antenna Azimuth Beamwidth	RSU_az	13.11	degrees
	Antenna Gain	RSU_g	19.76	dB
	Antenna Radiation Pattern Loss	RSU_gl	**3.00**	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	**15.00**	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	4.76	dB
	Minimum Received Signal Level (at rcvr)	RSU_mrsl	**-94.00**	dBm
	Maximum Interference Signal	RSU_int	**-114.00**	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	**60.00**	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	**60.00**	dB
	Isolation Tone to Adjacent Channel	RSU_TA	**80.00**	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	**40.00**	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	**60.00**	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	**63.00**	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	**50.00**	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	**60.00**	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	**70.00**	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	**60.00**	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	**60.00**	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	**80.00**	dB
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	**4.00**	dB
	Mimimum Received Signal Level (0 dB ant)	OBU_min	**-40.00**	dBm
	Maximum Received Signal Level (0 dB ant)	OBU_max	**-14.00**	dBm
	Maximum Interference Signal Level (0 dB ant)	OBU_int	**-60.00**	dBm
	Maximum Transmit EIRP	OBU_Pmax	**-24.00**	dBm
	Windscreen Loss, One-Way	L_w	**3.00**	dB
	Modulation Loss	L_m	**3.00**	dB
	Realization Margin	L_r	**4.00**	dB
	RF Amplifier Gain	OBU_rf	**10.00**	dB
	Minimum Conversion Gain	OBU_Gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	**18.00**	dB

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

Beacon 1 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	15.06	dBm
	Transmit Power for Successful Uplink	Pt_u	11.13	dBm
	Transmit Power for Up and Down Link	Pt	15.06	dBm
	Transmit EIRP	RSU_EIRP	34.82	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-29.18	dBm

Beacon 2 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
Sidelobe	Same Channel		717.19	feet
	Adjacent Channel		90.29	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

LOCATION	PARAMETER	LABEL	VALUE	UNITS
Sidelobe	Tone To Lower Uplink Band		113.63	feet
	Tone To Upper Uplink Band		113.63	feet
	Tone To Adjacent Channel		11.36	feet
	Class A: Modulated to Lower Uplink Band		1,136.31	feet
	Class A: Modulated to Upper Uplink Band		113.63	feet
	Class A: Modulated to Adjacent Channel		80.44	feet
	Class B: Modulated to Lower Uplink Band		359.33	feet
	Class B: Modulated to Upper Uplink Band		113.63	feet
	Class B: Modulated to Adjacent Channel		35.93	feet
	Class C: Modulated to Lower Uplink Band		113.63	feet
	Class C: Modulated to Upper Uplink Band		113.63	feet
	Class C: Modulated to Adjacent Channel		11.36	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

LOCATION	PARAMETER	LABEL	VALUE	UNITS
Sidelobe	Same Channel		131.12	feet
	Tone – Adjacent Channel		0.01	feet
	Class A: Modulated – Adjacent Channel		0.09	feet
	Class B: Modulated – Adjacent Channel		0.04	feet
	Class C: Modulated – Adjacent Channel		0.01	feet

Uplink on Downlink Separation Distance OBU to OBU Antennas

LOCATION	PARAMETER	LABEL	VALUE	UNITS
Sidelobe	Same Channel		0.83	feet
	Adjacent Channel		0.10	feet

APPENDIX C-2

In-Vehicle Signing Beacons with 100′ Operating Range

Calculations of Minimum Separation Distances

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2)

Beacon Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	5.85	GHz
	Height of RSU Antenna	RSU_h	20.00	feet
	Height of OBU Antenna	OBU_h	5.00	feet
	Maximum Lateral Separation Distance	Sep_max	100.00	feet
	Minimum RSU Ant. Angle From Vertical	Ang_min	45.00	degrees
	Minimum Lateral Separation Distance	Sep_min	15.00	feet
	Maximum Operating Range	Rmax	101.12	feet
	Maximum Operating Range in dB	Rmax_dB	20.50	dB feet
	Minimum Operating Range	Rmin	21.21	feet
	Minimum Operating Range in dB	Rmin_dB	13.27	dB feet
	Width of Antenna Beam at Longest Range	Wmax	12.00	feet
	Speed of Light	Cf	9.84E+08	feet/sec.
	Wavelength	Lambda	0.168248	feet
	Wavelength in dB	Lambda_dB	-7.74	dB feet
	4*PI	F_PI	10.99	dB
ARSU	Antenna Elevation Beamwidth	RSU_el	28.30	degrees
	Antenna Azimuth Beamwidth	RSU_az	13.11	degrees
	Antenna Gain	RSU_g	19.76	dB
	Antenna Radiation Pattern Loss	RSU_gl	3.00	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	15.00	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	6.51	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	-94.00	dBm
	Maximum Interference Signal Level	RSU_int	-114.00	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	60.00	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	60.00	dB
	Isolation Tone to Adjacent Channel	RSU_TA	80.00	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	40.00	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	60.00	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	63.00	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	50.00	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	60.00	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	70.00	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	60.00	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	60.00	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	80.00	dB
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	4.00	dB
	Minimum Received Signal Level (0 dB ant.)	OBU_min	-40.00	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	-14.00	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	-60.00	dBm
	Maximum Transmit EIRP	OBU_Pmax	-24.00	dBm
	Windscreen Loss, One Way	L_w	3.00	dB
	Modulation Loss	L_m	3.00	dB
	Realization Margin	L_r	4.00	dB
	RF Amplifier Gain	OBU_rf	10.00	dB
	Minimum Conversion Gain	OBU_gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	18.00	dB

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

Beacon 1 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	19.05	dBm
	Transmit Power for Successful Uplink	Pt_u	19.10	dBm
	Transmit Power for Up and Down Link	Pt	19.10	dBm
	Transmit EIRP	RSU_EIRP	40.61	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-23.39	dBm

Uplink on Uplink Separation Distance OBU to RSU Antennas

RSU ANT.	SCENARIO	LABEL	VALUE	UNITS
Sidelobe	Same Channel		896.13	feet
	Adjacent Channel		112.82	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

RSU ANT.	SCENARIO	LABEL	VALUE	UNITS
Sidelobe	Tone To Lower Uplink Band		270.97	feet
	Tone To Upper Uplink Band		270.97	feet
	Tone To Adjacent Channel		27.10	feet
	Class A: Modulated to Lower Uplink Band		2,709.71	feet
	Class A: Modulated to Upper Uplink Band		270.97	feet
	Class A: Modulated to Adjacent Channel		191.83	feet
	Class B: Modulated to Lower Uplink Band		856.89	feet
	Class B: Modulated to Upper Uplink Band		270.97	feet
	Class B: Modulated to Adjacent Channel		85.69	feet
	Class C: Modulated to Lower Uplink Band		270.97	feet
	Class C: Modulated to Upper Uplink Band		270.97	feet
	Class C: Modulated to Adjacent Channel		27.10	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU ANT.	SCENARIO	LABEL	VALUE	UNITS
Sidelobe	Same Channel		255.44	feet
	Tone - Adjacent Channel		0.03	feet
	Class A: Modulated - Adjacent Channel		0.18	feet
	Class B: Modulated - Adjacent Channel		0.08	feet
	Class C: Modulated - Adjacent Channel		0.03	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU ANT.	SCENARIO	2 on 1	1 on 2	UNITS
N/A	Same Channel	0.59	0.84	feet
	Adjacent Channel	0.07	0.11	feet

APPENDIX D-l

INTERSECTION BEACONS WITH 50′ OPERATING RANGE

CALCULATIONS OF MINIMUM SEPARATION DISTANCES

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2)

Beacon Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	5.85	GHz
	Height of RSU Antenna	RSU_h	20.00	feet
	Height of OBU Antenna	OBU_h	5.00	feet
	Maximum Lateral Separation Distance	Sep_max	50.00	feet
	Minimum RSU Ant. Angle From Vertical	Ang_min	30.00	degrees
	Minimum Lateral Separation Distance	Sep_min	8.66	feet
	Maximum Operating Range	Rmax	52.20	feet
	Maximum Operating Range in dB	Rmax_dB	17.18	dB feet
	Minimum Operating Range	Rmin	17.32	feet
	Minimum Operating Range in dB	Rmin_dB	12.39	dB feet
	Width of Antenna Beam at Longest Range	Wmax	12.00	feet
	Speed of Light	Cf	9.84E+08	feet/sec.
	Wavelength	Lambda	0.168248	feet
	Wavelength in dB	Lambda_dB	-7.74	dB feet
	4*PI	F_PI	10.99	dB
ARSU	Antenna Elevation Beamwidth	RSU_el	60.00	degrees
	Antenna Azimuth Beamwidth	RSU_az	13.11	degrees
	Antenna Gain	RSU_g	16.49	dB
	Antenna Radiation Pattern Loss	RSU_gl	3.00	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	15.00	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	1.49	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	-94.00	dBm
	Maximum Interference Signal Level	RSU_int	-114.00	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	60.00	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	60.00	dB
	Isolation Tone to Adjacent Channel	RSU_TA	80.00	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	40.00	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	60.00	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	63.00	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	50.00	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	60.00	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	70.00	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	60.00	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	60.00	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	80.00	dB
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	4.00	dB
	Minimum Received Signal Level (0 dB ant.)	OBU_min	-40.00	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	-14.00	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	-60.00	dBm
	Maximum Transmit EIRP	OBU_Pmax	-24.00	dBm
	Windscreen Loss, One Way	L_w	3.00	dB
	Modulation Loss	L_m	3.00	dB
	Realization Margin	L_r	4.00	dB
	RF Amplifier Gain	OBU_rf	10.00	dB
	Minimum Conversion Gain	OBU_gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	18.00	dB

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

Beacon 1 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	18.33	dBm
	Transmit Power for Successful Uplink	Pt_u	17.65	dBm
	Transmit Power for Up and Down Link	Pt	18.33	dBm
	Transmit EIRP	RSU_EIRP	34.82	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-27.42	dBm

Uplink on Uplink Separation Distance OBU to RSU Antennas

	SCENARIO	Sidelobe	Mainlobe	UNITS
	Same Channel	502.78	2,827.35	feet
	Adjacent Channel	63.30	355.94	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

	SCENARIO	Sidelobe	Mainlobe	UNITS
	Tone To Lower Uplink Band	78.04	2,467.87	feet
	Tone To Upper Uplink Band	78.04	2,467.87	feet
	Tone To Adjacent Channel	7.80	246.79	feet
	Class A: Modulated to Lower Uplink Band	780.41	24,678.69	feet
	Class A: Modulated to Upper Uplink Band	78.04	2,467.87	feet
	Class A: Modulated to Adjacent Channel	55.25	1,747.12	feet
	Class B: Modulated to Lower Uplink Band	246.79	7,804.09	feet
	Class B: Modulated to Upper Uplink Band	78.04	2,467.87	feet
	Class B: Modulated to Adjacent Channel	24.68	780.41	feet
	Class C: Modulated to Lower Uplink Band	78.04	2,467.87	feet
	Class C: Modulated to Upper Uplink Band	78.04	2,467.87	feet
	Class C: Modulated to Adjacent Channel	7.80	246.79	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU ANT.	SCENARIO	Sidelobe	Mainlobe	UNITS
Sidelobe	Same Channel	131.12	737.37	feet
	Tone - Adjacent Channel	0.01	0.07	feet
	Class A: Modulated - Adjacent Channel	0.09	0.52	feet
	Class B: Modulated - Adjacent Channel	0.04	0.23	feet
	Class C: Modulated - Adjacent Channel	0.01	0.07	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU ANT.	SCENARIO		VALUE	UNITS
N/A	Same Channel		0.84	feet
	Adjacent Channel		0.11	feet

APPENDIX D-2

INTERSECTION BEACONS WITH 100′ OPERATING RANGE

CALCULATIONS OF MINIMUM SEPARATION DISTANCES

CALCULATION OF RE-USE DISTANCE BETWEEN INTERSECTION BEACONS

General Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	**5.85**	GHz
	Height of RSU Antenna	RSU_h	**20.00**	feet
	Height of OBU Antenna	OBU_h	**5.00**	feet
	Maximum Lateral Separation Distance	Sep_max	**100.00**	feet
	Minumum RSU Ant. Angle From Vertical	Ang_min	**30.00**	degrees
	Minimum Lateral Separation Distance	Sep_min	8.66	feet
	Maximum Operating Range	Rmax	101.12	feet
	Maximum Operating Range in dB	Rmax_dB	20.05	dB feet
	Minimum Operating Range	Rmin	17.32	feet
	Minimum Operating Range in dB	Rmin_dB	12.39	dB feet
	Width of Antenna Beam at Longest Range	Wmax	**12.00**	feet
	Speed of Light	Cf	9.84E+08	feet/sec.
	Wavelength	Lambda	**0.168248**	feet
	Wavelength in dB	Lambda_dB	**-7.74**	dB feet
	4*PI	F_PI	10.99	dB
RSU	Antenna Elevation Beamwidth (Hor. to Ang_min)	RSU_el	60.00	degrees
	Antenna Azimuth Beamwidth	RSU_az	6.79	degrees
	Antenna Gain	RSU_g	19.35	dB
	Antenna Radiation Pattern Loss	RSU_gl	**3.00**	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	**15.00**	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	4.35	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	**-94.00**	dBm
	Maximum Interference Signal Level	RSU_int	**-114.00**	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	**60.00**	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	**60.00**	dB
	Isolation Tone to Adjacent Channel	RSU_TA	**80.00**	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	**40.00**	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	**60.00**	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	**63.00**	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	**50.00**	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	**60.00**	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	**70.00**	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	**60.00**	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	**60.00**	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	**80.00**	dB
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	**4.00**	dB
	Mimimum Received Signal Level (0 dB ant.)	OBU_min	**-40.00**	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	**-14.00**	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	**-60.00**	dBm
	Maximum Transmit EIRP	OBU_Pmax	**-24.00**	dBm
	Windscreen Loss, One-Way	L_w	**3.00**	dB
	Modulation Loss	L_m	**3.00**	dB
	Realization Margin	L_r	**4.00**	dB
	RF Amplifier Gain	OBU_rf	**10.00**	dB
	Minimum Conversion Gain	OBU_Gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	**18.00**	dB

CALCULATIONS OF RE-USE DISTANCES: IN-VEHICLE SIGNING (1) TO EXIT BEACON (2) (CONTINUED)

RSU Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	21.21	dBm
	Transmit Power for Successful Uplink	Pt_u	23.42	dBm
	Transmit Power for Up and Down Link	Pt	23.42	dBm
	Transmit EIRP	RSU_EIRP	42.77	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-19.46	dBm

Uplink on Uplink Separation Distance OBU to RSU Antennas

	SCENARIO	Sidelobe	Mainlobe	UNITS
	Same Channel	698.65	3,928.78	feet
	Adjacent Channel	87.95	494.60	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

	SCENARIO	Sidelobe	Mainlobe	UNITS
	Tone To Lower Uplink Band	270.97	8,568.85	feet
	Tone To Upper Uplink Band	270.97	8,568.85	feet
	Tone To Adjacent Channel	27.10	856.89	feet
	Class A: Modulated to Lower Uplink Band	2,709.71	85,688.54	feet
	Class A: Modulated to Upper Uplink Band	270.97	8,568.85	feet
	Class A: Modulated to Adjacent Channel	191.83	6,066.28	feet
	Class B: Modulated to Lower Uplink Band	856.89	27,097.10	feet
	Class B: Modulated to Upper Uplink Band	270.97	8,568.85	feet
	Class B: Modulated to Adjacent Channel	85.69	2,709.71	feet
	Class C: Modulated to Lower Uplink Band	270.97	8,568.85	feet
	Class C: Modulated to Upper Uplink Band	270.97	8,568.85	feet
	Class C: Modulated to Adjacent Channel	27.10	856.89	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

	SCENARIO	Sidelobe	Mainlobe	UNITS
	Same Channel	327.65	1,842.49	feet
	Tone – Adjacent Channel	0.03	0.18	feet
	Class A: Modulated – Adjacent Channel	0.23	1.30	feet
	Class B: Modulated – Adjacent Channel	0.10	0.58	feet
	Class C: Modulated – Adjacent Channel	0.03	0.18	feet

Uplink on Downlink Separation Distance OBU to OBU Antennas

	SCENARIO		VALUE	UNITS
	Same Channel		0.84	feet
	Adjacent Channel		0.11	feet

APPENDIX E
BUS STOP BEACONS
CALCULATIONS OF MINIMUM SEPARATION DISTANCES

CALCULATION OF RE-USE DISTANCE BETWEEN BUS STOP BEACONS

General Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	5.85	GHz
	Height of RSU Antenna	RSU_h	20.00	feet
	Height of OBU Antenna	OBU_h	12.00	feet
	Maximum Lateral Separation Distance	Sep_max	4.00	feet
	Minimum Lateral Separation Distance	Sep_min	8.00	feet
	Maximum Operating Range	Rmax	8.94	feet
	Maximum Operating Range in dB	Rmax_dB	9.52	dB feet
	Minimum Operating Range	Rmin	5.00	feet
	Minimum Operating Range in dB	Rmin_dB	6.99	dB feet
	Width of Antenna Beam at Longest Range	Wmax	5.00	feet
	Speed of Light	Cf	9.84E+08	feet/sec.
	Wavelength	Lambda	0.168248	feet
	Wavelength in dB	Lambda_dB	-7.74	dB feet
	4*PI	F_PI	10.99	dB
RSU	Antenna Elevation Beamwidth	RSU_el	31.23	degrees
	Antenna Azimuth Beamwidth	RSU_az	31.23	degrees
	Antenna Gain	RSU_g	15.56	dB
	Antenna Radiation Pattern Loss	RSU_gl	3.00	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	15.00	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	0.56	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	-94.00	dBm
	Maximum Interference Signal Level	RSU_int	-114.00	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	60.00	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	60.00	dB
	Isolation Tone to Adjacent Channel	RSU_TA	80.00	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	40.00	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	60.00	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	63.00	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	50.00	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	60.00	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	70.00	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	60.00	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	60.00	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	80.00	dB
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	4.00	dB
	Minimum Received Signal Level (0 dB ant.)	OBU_min	-40.00	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	-14.00	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	-60.00	dBm
	Maximum Transmit EIRP	OBU_Pmax	-24.00	dBm
	Windscreen Loss, One Way	L_w	3.00	dB
	Modulation Loss	L_m	3.00	dB
	Realization Margin	L_r	4.00	dB
	RF Amplifier Gain	OBU_rf	10.00	dB
	Minimum Conversion Gain	OBU_gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	18.00	dB

CALCULATION OF RE-USE DISTANCE BETWEEN BUS STOP BEACONS (CONTINUED)

RSU Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	3.94	dBm
	Transmit Power for Successful Uplink	Pt_u	11.13	dBm
	Transmit Power for Up and Down Link	Pt	3.94	dBm
	Transmit EIRP	RSU_EIRP	19.50	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-31.95	dBm

Uplink on Uplink Separation Distance OBU to RSU Antennas

RSU ANT.	SCENARIO	LABEL	VALUE	UNITS
Sidelobe	Same Channel		57.19	feet
	Adjacent Channel		7.20	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

RSU ANT.	SCENARIO	LABEL	VALUE	UNITS
Sidelobe	Tone To Lower Uplink Band		12.01	feet
	Tone To Upper Uplink Band		12.01	feet
	Tone To Adjacent Channel		1.20	feet
	Class A: Modulated to Lower Uplink Band		120.09	feet
	Class A: Modulated to Upper Uplink Band		12.01	feet
	Class A: Modulated to Adjacent Channel		8.50	feet
	Class B: Modulated to Lower Uplink Band		37.98	feet
	Class B: Modulated to Upper Uplink Band		12.01	feet
	Class B: Modulated to Adjacent Channel		3.80	feet
	Class C: Modulated to Lower Uplink Band		12.01	feet
	Class C: Modulated to Upper Uplink Band		12.01	feet
	Class C: Modulated to Adjacent Channel		1.20	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU ANT.	SCENARIO	LABEL	VALUE	UNITS
Sidelobe	Same Channel		4.00	feet
	Tone - Adjacent Channel		0.00	feet
	Class A: Modulated - Adjacent Channel		0.00	feet
	Class B: Modulated - Adjacent Channel		0.00	feet
	Class C: Modulated - Adjacent Channel		0.00	feet

Uplink on Downlink Separation Distance OBU to OBU Antennas

RSU ANT.	SCENARIO	LABEL	VALUE	UNITS
N/A	Same Channel		0.11	feet
	Adjacent Channel		0.01	feet

APPENDIX F

Off line Verification Beacon Versus Intersection Beacon Calculations of Minimum Separation Distances

CALCULATIONS OF RE-USE DISTANCES: INTERSECTION (1) TO OFF-LINE VERIFICATION (2)

Beacon Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	5.85	GHz
	Speed of Light	Cf	984251969	feet/sec.
	Wavelength	Lambda	0.1682482	feet
	Wavelength in dB	Lambda_dB	-7.74	dB feet
	4*PI	F_PI	10.99	dB
Beacon 1 (Intersection)	Height of RSU Antenna	RSU_h	20.00	feet
	Height of OBU Antenna	OBU_h	5.00	feet
	Maximum Lateral Separation Distance	Sep_max	50.00	feet
	Minimum RSU Ant. Angle From Vertical	Ang_min	30.00	degrees
	Minimum Lateral Separation Distance	Sep_min	8.66	feet
	Maximum Operating Range	Rmax	52.20	feet
	Maximum Operating Range in dB	Rmax_dB	17.18	dB feet
	Minimum Operating Range	Rmin	17.32	feet
	Minimum Operating Range in dB	Rmin_dB	12.39	dB feet
	Width of Antenna Beam at Longest Range	Wmax	12.00	feet
	Antenna Elevation Beamwidth	RSU_el	60.00	degrees
	Antenna Azimuth Beamwidth	RSU_az	13.11	degrees
	Antenna Gain	RSU_g	16.49	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	1.49	dB
Beacon 2 (Off-Line Ver)	Maximum Operating Range	Rmax2	30.00	feet
	Maximum Operating Range in dB	Rmax2_dB	14.77	dB feet
	Minimum Operating Range	Rmin2	6.00	feet
	Minimum Operating Range in dB	Rmin2_dB	7.78	dB feet
	Antenna Elevation Beamwidth	RSU2_el	20.00	degrees
	Antenna Azimuth Beamwidth	RSU2_az	20.00	degrees
	Antenna Gain	RSU2_g	19.43	dB
	Maximum Antenna Gain Through Sidelobes	RSU2_gsl	4.43	dB
RSU General	Antenna Radiation Pattern Loss	RSU_gl	3.00	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	16.00	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	-94.00	dBm
	Maximum Interference Signal Level	RSU_int	-114.00	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	60.00	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	60.00	dB
	Isolation Tone to Adjacent Channel	RSU_TA	80.00	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	40.00	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	60.00	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	63.00	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	50.00	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	60.00	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	70.00	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	60.00	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	60.00	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	80.00	dB

CALCULATIONS OF RE-USE DISTANCES: INTERSECTION (1) TO OFF-LINE VERIFICATION (2) (CONTINUED)

OBU Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	4.00	dB
	Minimum Received Signal Level (0 dB ant.)	OBU_min	-40.00	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	-14.00	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	-60.00	dBm
	Maximum Transmit EIRP	OBU_Pmax	-24.00	dBm
	Windscreen Loss, One Way	L_w	3.00	dB
	Modulation Loss	L_m	3.00	dB
	Realization Margin	L_r	4.00	dB
	RF Amplifier Gain	OBU_rf	10.00	dB
	Minimum Conversion Gain	OBU_gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	18.00	dB

Beacon 1 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	18.33	dBm
	Transmit Power for Successful Uplink	Pt_u	17.65	dBm
	Transmit Power for Up and Down Link	Pt	18.33	dBm
	Transmit EIRP	RSU_EIRP	34.82	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-27.42	dBm

Beacon 2 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt2_d	10.58	dBm
	Transmit Power for Successful Uplink	Pt2_u	2.15	dBm
	Transmit Power for Up and Down Link	Pt2	10.58	dBm
	Transmit EIRP	RSU2_EIRP	30.01	dBm
OBU	Max. Received Signal Level (0 dB ant.)	BU2_Rmax	-23.02	dBm

CALCULATIONS OF RE-USE DISTANCES: INTERSECTION (1) TO OFF-LINE VERIFICATION (2) (CONTINUED)

Uplink on Uplink Separation Distance OBU to RSU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Main 1 Side 2	Same Channel	2,827.35	705.15	feet
	Adjacent Channel	355.94	88.77	feet
	Adjacent Channel – Off-Line Distance = 10 Feet	N/A	9.96	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe of Off-Line Ver. Beacon (2) Mainlobe of Intersection Beacon (1)	Tone To Lower Uplink Band	252.21	615.50	feet
	Tone To Upper Uplink Band	252.21	615.50	feet
	Tone To Adjacent Channel	25.22	61.55	feet
	Class A: Modulated to Lower Uplink Band	2,522.09	6,154.99	feet
	Class A: Modulated to Upper Uplink Band	252.21	615.50	feet
	Class A: Modulated to Adjacent Channel	178.55	435.74	feet
	Class B: Modulated to Lower Uplink Band	797.55	1,946.38	feet
	Class B: Modulated to Upper Uplink Band	252.21	615.50	feet
	Class B: Modulated to Adjacent Channel	79.76	194.64	feet
	Class C: Modulated to Lower Uplink Band	252.21	615.50	feet
	Class C: Modulated to Upper Uplink Band	252.21	615.50	feet
	Class C: Modulated to Adjacent Channel	25.22	61.55	feet
	Class C: Adj. Channel – Off-Line Distance = 10 Ft	N/A	6.91	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe of Off-Line Ver. (2) Mainlobe of Intersection (1)	Same Channel	75.36	737.37	feet
	Tone - Adjacent Channel	0.01	0.07	feet
	Class A: Modulated - Adjacent Channel	0.05	0.52	feet
	Class B: Modulated - Adjacent Channel	0.02	0.23	feet
	Class C: Modulated - Adjacent Channel	0.01	0.07	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU Antenna	SCENARIO	2 on 1	1 on 2	UNITS
N/A	Same Channel	0.84	0.84	feet
	Adjacent Channel	0.11	0.11	feet

Appendix E: Environmental Analysis Framework and Methodology

1.0 Introduction

GTRI is supporting ARINC under Tasks D & E of the ATIS Communications Alternatives Test and Evaluation contract from the Federal Highway Administration (FHWA). The objective of GTRI's effort is to analyze Vehicle to Roadside Communications (DSRC) technologies to determine their applicability to the Intelligent Transportation Systems (ITS) architecture. This analysis is geared toward the refinement of the assessments of the technology for use in ITS.

This report summarizes a framework and methodology for the environmental analysis of DSRC equipment The environmental analysis will include the analysis of the effects of the following:

a. Weather Propagation Effects
   (1) Fog
   (2) Rain (mist to deluge)
   (3) Snow
   (4) Dust
   (5) Hail.

b. Electromagnetic Environment Effects
   (1) Other DSRC System Emitters
   (2) Other Non-DSRC Emitters
   (3) Unintentional Emitters

c. Physical Effects
   (1) Blockage/Diffraction
   (2) Multipath

2.0 Methodology for the Environmental Analysis

The framework for the methodology will be presented in the following three sections corresponding to the three areas of analysis: weather propagation effects, electromagnetic environment and physical effects. The purpose of this report is primarily to assemble the tools needed to analyze DSRC system performance including range of operation, reliability, effective data rate (capacity), and protocol. These tools will also be useful in the analysis of the design impacts involved in the migration of the 902-928 MHz devices to the 5.850-5.925 GHz band.

The tools and methods presented in the following sections are a collection designed to cover most of the DSRC systems that will be analyzed. Due to the wide variety of DSRC systems, including beacons and ETTM devices, currently available on the market, the analysis of each device or system will likely be unique.

2.1 Weather Propagation Effects

Weather propagation effects on electromagnetic propagation have been studied extensively, especially in the military domain. The primary source of information for this section of the report is a RF propagation study for network planning performed by GTRI for the U.S. Army. [l] Weather or atmospheric related effects on propagation are generally modeled as a point specific attenuation in units of dB/km. For short range communications systems such as DSRC, the effects can be accurately approximated by assuming the attenuation is constant over the length of the communications channel. If a, is the attenuation factor due to atmospheric or weather effects (usually expressed in dB/km), the received signal power in free space is calculated by

$$signal = \left(\frac{P_T G_T G_R\, l^2}{4p^2 R^2 L(a^1{}_r)^R} \right)$$

where:

	P_T	=	transmitter or emitter power (W),
	G_T	=	transmitter antenna gain (linear),
	G_R	=	receiver antenna gain (linear),
	l	=	wavelength (meters),
	R	=	range (meters),
	L	=	miscellaneous receiver losses, and
	$\alpha^1{}_r$	=	linear atmospheric attenuation factor
		=	$10^{\alpha\, r/10}$

Atmospheric effects on propagation are generally divided into two categories: attenuation due to gases and attenuation due to hydrometeors (water in liquid or vapor form).

Gaseous attenuation is caused by the resonance frequencies of certain gas molecules in the atmosphere. Therefore, their effects are at fairly specific frequencies in the SHF (3–30 GHz) and EHF (30 - 100 GHz) bands. The resonance of oxygen molecules creates significant attenuation near 60 GHz and 119 GHz. Water vapor resonance affects frequencies near 22 GHz. Below 10 GHz, the attenuation effects of gases in the atmosphere are less than 0.01 dB/km. [3] Therefore, atmospheric attenuation due to gases in the atmosphere is not considered to have a significant impact on the performance of DSRC operating at 902-928 MHz or near 5.8 GHz.

Hydrometeors include rain, sleet, snow, hail, mist and fog. Of these hydrometeors, rain has the most significant impact on the atmospheric attenuation. The frozen precipitations, including sleet, snow and hail, have a significantly lower attenuation than the equivalent the equivalent rainfall rate due to the lower scattering cross section and lower absorption. Also, even dense fog has a lower attenuation than 10 mm/hr (light) rainfall. Therefore, only rainfall need be considered in the analysis of link performance.

The most commonly used model for determining the specific attenuation or attenuation factor due to rain is of the form:

$$\alpha_r = a(R_r)^b \quad \text{(dB/km)}$$

where R_r is the rain rate in mm/hr, and a and b are functions of temperature, rain drop size, rain drop distribution and frequency. Theoretical values for a and b have been derived by several authors using uniformly random rain drop distributions, raindrops modeled as some shape (such as water spheres), and Mie scattering theory. Tables summarizing the various values of a and b for most of these are available in [2]. Variations due to temperature are very small compared to the variation due to frequency or rain rate. Figure 1 shows the attenuation prediction for 10 mm/hr (light) rainfall using the Laws and Parsons low rain rate (LP(L)), Marshall-Palmer (MP), Joss "drizzle" (J-D), and International Radio Consultative Committee (CCIR) models. Figure 2 plots the predicted rainfall attenuation for 100 mm/hr (heavy) rainfall using the Laws and Parsons high rain rate (LP(H)), MP, Joss "thunderstorm" (J-T), and CCIR models. These figures show the effects of a variety of the more common rainfall models.

Figure 1: Attenuation Predictions for R=10 mm/hr

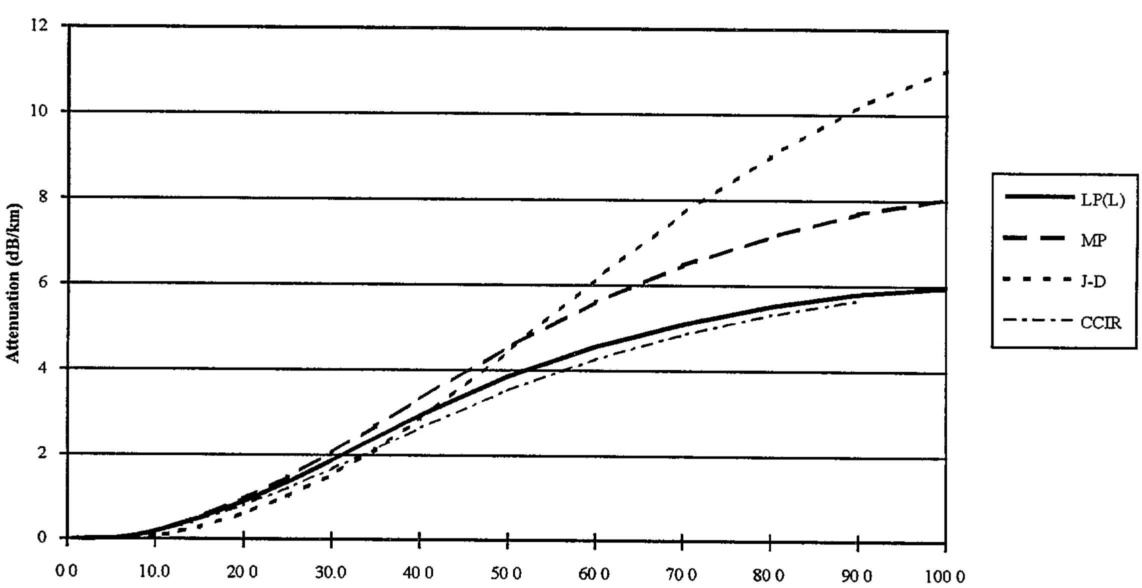
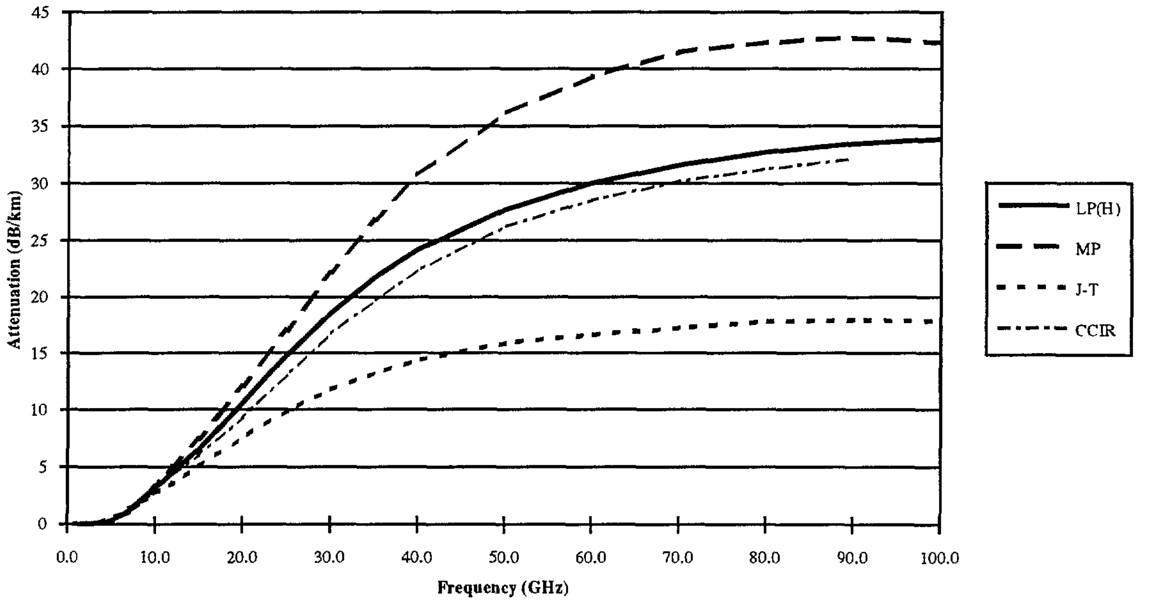


Figure 2: Attenuation Predictions for R=100 mm/hr



Note from Figures 1 and 2 that even at very heavy (100 mm/hr) rainfall rates, the attenuation due to rainfall is less than 1 dB/km for frequencies of 6 GHz or less. Since DSRC systems generally operate over ranges less than or equal to 1 km, then rainfall has no significant impact on the performance of DSRC systems operating at 902-928 MHz or near 5.8 GHz. Consequently, atmospheric effects as a whole have no significant impact on these DSRC systems.

The only remaining weather related or atmospheric effect to consider is the presence of dust or smoke in the atmosphere. The effects of dust and smoke on propagation have been investigated primarily on millimeter wave (MMW) communication systems. Dust has a lesser effect generally than does rainfall, especially at frequencies below MMW. Again, since the DSRC systems generally operate at ranges of 1 km or less, the effects of dust on operation are assumed to be negligible.

Since atmospheric effects are largely negligible at the frequencies of interest here, signal power in free space (or at short ranges) can be calculated by using the following reduced equation for the received signal power (in free space):

$$signal = \left(\frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2 L} \right).$$

For operating ranges R much greater than the multiple of the transmitter and receiver antenna heights, the received signal power can be estimated using

$$signal = P_T G_T G_R \left(\frac{h_T h_R}{R^2}\right)^2$$

where h_T and h_R are the transmit and receive antenna heights, respectively. This estimate is based on the assumption of single reflected signal combining with a direct path over a flat surface. It is useful in estimating the average received power in mobile, ground-based communications systems. This method will only be useful in estimating receive power levels for longer range beacon-type DSRC systems. It is not as a rule applicable to shorter range electronic toll collection (ETC) or similar systems which operate at very short ranges.

The equations presented above for calculating receive signal power can be used to estimate a DSRC system's operating range. If the specifications of the system include a minimum receive signal level (MRSL) or minimum signal level (MSL), then this can be substituted for *signal L* in the above equations. The equations can then be solved for the range R in free space using:

$$R = \sqrt{\frac{P_T G_T G_R \lambda^2}{(4\pi)^2 MSL}}$$

If the MSL or MRSL is not provided, then the modulation type, coding and required reliability (i.e. bit error rate) must be considered in order to determine the minimum signal-to-noise ratio (SNR). The SNR can be determined from any of a number of communications books. SNR is equal to the received signal power *(signal)* divided by the received noise power *(noise)*. The receive noise power can be calculated from

$$noise = K \cdot T_o \cdot B \cdot NF$$

where	K	=	Boltzmann's constant = 1.38054 * 10^{-23} (W•sec/°K),
	T_0	=	receiver temperature, typically 290 °K,
	B	=	receiver IF bandwidth (Hz), and
	NF	=	receiver noise figure.

Combining the equations for received signal power and receiver noise, using the minimum required SNR *(SNR_{min})*, and solving for range (assuming free space) results in the following formula for maximum operating range:

$$R = \sqrt{\frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2}{(4\pi)^2 K \cdot T_o \cdot B \cdot NF \cdot SNR_{\min}}}$$

2.2 Electromagnetic Environment Effects

It is difficult to develop a simple methodology for the analysis of the electromagnetic environment effects on DSRC equipment. Many of the effects can only be assessed in specific locations, configurations and surrounding environments. This section will attempt to summarized the primary considerations that must be included in the electromagnetic environment effects analysis. This section is divided into the analysis of the effects of other DSRC system emitters, non-DSRC emitters, and unintentional emitters.

2.2. I Effects of Other DSRC Emitters

The general effects of other DSRC emitters can be assessed by calculating the interference power received at a particular DSRC receiver. Calculating the interference power at a receiver is similar to calculating the receive power. Adjustments must be made to account for bandwidth mismatch and antenna misdirection (i.e. off-center orsidelobe gain of antennas). The following equation can be used to calculate the interference power received:

$$interference = \left(\frac{P^1_T G^1_T G^1_R\, l^2}{(4p)^2 R^2 L} \right)$$

where: P^1_T = transmitted power in the bandwidth of the receiver (W),
G^1_T = transmit antenna gain in the direction of the receiver, and
G^1_R = receiver antenna gain in the direction of the transmitter.

Interference from other DSRC systems must be managed through frequency control, physical separation, antenna directionality and encoding (with or without encryption). Some standards must exist in order to prevent communication disabling interference resulting from two separate DSRC systems operating at the same location and frequency. Assuming that the disabling interference situation described above is avoided through careful spectrum management or coding, the case of unintentional interference must still be resolved. The most common occurrences of interference will likely be interference between multiple systems located on the same vehicle and co-channel interference within a single DSRC system. Multiple systems on a single vehicle should be avoided if they operate at the same or nearly the same frequencies. That is the goal of standardization and the development of a single system architecture.

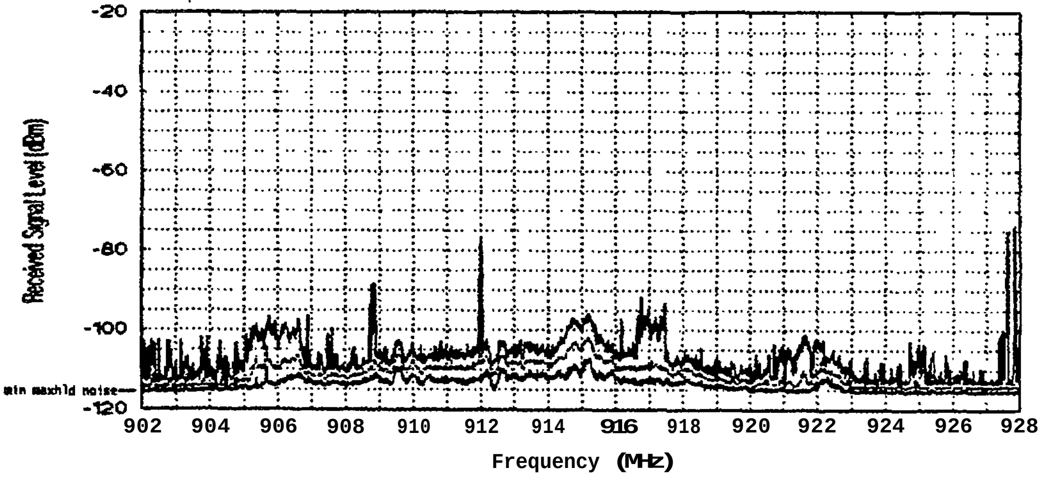
Co-channel interference within a single DSRC system has already been identified as a problem for ETC and commercial vehicle operation (CVO) equipment. Electronic toll tags or CVO transponders in vehicles in adjacent lanes responding to queries intended for a single lane have caused some problems. Typically, the cause is not simply communications through antenna sidelobes, it is often reflections off of the intended vehicle. This problem is not completely solved, though some work is being done with array antennas and shaped beams.

2.2.2 Non-DSRC Emitters

DSRC equipment is not the only type of communications equipment in the 902-928 MHz or the 5.8 GHz bands. The 902-928 MHz band is allocated for military radiolocation systems (radars), industrial scientific and medical (ISM), automatic vehicle monitoring (AVM), spread spectrum devices, microwave ovens, digital communications and repeaters. [3] The 5.725 - 5.8750 GHz band is allocated to radiolocation (military radios), ISM (5.800 GHz ± 75 MHz) and amateur (Part 15 - spread spectrum, unlicensed, etc.) systems. [4] Many of the DSRC systems in either of these bands are designed to operate under Part 15 (unlicensed) of the FCC code. Thus they are not protected from interference from either the radiolocation systems or the ISM systems in the bands.

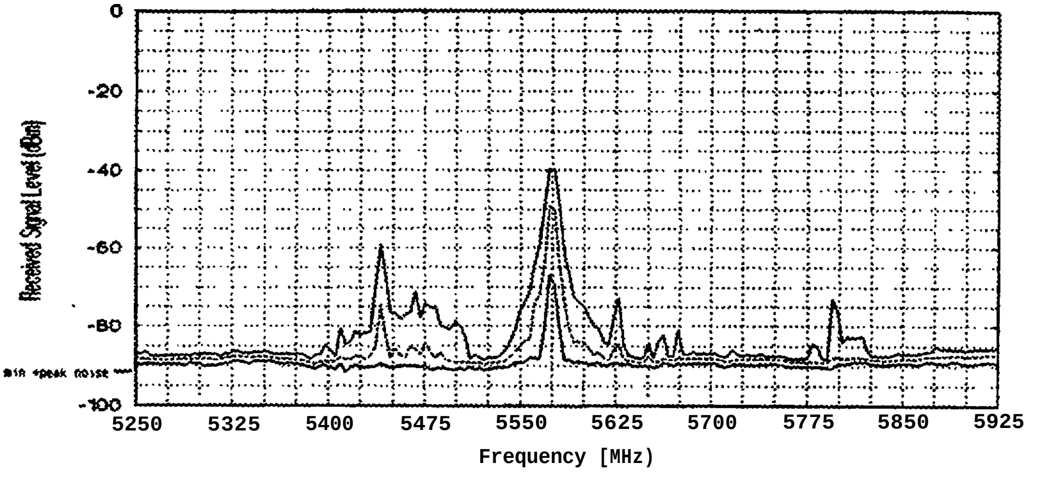
Measurements made in the Denver, Colorado area [3] show that in the absence of military radars, the general background interference is fairly low. Using a 6.1 dB gain antenna with a 45" polarization, the received signal levels in the 902-928 MHZ band were usually below -90 dBm (10 kHz bandwidth). There were a few strong signals detected in this band as shown in Figure 3.

Figure 3. NTIA Spectrum Survey Graph Summarizing 23,400 sweep across the 902-928 MHz range (10 kHz bandwidth) at Denver, Colorado [3]



Measurements made at 5.250-5.925 GHz also in the Denver area are summarized in Figure 4. These measurements were taken in several scans using an omnidirectional antenna with a gain of 3.1 dB and show a received signal level of about -82 dBm at 5.8 GHz. All of the prominent signals in the band were the result of radar systems.

Figure 4. NTIA Spectrum Survey Graph Summarizing 26 Scans Across the 5.250-5.925 GHz range (3 MHz bandwidth) at Denver, Colorado [3]



While the measurements made in Denver cannot be applied to all locations or even at all times in Denver, they do represent a typical background signal levels for the 902-928 MHz and 5.8 GHz bands.

Comparing the MRSL of a system to the background noise depicted in Figures 3 and 4 can provide more information on the operating range of the DSRC emitters. The interference power levels received by a DSRC system can be calculated from the signal levels in the Denver measurements by compensating for bandwidth. The received interference power (in dBm) is calculated by

$$\textbf{received-interference} = P_m + B_R - B_m$$

where P_m = power measured at Denver (in dBm),
B_R = 10 log(bandwidth of the DSRC receiver), and
B_m = 10 log(bandwidth used in the Denver measurements).

The minimum power level at the receiver needed to overcome the interference sources can be calculated by adding the received interference power level to the SNR required at the receiver. If this sum is greater than the MRSL quoted for the system, then the minimum received power level calculated here must be used in place of MRSL in the calculations of maximum operating range discussed in the Weather Propagation Effects section above. Note that this result can only be used as an estimate of the actual system's performance. A spectral site survey is required to identify the background noise and potential interference sources at any specific location.

Special Note: The 5.795-5.805 GHz band is of interest in this current analysis, but of emerging interest is the 5.850-5.925 GHz band for ITS DSRC applications. The latter band is allotted for Government radiolocation and fixed earth-to-space satellite transmissions. ISM emitters are not allowed in this band. Efforts are currently under way to have ITS DSRC systems allotted on a co-primary basis in this band with the satellite earth stations. This would provide the DSRC systems a significant measure of protection from interference from Part 15 (unlicensed) emitters. Also, the satellite ground station emissions are very compatible with the short range DSRC systems and would not likely cause significant interference problems between the two.

2.2.3 Unintentional Emitters

Unintentional emitters consist of natural and man-made sources. The most common method for evaluating the effects of unintentional emissions is to characterize the overall background noise levels caused by these emitters. In Figure 5, the noise levels resulting from the more common unintentional emitters are characterized. The noise levels are given in terms of the antenna noise figure, F_a, due to the external noise. The RMS field strength for a particular bandwidth receiver can be calculated by

$$E_n = F_a + 20\log(f_{MHz}) + B - 95.5$$

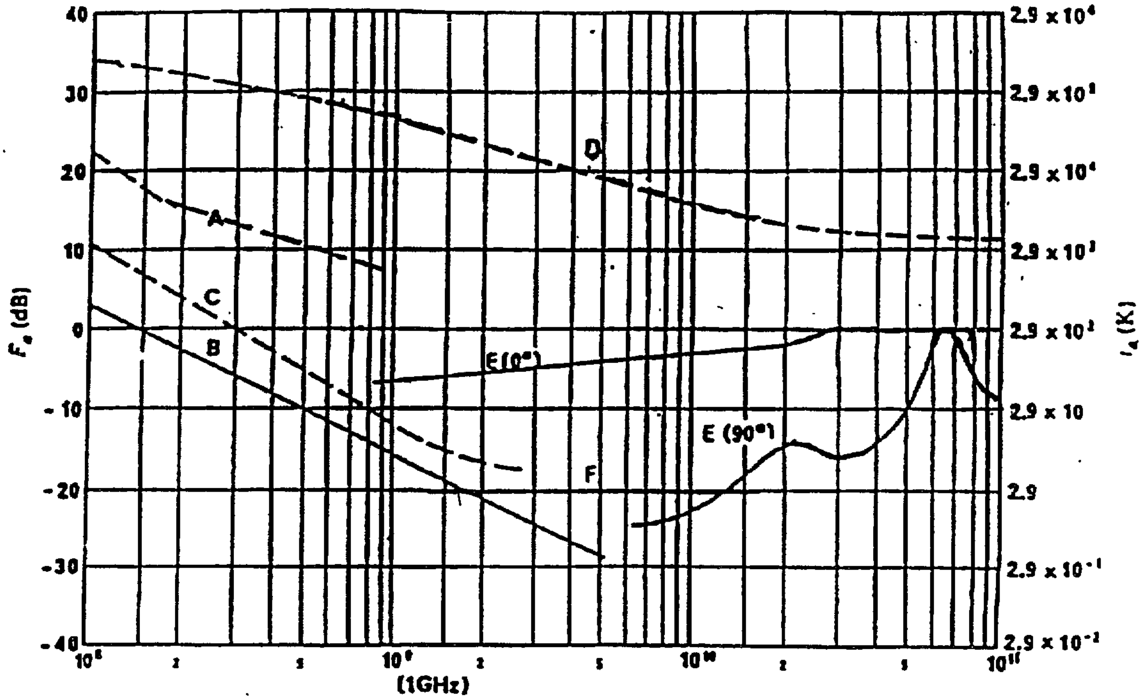
where E_n = $20\log(e_n)$ (dB(µV/m)),
e_n = RMS field strength @V/m),
f_{MHz} = center frequency in MHz,
B = $10\log(b)$, and
b = receiver bandwidth (MHz).

The received power due to the noise, P_n, can be calculated from the field strength using

$$P_n = 10\log\left(\frac{(e_n \cdot 10^{-6})^2}{377}\ \frac{G \cdot l^2}{4p}\right) - 30 \text{ (dBm)}$$

where G = receiver antenna gain (linear). [3]

Figure 5. F_a versus Frequency (100 MHz to 100 GHz) [3]



A. Estimated median business area man-made noise

B. Galactic noise

C. Galactic noise (toward galactic center with infinitely narrow beamwidth)

D. Quiet sun (1/2 degree beamwidth directed at sun)

E. Sky noise due to oxygen and water vapor (very narrow beam antenna; upper curve 0° elevation angle, lower curve, 90° elevation angle

F. Cosmic background, 2.7K

Figure 5 characterizes the noise levels due to galactic noise, sky noise, quiet sun, cosmic background and estimated median business area man-made noise. The highest noise levels are measured with a l/2 degree beamwidth antenna directed at a quiet sun. Since DSRC systems will likely never direct a narrowband antenna toward the sun, this noise is of little consequence.

The next highest source of noise is the median business area man-made noise. Measurements indicate that this noise is almost entirely due to automotive ignition noise. The measurements that derived this curve in Figure 5 were taken in the mid 1970's and other sources [4] have shown that the automotive ignition noise level is now substantially lower, about 5 dB at the frequencies of interest here. [4] Given that these results are general background noise levels and may not consider the noise level on the roadway itself, it is probably safer to use the levels in Figure 5 when estimating noise due to automotive ignition and its effects on DSRC systems.

The only natural source of noise or interference which is not shown in Figure 5 is lightning. Lightning produces significant interference at frequencies below 100 MHz, but is not significant at the frequencies considered for DSRC in this analysis, especially at 5.8 GHz. [5] Therefore, further analysis of interference due to lightning is not considered in this report.

The effect of the unintentional emitters on the performance of the DSRC system performance is straight-forward analysis. If the noise power from the unintentional emitters (man-made or natural) is significantly higher than receiver noise power (see Section 2.1) and the interference power due to other DSRC and non-DSRC emitters (see Sections 2.2.1 and 2.2.2) , then use the power level for the unintentional emitters in determining the maximum operating range of the DSRC system under study.

2.3 Physical Effects

In this section, an overview of the effects of blockage/diffraction and multipath will be considered. General theory for evaluating the effects of these physical situations on the performance of DSRC systems will be presented. The specific method and calculations required to perform the analysis of diffraction and multipath can use the results presented in this section. However, the precise methodology for assessing the performance of the DSRC systems is highly dependent on the physical implementation of the system.

2.3. I Diffraction Calculations

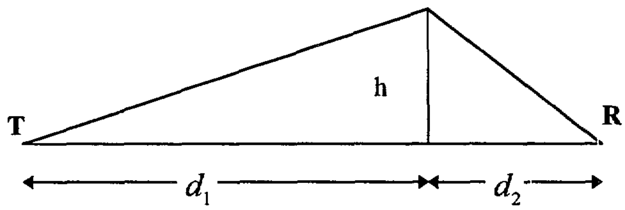
2.3.1.1 Introduction

This section serves three functions. It summarizes the correct analytical formulations required to do knife-edge diffraction loss, it provides a simplified means of doing those calculations, and it then summarizes how knife-edge diffraction can be taken account of in some simple, baseline vehicle-beacon scenarios. Knife edge diffraction can then be used to estimate diffraction around objects which block the line of sight between the DSRC transceivers.

2.3.1.2 Results from Classical Diffraction Theory

In the developments of this section, the parameter v, a kind of height parameter normalized to wavelength, plays an important role. This parameter is expressed in terms of the parameters defined in Figure 6. Any actual diffraction problem geometry must be

Figure 6. Diffraction geometry



mapped onto this geometry. What appears here as the linear distance between T and R, must be measured along the line of sight, h being the length of the orthogonal projection from the knife-edge diffraction point onto the LOS path.

In terms of the quantity [8]

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}$$

and the Fresnel integrals

$$C(v) = \int_0^v \cos\left(\frac{\pi}{2}t^2\right)dt \qquad \text{and} \qquad S(v) = \int_0^v \sin\left(\frac{\pi}{2}t^2\right)dt$$

the complex ratio of the field that exists due to diffraction to the field that would have existed had there been no knife edge is

$$F(v) = \frac{E}{E_0} = \frac{(1+j)}{2}\left[X(v) - jY(v)\right]$$

where

$$X(v) = \frac{1}{2} - C(v) \qquad \text{and} \qquad Y(v) = \frac{1}{2} - S(v)$$

2.3.1.3 Approximations to Classical Diffraction Theory

It is a simple matter to take the magnitude-squared value of *F(v),* represent it in decibels, and then take the derivative to obtain

$$\frac{d}{dv}\left[|F(v)|^2\right]_{dB} = \frac{10}{\ln 10}\frac{1}{|F(v)|^2}\frac{d}{dv}\left[|F(v)|^2\right]$$
$$= \frac{20}{\ln 10}\cdot\frac{X(v)X'(v)+Y(v)Y'(v)}{X^2(v)+Y^2(v)}$$

Evaluating this expression at the zero point, we have

$$\left.\frac{d}{dv}\left[|F(v)|^2\right]_{dB}\right|_{v=0} = \frac{-20}{\ln 10} = -8.69 \text{ dB}$$

which immediately gives the linear approximation for the region centered at v=0.

Two approximations were used for simple diffraction loss calculations. The expressions give the signal level in dB according to the following:

$$FdB(v) = \begin{cases} -6-8.69v & |v|<1 \\ 20\log\left(\frac{.225}{v}\right) & v \geq 1 \end{cases}$$

The first of these, as described above, was developed at GTRI for this program. The second is due to Lee [7]. Because of a discontinuity at the point $v=1$, these curves were spliced together over a region $v_1 \leq v \leq v_2$ containing the $v=1$ point. Using weighting functions defined according to

$$w_L(v) = 1-\frac{v-v_1}{v-v_2} \quad \text{and} \quad w_R(v) = 1-\frac{v_2-v}{v_2-v_1}$$

and defining the left-hand ($|v|<1$) and right-hand ($v \geq 1$) expressions

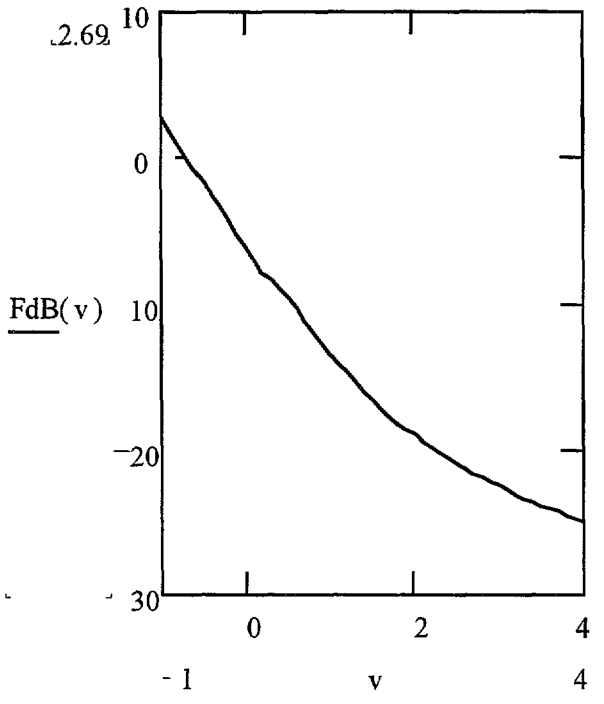
$$FLdB(v) = -6-8.69v \qquad |v|<1$$
$$FRdB(v) = 20\log\left(\frac{.225}{v}\right) \qquad v \geq 1$$

we use

$$FdB(v) = \begin{cases} FLdB(v) & v < v_1 \\ w_L(v) FLdB(v) + w_R(v) FRdB(v) & v_1 \le v \le v_2 \\ FRdB(v) & v > v_2 \end{cases}$$

for the smooth curve expression covering both ranges. The plot resulting from this expression is shown in Figure 7 (using $v_1 = 0.75$ and $v_2 = 1.25$) and aligns very precisely with the classical results that are calculated with much greater labor. [8]

Figure 7. Diffraction loss



2.3.1.4 Sample Calculation

In order to exercise the derived mathematical results and develop some insights into the manner in which results will differ according to the different operating frequencies, we set up a "snapshot" calculation of an electronic toll collection (ETC) scenario. In this scenario, a relatively large truck (18' high) is followed by a much smaller vehicle (receiving antenna 3' off the ground). The car is closely following the truck such that the antenna of the smaller vehicle is 15' behind the truck. The ETC fixed antenna is mounted at a height of 21' and the antenna beam is elevated 60° from downward vertical toward the oncoming traffic. The "snapshot" takes place at just that instant that the trailing top corner of the truck passes through the center of the antenna beam.

The physical situation described above must be mapped onto the geometry used to define the parameters in Figure 6. Although tedious, there are no conceptual challenges to such a mapping and the results are:

$$h = 1.19$$
$$d_1 = 5.88$$
$$d_2 = 21.17$$

The one remaining undefined parameter in the definition of v is the wavelength (frequency). These are:

$$f_1 = 915MHz \quad (l = 1.07 \text{ ft})$$
$$f_2 = 5.8Ghz \quad (l = .17\text{ft})$$

For each of these, the parameters VP and VP follow easily and the corresponding signal levels S, and S, can easily be calculated from the equations above. Corresponding to the frequencies just given, these values are:

$$S_1 = -11.45\text{dB and } S_2 = -18.70\text{dB}$$

Therefore, blockage has a significantly greater impact on the received power at the vehicle at 5.8 GHz than at 915 MHz.

2.3.2 Multipath Calculations

Multipath between beacons and vehicles, unless specific efforts are made to avoid it, can be an extremely degrading influence on communications --- and extremely difficult to analyze.

Despite the complexity of multipath phenomena, insights into multipath can be gained by considering some very simple models. It is reasonable, in developing simple guideline equations for calculating the effects of multipath, to ignore the free space loss of the LOS path, which can be calculated separately using simple expressions, and concentrate on the effects of the multipath.

The simplest multipath model of all is the single reflection model. This model consists of two antennas at heights h_1 and h_2, each separated from a ground reflection point by distances d_1 and d_2 respectively. The direct LOS path of distance R between the antennas differs from the length of the reflected path in such a way as to introduce a delay difference t (t) between the two paths. In the current application, this delay difference, ofcourse, is generally time-varying due to the motion of the vehicle.

2.3.2.1 Fade Spacing

For the model described above, the deep fade centers occur whenever

$$f \cdot t(t) = n \qquad n=0, \pm1, \pm2;$$

i.e. whenever the delay difference t (t) changes by an amount

$$\Delta\tau = \frac{1}{f}$$

From this it follows immediately that for some $f_2 > f_1$, it follows that $\Delta\tau_2$, is smaller than $\Delta\tau_1$, by an amount $f_1 \mid f_2$, i.e.

$$\Delta\tau_2 = \frac{f_1}{f_2} \cdot \Delta\tau_1$$

For f_1 = 915 MHz and f_2 = 5.8 GHz, the ratio is 0.158. The result of this analysis shows that the fades will occur much more frequently for a DSRC system operating at 5.8 GHz than for a similarly configured system operating at 915 MHz. The effects of the decreased fade intervals at 5.8 GHz are dependent on the difference in data rate, modulation and coding between the systems operating at the different frequencies. The actual calculations of the fade interval are highly dependent on the actual configuration of the DSRC system. This analysis presents only a comparison of the fade intervals.

2.3.2.2 Fade Durations

For the simple model given above, the complex representation of the fading on a single tone of frequency f is given by

$$s(t) = (1 + a(t)e^{-j2\pi\tau(t)})e^{-j2\pi t})$$

where τ (t) is the delay difference and $\alpha(t)$ is the generally time-varying reflection coefficient. For movement of the vehicle through a small localized area it is reasonable to treat the reflection coefficient as if it were constant.

By examining a phasor diagram, drawing a fade circle of radius L and a rotating phasor arm of length a l, it is possible to determine the fraction of the phasor rotation cycle that the resultant phasor has magnitude less than L. The result is the fraction of time that that fades are below the level L. This formula is given by

$$G(L,a) = \left(\frac{\alpha}{\pi}\right) \cos^{-1}\left\{\frac{1}{2\alpha}[1+(a^2 - L^2)\right\}$$

This expression has not yet been plotted or checked other than in a trivial way, and may need to be modified. Note, however, that it does not depend on frequency. To obtain the amount of absolute time that a fading signal spends below a certain level, one must first determine the fade spacing as in the previous section. Fade spacing or interval, definitely dependent on frequency, are equal to the period of the rotation of the phasor. One then

[1] To get non-zero results, this must be done in such a way that $1 - \alpha < L$.

multiplies by the fraction given here, G, to determine the true, absolute duration of time (over one period) that the signal will spend below a certain level.

Note that G can also be used to give a rough estimate of the bit error rate (BER) of the channel due to fading. If it is determined that a fade less than *L* results in random bit sequences being received, then the average BER due to fading is approximately 0.5/G. If the DSRC system is using a sufficient interleaver, then the bit errors can be assumed to be randomly occurring (as opposed to burst errors).

Other simple multipath models for specific implementations of DSRC systems have been assessed through computer modeling. One particular paper analyzed an ETC system and demonstrated that the multipath environment differed depending on the type of vehicle passing through the toll collection zone. In this example, the primary multipath reflector for a car was the hood, but for a van with no hood the primary reflector was the road surface. These two vehicles had dramatically different multipath characteristics. **[9]**

3.0 Conclusions and Overview of the Environmental Analysis Methodology

The exact "methodology" for evaluating a particular DSRC system will ultimately depend on the system configuration and implementation. The methods of evaluation presented in Section 2.0 provide the basic tools for conducting a system-level analysis of the performance of DSRC systems.

Section 2.1 provides the equations necessary to calculate maximum communications range for a given system. In this analysis, only basic propagation is considered. Equations for free space propagation are included. Also provided is an equation for estimating the mean received power for longer range DSRC systems including the basic effect of multipath (not fading). The analysis shows that weather will have very little effect on the performance of DSRC systems operating in either the 902-928 MHz or the 5.8 GHz frequency bands. Therefore, only basic propagation equations need to be considered.

Section 2.2 demonstrates the analysis methods for the consideration of interference. This section provides the formulas for deriving noise or interference power levels. These interference power levels can be used in place of or in connection with the receiver noise level in Section 2.1 to derive the maximum operating range for the DSRC systems.

The analysis of the interference due to other emitters in the frequency band of the DSRC (Section 2.2.1) is conducted using modified free space equations to account for off-boresight antennas and mismatched bandwidths. Surveys of the spectrum around Denver, Colorado are the basis for the analysis of the general effects of non-DSRC emitters (Section 2.2.2). These provide a basic background noise level over the frequency bands of interest.

Unintentional emitters and natural noise sources are considered in Section 2.2.3. It is shown that the primary noise source is automotive ignition noise. Natural noise sources have considerably lower power than the ignition noise. Graphs and equations for estimating the background noise due to automotive ignitions are provided.

Section 2.3 presents the basic equations and theoretical results necessary to assess the effects of diffraction and fading. The diffraction results (Section 2.3.1) can be used to estimate the reduction in signal levels due to antenna blockage for very short range DSRC systems such as those used in electronic toll collection. Longer range blockage results will probably be best assessed using the theoretical Rician fading environment [l0].

The multipath environment (Section 2.3.2) is perhaps the most difficult environment to develop a simple methodology for analysis. The multitude of possible DSRC configurations makes defining a single model impossible. Multipath analysis is therefore characterized in this analysis by viewing a 2-ray multipath model. Using this model, an estimate of the fade intervals and the fraction of time in a fade is calculated. These parameters are highly dependent on frequency, physical implementation, and the coefficient of reflection of the surrounding objects (road surface, car hood, buildings, etc.),

This report provides the framework for analyzing primarily the maximum operating ranges of DSRC systems. Some analysis of the effects of multipath are also provided. To assess more detailed parameters such as bit error rate (BER), protocol performance or effective data rate will require analysis very specific to the individual DSRC system. The modulation, coding and link protocols will have to be evaluated. To summarize the methods for analyzing each type of DSRC system to this level of detail is beyond the scope of this report. Several good mobile communications, coding theory and network technical reference books exist which cover these analysis techniques.

The methods of analysis provided in this report will be modified, updated or added to as necessary to perform the analysis of the DSRC systems.

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Appendix F: Message Database

1.0 Introduction

This appendix contains the estimated message data expected to be transferred during DSRC sessions. Each message is part of a set that makes up a transaction. A transaction (message set) is a complete communications session that implements a data transfer between the roadside and a vehicle. It usually consists of the following sequence of events:

- The roadside device sends a message to the vehicle requesting data;
- The vehicle device responds with data;
- The roadside device sends a message adding data to the vehicle system;
- The vehicle device confirms that the data was received; and
- The roadside device sends a sign off notification.

However, transactions sometimes consist of only three messages. When the data flow does not need confirmation, three messages are used as follows:

- The roadside device sends a message to the vehicle requesting data;
- The vehicle device responds with data; and
- The roadside device sends a sign off notification.

A special case exists for some transactions, i.e., in-vehicle signing. These transactions may send a single message to all vehicles, as a broadcast, and do not request confirmation. This is a special case of data transfer for transaction types that already have message sets with three or five messages. The single message variant is not listed because it does not increase the number of transaction types or affect the maximum estimated data rate.

2.0 Message Map

The message map (MSG_MAP) is a database that contains information about the DSRC messages. Each record (row) contains information about a single message in the database. The database fields and information content are listed below:

- ID - Database row number;
- Physical Flow - Transaction name from Architecture documents;
- Architecture Flow - Architecture Flow name from Architecture documents;
- Message - Message name; from CVO User Requirements or ARINC Estimate;
- Src - Source;
- Dst - Destination;
- Data Element and Data Size, in bits, numbered 1 to 25; and
- Message Size; the sum of the data sizes in the row.

Architecture names do not exist for all the messages because the message structures were developed from additional analysis performed to produce the CVO User's Requirements and from additional ARINC analysis. Also, the 25 Data Element and Size fields exist to accommodate the maximum number of data elements assigned to a message. The fields are only filled in for the data proposed for each message. Therefore, a large number of the Data Element fields are blank and many of the Size fields contain zeroes.

The Data Element fields represent the content of the messages and follow format as described below (and illustrated in figure 1):

Header Code - The Header defines the start of each message and consists of an 8-bit self-synchronization pattern (Selsyn) and an 4-bit start-of-message flag for a total of 12 bits.

Transaction Code - 16 bit word indicating message purpose. There will be a specific code for each of the data structures listed below. This code will also provide an indication of which version of the message is required.

Message Length - 12 bit field that contains the length of the message in bytes. The byte count includes the cyclic redundancy check (CRC) but not the message length or transaction code.

Message Text - Variable length; Data Elements; sources described below.

CRC - 16 bit word used to detect errors in message transmission. (Although it is included in this discussion of messages, it is actually associated with the communication protocol.)

Header	Transaction Code	Message Length	Message Text	Cyclic Redundancy Check

Figure 1 Data Structure Format

The data elements listed as part of the Message Text were assembled from the Dedicated Short Range Communications Requirements For Commercial Vehicle Operations [1], the ITS Architecture Dedicated Short Range Communications Standards Requirements Package [2] the ITS Logical Architecture [3] and ARINC forecasts of data requirements. The maximum message size is usually in the range of 5 12 bits. Many messages fall in this range. Those messages that are larger than 512 bits would be divided into separate messages in actual operation. However, in order to maintain model simplicity, the approach used in this analysis retains all related data in a single message.

Two messages that are used by multiple message sets are listed below. See the referenced documents for details about the other messages and data elements:

Acknowledgment - This data structure is transmitted by the tag to confirm the reception and write into memory of messages transmitted by the roadside. It includes an 8 bit field that provides the confirmation as well as error diagnosis.
(data element **- Operation-Status)**

Sign-off - This data structure is transmitted by the roadside to end a communication session. It includes an 8 bit field that indicates the duration of time the tag should be deactivated so that it will not attempt to respond to the current reader's request to initiate a transaction. (data element **- Time-Out)**

References

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[2] Loral Federal Systems/Rockwell International, ITS Architecture, Dedicated Short Range Communications Standards Requirements Package, January 1996.

[3] Loral Federal Systems/Rockwell International, ITS Architecture, Logical Architecture, April 1996.

ID	Physical Flow	Architecture Flow	Message	Message Size
1	toll payment	request tag data	Payment ID Request	72
2	toll payment	tag data	Payment ID	240
3	toll payment	tag update	Transaction Status	124
4	parking payment	request tag data	Payment ID Request	72
5	parking payment	tag data	Payment ID	240
6	parking payment	tag update	Transaction Status	124
7	obtain parking fee	request tag data	Payment ID Request	72
8	obtain parking fee	tag data	Obtain Parking Fee	80
9	obtain parking fee	tag update	Parking Fee	124
10	drive-thru_payment		Payment ID Request	232
11	drive-thru_payment	tag data	Payment ID	232
12	drive-thru_payment		Transaction Status	276
13	roadway sign info		Vehicle ID Request	72
14	roadway sign info		Vehicle ID	175
15	roadway sign info	vehicle signage data	Electronic Signage	136
16	entry/exit permission		Gate Access ID Request	72
17	entry/exit permission		Gate Access ID Response	175
18	entry/exit permission		Gate Access Response & Sign_off	72
19	on board safety data	on board safety request	On_Board_ Safety_Data_Request	56
20	on board safety data	on board safety data	On_Board_ Safety_Data_Response	162
21	border clearance request	border clearance request	CV Border Clearance Request	88
22	border clearance request	border clearance data	CV Border Clearance Data	200
23	border clearance request	pass/pull-in & border clearance event record	CV Border Clearance Event	131
24	lock tag data	lock tag data request	Lock Request	56
25	lock tag data	lock tag data	Lock Data	109
26	CV screening request	screening request	CV Screening Request	88
27	CV screening request	screening data	CV Screening Data	1042
28	CV screening request	pass/pull-in & clearance event record	CV Screening Event	310
29	safety inspection record	on board safety request	CV Inspection Request	88
30	safety inspection record	on board safety data	CV Inspection Data	151
31	safety inspection record	pass/pull-in	CV Inspection Event	156
32	Driver's Daily Log		Driver's Daily Log Request	72
33	Driver's Daily Log		Driver's Daily Log	180
34	signal preemption request		Vehicle ID Request	72
35	signal preemption request	emergency vehicle preemption request	Vehicle ID	88
36	/signal preemption request		Signal Preemption Response	104

ID	Src	Dst	Data Element 1	Size 1	Data Element 2	Size 2	Data Element 3	Size 3	Data Element 4	Size 4
1	TCS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
2	VS	TCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
3	TCS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
4	PMS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
5	VS	PMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
6	PMS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
7	PMS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
8	VS	PMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
9	PMS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
10	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
11	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
12	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
13	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
14	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
15	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
16	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
17	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
18	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
19	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
20	CVS	CVCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
21	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
22	CVS	CVCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
23	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
24	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
25	CVS	CVCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
26	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
27	CVS	CVCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
28	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
29	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
30	CVS	CVCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
31	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
32	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
33	CVS	CVCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
34	RS	EVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
35	EVS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
36	RS	EVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12

ID	Data Element 5	Size 5	Data Element 6	Size 6	Data Element 7	Size 7
1	State/Region	8	Group/Agency	8	CRC	16
2	Vehicle_Type	4	Vehicle_Profile	4	Vehicle_Axles	4
3	Group/Agency	8	Plaza_ID	7	Lane_ID	5
4	State/Region	8	Group/Agency	8	CRC	16
5	Vehicle_Type	4	Vehicle_Profile	4	Vehicle_Axles	4
6	Group/Agency	8	Plaza_ID	7	Lane_ID	5
7	State/Region	8	Group/Agency	8	CRC	16
8	Vehicle_Type	4	Vehicle_Profile	4	Vehicle_Axles	4
9	Group/Agency	8	Plaza_ID	7	Lane_ID	5
10	Company_ID	160	Charge_Amount	16	CRC	16
11	Payment_Amount	16	Payment_ID	160	CRC	16
12	Company_ID	160	Payment_Amount	16	Plaza_ID	7
13	State/Region	8	Group/Agency	8	CRC	16
14	Vehicle_Identification_Number	119	CRC	16		0
15	Electronic Signage	80	CRC	16		0
16	State/Region	8	Group/Agency	8	CRC	
17	Vehicle_Identification_Number	119	CRC			
18	Entry/exit permission	8	Time_Out	8	CRC	
19	CRC					
20	Wheel_Based_Vehicle_Speed	24	Engine_Speed	16	Anti-lock_Brake_Active	2
21	Roadside_ID	32	CRC	16		0
22	Trip_ID	60	Roadside_ID	32	Roadside_Date	9
23	Roadside_ID	32	Roadside_Date	9	Roadside_Time	11
24	CRC	16		0		0
25	Roadside_ID	32	Roadside_Date	9	Roadside_Time	11
26	Roadside_ID	32	CRC	16		0
27	Carrier_Unique_ID	96	Vehicle_VIN_Power_Unit	102	Vehicle_VIN_Other_Components	108
28	Roadside_ID	32	Roadside_Date	9	Roadside_Time	11
29	Roadside_ID	32	CRC	16		0
30	Roadside_ID	32	Roadside_Date	9	Roadside_Time	11
31	Roadside_ID	32	Roadside_Date	9	Roadside_Time	11
32	State/Region	8	Group/Agency	8	CRC	16
33	Driver_Screening_Identification	92	Hours_in_service	16	Hours_resting	16
34	State/Region	8	Group/Agency	8	CRC	16
35	Signal_Preemption_Request	2	Time	18	Agency_Specific_Data	12
36	Password	18	Reader_ID	12	Seconds	18

ID	Data Element 8	Size 8	Data Element 9	Size 9	Data Element 10	Size 10	Data Element 11
1		0		0		0	
2	Agency_Specific_Data	12	Fare_Payment_ID	160	CRC	16	
3	Seconds	32	Fare_Payment_Amount	16	CRC	16	
4		0		0		0	
5	Agency_Specific_Data	12	Fare_Payment_ID	160	CRC	16	
6	Seconds	32	Fare_Payment_Amount	16	CRC	16	
7		0		0		0	
8	Agency_Specific_Data	12	CRC	16		0	
9	Seconds	32	Fare_Payment_Amount	16	CRC	16	
10		0		0		0	
11		0		0		0	
12	Lane_ID	5	Seconds	32	CRC	16	
13		0		0		0	
14		0		0		0	
15		0		0		0	
16		0		0		0	
17		0		0		0	
18		0		0		0	
19		0		0		0	
20	Tire_Temperature (bits per tire)	16	Tire-Pressure (bits per tire)	8	Brake Application_Pressure	8	Brake_Primary_Pressure
21		0		0		0	
22	Roadside_Time	11	Trip_Vehicle_Gross_Weight	12	Trip_Cargo_Release_Status	1	Trip_Vehicle_Release_Status
23	Trip_Vehicle_Gross_Weight	12	Trip_Cargo_Release_Status	1	Trip_Vehicle_Release_Status	1	Trip_Driver_Release_Status
24		0		0		0	
25	Shipment_Lock_Status	1	CRC	16		0	
26		0		0		0	
27	Vehicle_VIN_Other Components	102	Vehicle_VIN_Other_Components	102	License_Number	174	Shipment_Type
28	Trip_Vehicle_Gross_Weight	12	Trip_Vehicle_Num_Axles	4	Trip_Vehicle_Wgt_Axle1	12	Trip_Vehicle_Wgt_Axle2
29		0		0		0	
30	Vehicle_Inspection_Level	6	Vehicle_CVSA_Certification_Flag	1	Vehicle_CVSA_Expire_Date	36	CRC
31	Veicle_Inspection_Level	6	Vehicle_CVSA_Certification_Flag	6	Vehicle_CVSA_Expire_Date	36	VCRC
32		0		0		0	
33	CRC	16		0		0	
34		0		0		0	
35	CRC	16		0		0	
36	CRC	16		0		0	

ID	Data Element 15	Size 15	Data Element 16	Size 16	Data Element 17	Size 17	Data Element 18	Size 18
1		0		0		0		0
2		0		0		0		0
3		0		0		0		0
4		0		0		0		0
5		0		0		0		0
6		0		0		0		0
7		0		0		0		0
8		0		0		0		0
9		0		0		0		0
10		0		0		0		0
11		0		0		0		0
12		0		0		0		0
13		0		0		0		0
14		0		0		0		0
15		0		0		0		0
16		0		0		0		0
17		0		0		0		0
18		0		0		0		0
19		0		0		0		0
20	CRC	16		0		0		0
21		0		0		0		0
22		0		0		0		0
23		0		0		0		0
24		0		0		0		0
25		0		0		0		0
26		0		0		0		0
27	Roadside_Date	9	Roadside_Time	11	Trip_Vehicle_Gross_Weight	12	Trip_Vehicle_Num_Axles	4
28	Trip_Vehicle_Wgt_Axle6	12	Trip_Vehicle_Wgt_Axle7	12	Trip_Vehicle_Wgt_Axle8	12	Trip_Vehicle_Wgt_Axle9	12
29		0		0		0		0
30		0		0		0		0
31		0		0		0		0
32		0		0		0		0
33		0		0		0		0
34		0		0		0		0
35		0		0		0		0
36		0		0		0		0

ID	Size 11	Data Element 12	Size 12	Data Element 13	Size 13	Data Element 14	Size 14
1	0		0		0		0
2	0		0		0		0
3	0		0		0		0
4	0		0		0		0
5	0		0		0		0
6	0		0		0		0
7	0		0		0		0
8	0		0		0		0
9	0		0		0		0
10	0		0		0		0
11	0		0		0		0
12	0		0		0		0
13	0		0		0		0
14	0		0		0		0
15	0		0		0		0
16	0		0		0		0
17	0		0		0		0
18	0		0		0		0
19	0		0		0		0
20	8	Brake_Secondary_Pressure	8	Hydraulic_Retarder_Pressure	8	Steering_Axle_Temperature	8
21	0		0		0		0
22	1	Trip_Driver_Release_Status	1	Driver_Signaling	8	CRC	16
23	1	Driver_Signaling	8	CRC	16		0
24	0		0		0		0
25	0		0		0		0
26	0		0		0		0
27	6	Vehicle_CVSA_Expire_Date	24	Roadside_Date	24	Roadside_ID	32
28	12	Trip_Vehicle_Wgt_Axle3	12	Trip_Vehicle_Wgt_Axle4	12	Trip_Vehicle_Wgt_Axle5	12
29	0		0		0		0
30	16		0		0		0
31	16		0		0		0
32	0		0		0		0
33	0		0		0		0
34	0		0		0		0
35	0		0		0		0
36	0		0		0		0

ID	Data Element 19	Size 19	Data Element 20	Size 20	Data Element 21	Size 21	Data Element 22	Size 22
1		0		0		0		0
2		0		0		0		0
3		0		0		0		0
4		0		0		0		0
5		0		0		0		0
6		0		0		0		0
7		0		0		0		0
8		0		0		0		0
9		0		0		0		0
10		0		0		0		0
11		0		0		0		0
12		0		0		0		0
13		0		0		0		0
14		0		0		0		0
15		0		0		0		0
16		0		0		0		0
17		0		0		0		0
18		0		0		0		0
19		0		0		0		0
20		0		0		0		0
21		0		0		0		0
22		0		0		0		0
23		0		0		0		0
24		0		0		0		0
25		0		0		0		0
26		0		0		0		0
27	Trip-Vehicle-Wgt-Axle1	12	Trip-Vehicle-Wgt-Axle2	12	Trip-Vehicle-Wgt-Axle3	12	Trip-Vehicle-Wgt-Axle4	12
28	Trip_Vehicle_Axle_Space1 2	8	Trip-Vehicle-Axle-Space23	8	Trip-Vehicle-Axle-Space34	8	Trip-Vehicle-Axle-Space46	8
29		0		0		0		0
30		0		0		0		0
31		0		0		0		0
32		0		0		0		0
33		0		0		0		0
34		0		0		0		0
35		0		0		0		0
36		0		0		0		0

ID	Data Element 23	Size 23	Data Element 24	Size 24	Data Element 25	Size 25	Data Element 26
1		0		0		0	
2		0		0		0	
3		0		0		0	
4		0		0		0	
5		0		0		0	
6		0		0		0	
7		0		0		0	
8		0		0		0	
9		0		0		0	
10		0		0		0	
11		0		0		0	
12		0		0		0	
13		0		0		0	
14		0		0		0	
15		0		0		0	
16		0		0		0	
17		0		0		0	
18		0		0		0	
19		0		0		0	
20		0		0		0	
21		0		0		0	
22		0		0		0	
23		0		0		0	
24		0		0		0	
25		0		0		0	
26		0		0		0	
27	Trip_Vehicle_Wgt_Axle5	12	Trip_Vehicle_Wgt_Axle6	12	Trip_Vehicle_Wgt_Axle7	12	Trip_Vehicle_Wgt_Axle8
28	Trip_Vehicle_Axle_Space56	8	Trip_Vehicle_Axle_Space67	8	Trip_Vehicle_Axle_Space78	8	Trip_Vehicle_Axle_Space89
29		0		0		0	
30		0		0		0	
31		0		0		0	
32		0		0		0	
33		0		0		0	
34		0		0		0	
35		0		0		0	
36		0		0		0	

ID	Data Element 27	Size 27	Data Element 28	Size 28	Data Element 29	Size 29	Data Element 30	Size 30
1		0		0		0		0
2		0		0		0		0
3		0		0		0		0
4		0		0		0		0
5		0		0		0		0
6		0		0		0		0
7		0		0		0		0
8		0		0		0		0
9		0		0		0		0
10		0		0		0		0
11		0		0		0		0
12		0		0		0		0
13		0		0		0		0
14		0		0		0		0
15		0		0		0		0
16		0		0		0		0
17		0		0		0		0
18		0		0		0		0
19		0		0		0		0
20		0		0		0		0
21		0		0		0		0
22		0		0		0		0
23		0		0		0		0
24		0		0		0		0
25		0		0		0		0
26		0		0		0		0
27	Trip_Vehicle_Wgt_Axle9	12	Trip_Vehicle_Axle_Space12	8	Trip_Vehicle_Axle_Space23	8	Trip_Vehicle_Axle_Space34	8
28	Trip_Vehicle_Scale_Quality	4	Clearance_Screening_Bypass_Flag	8	Vehicle_css_Flag	1	Driver_css_Flag	1
29		0		0		0		0
30		0		0		0		0
31		0		0		0		0
32		0		0		0		0
33		0		0		0		0
34		0		0		0		0
35		0		0		0		0
36		0		0		0		0

ID	Data Element 31	Size 31	Data Element 32	Size 32	Data Element 33	Size 33	Data Element 34	Size 34
1		0		0		0		0
2		0		0		0		0
3		0		0		0		0
4		0		0		0		0
5		0		0		0		0
6		0		0		0		0
7		0		0		0		0
8		0		0		0		0
9		0		0		0		0
10		0		0		0		0
11		0		0		0		0
12		0		0		0		0
13		0		0		0		0
14		0		0		0		0
15		0		0		0		0
16		0		0		0		0
17		0		0		0		0
18		0		0		0		0
19		0		0		0		0
20		0		0		0		0
21		0		0		0		0
22		0		0		0		0
23		0		0		0		0
24		0		0		0		0
25		0		0		0		0
26		0		0		0		0
27	Trip_Vehicle_Axle_Space45	8	Trip_Vehicle_Axle_Space56	8	Trip_Vehicle_Axle_Space67	8	Trip_Vehicle_Axle_Space78	8
28	CRC	16		0		0		0
29		0		0		0		0
30		0		0		0		0
31		0		0		0		0
32		0		0		0		0
33		0		0		0		0
34		0		0		0		0
35		0		0		0		0
36		0		0		0		0

ID	Data Element 35	Size 35	Data Element 36	Size 36	Data Element 37	Size 37	Data Element 38	Size 38
1		0		0		0		0
2		0		0		0		0
3		0		0		0		0
4		0		0		0		0
5		0		0		0		0
6		0		0		0		0
7		0		0		0		0
8		0		0		0		0
9		0		0		0		0
10		0		0		0		0
11		0		0		0		0
12		0		0		0		0
13		0		0		0		0
14		0		0		0		0
15		0		0		0		0
16		0		0		0		0
17		0		0		0		0
18		0		0		0		0
19		0		0		0		0
20		0		0		0		0
21		0		0		0		0
22		0		0		0		0
23		0		0		0		0
24		0		0		0		0
25		0		0		0		0
26		0		0		0		0
27	Trip_Vehicle_Axle_Space89	8	Trip_Vehicle_Scale_Quality	4	Clearance-Screening-Bypass-Flag	8	Vehicle_oos_Flag	1
28		0		0		0		0
29		0		0		0		0
30		0		0		0		0
31		0		0		0		0
32		0		0		0		0
33		0		0		0		0
34		0		0		0		0
35		0		0		0		0
38		0		0		0		0

ze 39	Data Element 40	Size 40
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
1	:RC	16
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0
0		0

ID	Physical Flow	Architecture Flow	Message	Message Size
37	I signaloriorityreauest		Vehicle ID Reauest	72
38	signal priority request	local signal priority request	Vehicle ID	88
39	lsianal oriority reauest		Signal Prioritv Response	104
40	vehicle probe data		Request Vehicle Probe Data	80
41	vehicle probe data	probe data	Vehicle Probe Data	193
42	intersection status		Vehicle ID Request	72
43	intersection status	intersection status	Vehicle ID	193
44	intersection status		Intersection Status	116
45	off-line verification		Off-Line Verification	80
46	off-line verification		Verification Data	712
47	off-line verification		Verification Event	312
48	AHS vehicle data		Vehicle ID Request	72
49	AHS vehicle data	AHS vehicle data	AHS vehicle condition	1241
50	AHS check response		Vehicle ID Request	72
51	AHS check response		Vehicle ID	205
52	AHS check response	AHS check response	AHS data	4153
53	AHS control data update		Vehicle ID Request	72
54	AHS control data update		Vehicle ID	205
55	AHS control data update	AHS control data update	AHS route data	4152
56	Speed and Headway		Speed and Headway Request	72
57	Speed and Headway	AHS management information	Speed and Headway	110
58	transit fleet status		Transit fleet status data ready	64
59	transit fleet status	transit fleet status request	Transit fleet status request	72
60	transit fleet status	transit fleet status response	Transit fleet status response	696
61	traveler information	traveler information requests	Other Services Vehicle Request	2456
62	traveler information	traveler information responses	Other Services Vehicle Response	2456
63	fare enforcement		Request Fare collection vehicle violation information	72
64	fare enforcement	fare payment and status	Fare collection vehicle violation information	480
65	fare enforcement	schedules, fare info, and request processing	Request transit user image	88
66	fare enforcement	fare payment and status	Transit user vehicle image	73784
67	advance payment for services		Reauest Transit Vehicle Advanced Pavment Info	72
68	advance payment for services	fare payment and status	Transit Vehicle Advanced Payment Request	1288
69	advance payment for services	schedules, fare info, and request processing	Transit Vehicle Advanced Payment Response	376
70	transit vehicle passenger and use data		Request tansit management data update	72
71	transit vehicle oassenaer and use data	vehicle measures and vehicle probe data	Transit manaaement data update	2944
72	driver instructions	driver instructions	Driver instructions	92721

ID	SRC	Dst	Data Element 1	Size 1	Data Element 2	Size 2	Data Element 3	Size 3	Data Element 4	Size 4
37	RS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
38	TRVS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
39	RS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
40	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
41	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
42	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
43	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
44	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
45	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
46	CVS	CVCS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
47	CVCS	CVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
48	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
49	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
50	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
51	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
52	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
53	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
54	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
55	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
56	RS	VS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
57	VS	RS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
58	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
59	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
60	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
61	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
62	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
63	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
64	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
65	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
66	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
67	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
68	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
69	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
70	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
71	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
72	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12

ID	Data Element 5	Size 5	Data Element 6	Size 6	Data Element 7	Size 7
37	State/Region	8	Group/Agency	8	CRC	16
38	Signal Priority Request	2	Time	18	Agency_Specific_Data	12
39	Password	18	Reader_ID	12	Seconds	18
40	State/Region	8	Group/Agency	8	Transaction Code	8
41	Vehicle_Identification_Number	119	Seconds	18	CRC	16
42	State/Region	8	Group/Agency	8	CRC	16
43	Vehicle_Identification_Number	119	Seconds	18	CRC	16
44	Password	18	Reader_ID	12	Seconds	18
45	State/Region	8	Group/Agency	8	Transaction Code	8
46	Motor_Carrier_ID	49	Vehicle_Identification_Number	119	Vehicle_Identification_Number	119
47	Verivication_Event_Status	256	CRC	16		0
48	State/Region	8	Group/Agency	8	CRC	16
49	Vehicle_Identification_Number	119	Seconds	18	ahs_data_input	16
50	State/Region	8	Group/Agency	8	CRC	16
51	Vehicle_Identification_Number	119	Seconds	18	Agency_Specific_Data	12
52	ahs_demand_accel_decel_profile	2048	ahs_demand_headway	2048	confirmation_flag	1
53	State/Region	8	Group/Agency	8	CRC	16
54	Vehicle_Identification_Number	119	Seconds	18	Agency_Specific_Data	12
55	ahs_demand_accel_decel_profile	2048	ahs_demand_headway	2048	CRC	16
56	State/Region	8	Group/Agency	8	CRC	16
57	speed	16	headway	8	Seconds	18
58	transit_fleet_status_data_ready	8	CRC	16		0
59	transit_conditions_request	16	CRC	16		0
60	transit_vehicle_conditions	640	CRC	16		0
61	other_services_vehicle_request	2400	CRC	16		0
62	other_services_vehicle_response	2400	CRC	16		0
63	request_fare_collection_vehicle_violation_information	16	CRC	16		0
64	fare_collection_vehicle_violation_information	424	CRC	16		0
65	request_transit_user_image	32	CRC	16		0
66	transit_user_vehicle_image	73728	CRC	16		0
67	request_transit_vehicle_advanced_payment	16	CRC	16		0
68	transit_vehicle_advanced_payment_request	1232	CRC	16		0
69	transit_vehicle_advanced_payment_response	320	CRC	16		0
70	request-transit-management_“pushed”-data-update	16	CRC	16		0
71	paratransit-transit-vehicle-availability	8	transit-vehicle-collected-trip-data	272	transit-vehicle-passenger-data	224
72	approved-corrective-plan	8192	paratransit-transit-driver-instructions	1024	CRC	16

ID	Data Element 8	Size 31	Data Element 32	Size 32	Data Element 33	Size 33	Data Element 34
37		0		0		0	
38	CRC	16		0		0	
39	CRC	16		0		0	
40	CRC	16		0		0	
41		0		0		0	
42		0		0		0	
43		0		0		0	
44	Intersection Status	12	CRC	16		0	
45	CRC	16		0		0	
46	Driver_ID	92	Commodity_Code	4		0	Vehicle-Out-of-Service-Status +
47		0		0		0	
48		0		0		0	
49	ahs_vehicle_data	8	ahs_vehicle_condition	1024	CRC	16	
50		0		0		0	
51	CRC	16		0		0	
52	CRC	16		0		0	
53		0		0		0	
54	CRC	16		0		0	
55		0		0		0	
56		0		0		0	
57	Agency_Specific_Data	12	CRC	16		0	
58		0		0		0	
59		0		0		0	
60		0		0		0	
61		0		0		0	
62		0		0		0	
63		0		0		0	
64		0		0		0	
65		0		0		0	
66		0		0		0	
67		0		0		0	
68		0		0		0	
69		0		0		0	
70		0		0		0	
71	Transit_vehicle_arrival_conditions	1024	Transit_vehicle_deviations_from_schedule	256	Transit_vehicle_eta	216	Transit_vehicle_location
72		0		0		0	

ID	Size 11	Data Element 12	Size 12	Data Element 13	Size 13	Data Element 14	Size 14
37	0		0		0		0
38	0		0		0		0
39	0		0		0		0
40	0		0		0		0
41	0		0		0		0
42	0		0		0		0
43	0		0		0		0
44	0		0		0		0
45	0		0		0		0
46	1	Driver_Out-of-Service_Status *	1	Last_Clearance_Site_Passed	18	Time_when_site_was_passed	32
47	0		0		0		0
48	0		0		0		0
49	0		0		0		0
50	0		0		0		0
51	0		0		0		0
52	0		0		0		0
53	0		0		0		0
54	0		0		0		0
55	0		0		0		0
56	0		0		0		0
57	0		0		0		0
58	0		0		0		0
59	0		0		0		0
60	0		0		0		0
61	0		0		0		0
62	0		0		0		0
63	0		0		0		0
64	0		0		0		0
65	0		0		0		0
66	0		0		0		0
67	0		0		0		0
68	0		0		0		0
69	0		0		0		0
70	0		0		0		0
71	232	transit_vehicle_location_for_deviation	232	transit_vehicle_location_for_store	232	transit_vehicle_schedule_deviation	192
72	0		0		0		0

ID	Data Element 15	Size 15	Data Element 16	Size 16	Data Element 17	Size 17	Data Element 18	Size 18
37		0		0		0		0
38		0		0		0		0
39		0		0		0		0
40		0		0		0		0
41		0		0		0		0
42		0		0		0		0
43		0		0		0		0
44		0		0		0		0
45		0		0		0		0
46	Gross_vehicle_weight	8	No._of_Axles	4	Weight_per_Axle	96	Spacing_between_Axles	112
47		0		0		0		0
48		0		0		0		0
49		0		0		0		0
50		0		0		0		0
51		0		0		0		0
52		0		0		0		0
53		0		0		0		0
54		0		0		0		0
55		0		0		0		0
56		0		0		0		0
57		0		0		0		0
58		0		0		0		0
59		0		0		0		0
60		0		0		0		0
61		0		0		0		0
62		0		0		0		0
63		0		0		0		0
64		0		0		0		0
65		0		0		0		0
66		0		0		0		0
67		0		0		0		0
68		0		0		0		0
69		0		0		0		0
70		0		0		0		0
71	CRC	16		0		0		0
72		0		0		0		0

ID	Data Element 19	Size 19	Data Element 20	Size 20	Data Element 21	Size 21	Data Element 22	Size 22
37		0		0		0		0
38		0		0		0		0
39		0		0		0		0
40		0		0		0		0
41		0		0		0		0
42		0		0		0		0
43		0		0		0		0
44		0		0		0		0
45		0		0		0		0
46	Bypass_Status_from_last_Reader	1	CRC	16		0		0
47		0		0		0		0
48		0		0		0		0
49		0		0		0		0
50		0		0		0		0
51		0		0		0		0
52		0		0		0		0
53		0		0		0		0
54		0		0		0		0
55		0		0		0		0
56		0		0		0		0
57		0		0		0		0
58		0		0		0		0
59		0		0		0		0
60		0		0		0		0
61		0		0		0		0
62		0		0		0		0
63		0		0		0		0
64		0		0		0		0
65		0		0		0		0
66		0		0		0		0
67		0		0		0		0
68		0		0		0		0
69		0		0		0		0
70		0		0		0		0
71		0		0		0		0
72		0		0		0		0

ID	Data Element 23	Size 23	Data Element 24	Size 24	Data Element 25	Size 25	Data Element 26
37		0		0		0	
38		0		0		0	
39		0		0		0	
40		0		0		0	
41		0		0		0	
42		0		0		0	
43		0		0		0	
44		0		0		0	
45		0		0		0	
46		0		0		0	
47		0		0		0	
48		0		0		0	
49		0		0		0	
50		0		0		0	
51		0		0		0	
52		0		0		0	
53		0		0		0	
54		0		0		0	
55		0		0		0	
56		0		0		0	
57		0		0		0	
58		0		0		0	
59		0		0		0	
60		0		0		0	
61		0		0		0	
62		0		0		0	
63		0		0		0	
64		0		0		0	
65		0		0		0	
66		0		0		0	
67		0		0		0	
68		0		0		0	
69		0		0		0	
70		0		0		0	
71		0		0		0	
72		0		0		0	

ID	Data Element 27	Size 27	Data Element 28	Size 28	Data Element 29	Size 29	Data Element 30	Size 30
37		0		0		0		0
38		0		0		0		0
39		0		0		0		0
40		0		0		0		0
41		0		0		0		0
42		0		0		0		0
43		0		0		0		0
44		0		0		0		0
45		0		0		0		0
46		0		0		0		0
47		0		0		0		0
48		0		0		0		0
49		0		0		0		0
50		0		0		0		0
51		0		0		0		0
52		0		0		0		0
53		0		0		0		0
54		0		0		0		0
55		0		0		0		0
56		0		0		0		0
57		0		0		0		0
58		0		0		0		0
59		0		0		0		0
60		0		0		0		0
61		0		0		0		0
62		0		0		0		0
63		0		0		0		0
64		0		0		0		0
65		0		0		0		0
66		0		0		0		0
67		0		0		0		0
68		0		0		0		0
69		0		0		0		0
70		0		0		0		0
71		0		0		0		0
72		0		0		0		0

ID	Data Element 31	Size 31	Data Element 32	Size 32	Data Element 33	Size 33	Data Element 34	Size 34
37		0		0		0		0
38		0		0		0		0
39		0		0		0		0
40		0		0		0		0
41		0		0		0		0
42		0		0		0		0
43		0		0		0		0
44		0		0		0		0
45		0		0		0		0
46		0		0		0		0
47		0		0		0		0
48		0		0		0		0
49		0		0		0		0
50		0		0		0		0
51		0		0		0		0
52		0		0		0		0
53		0		0		0		0
54		0		0		0		0
55		0		0		0		0
56		0		0		0		0
57		0		0		0		0
58		0		0		0		0
59		0		0		0		0
60		0		0		0		0
61		0		0		0		0
62		0		0		0		0
63		0		0		0		0
64		0		0		0		0
65		0		0		0		0
66		0		0		0		0
67		0		0		0		0
68		0		0		0		0
69		0		0		0		0
70		0		0		0		0
71		0		0		0		0
72)		0		0		0		0

ID	Data Element 35	Size 35	Data Element 36	Size 36	Data Element 37	Size 37	Data Element 38	Size 38
37		0		0		0		0
38		0		0		0		0
39		0		0		0		0
40		0		0		0		0
41		0		0		0		0
42		0		0		0		0
43		0		0		0		0
44		0		0		0		0
45		0		0		0		0
46		0		0		0		0
47		0		0		0		0
48		0		0		0		0
49		0		0		0		0
50		0		0		0		0
51		0		0		0		0
52		0		0		0		0
53		0		0		0		0
54		0		0		0		0
55		0		0		0		0
56		0		0		0		0
57		0		0		0		0
58		0		0		0		0
59		0		0		0		0
60		0		0		0		0
61		0		0		0		0
62		0		0		0		0
63		0		0		0		0
64		0		0		0		0
65		0		0		0		0
66		0		0		0		0
67		0		0		0		0
68		0		0		0		0
69		0		0		0		0
70		0		0		0		0
71		0		0		0		0
72		0		0		0		0

ID	Data Element 39	Size 39	Data Element 40	Size 40
37		0		0
38		0		0
39		0		0
40		0		0
41		0		0
42		0		0
43		0		0
44		0		0
45		0		0
46		0		0
47		0		0
48		0		0
49		0		0
50		0		0
51		0		0
52		0		0
53		0		0
54		0		0
55		0		0
56		0		0
57		0		0
58		0		0
59		0		0
60		0		0
61		0		0
62		0		0
63		0		0
64		0		0
65		0		0
66		0		0
67		0		0
68		0		0
69		0		0
70		0		0
71		0		0
72		0		0

ID	Physical Flow	Architecture Flow	Message	Message Size
73	update the in-vehicle kiosk	schedules, fare info, and request processing	Update the in-vehicle kiosk	4915808
74	reservation and fare payment (credit card)	fare payment and status	Request Vehicle Fare Payment	648
75	reservation and fare payment (credit card)	schedules, fare info, and request processing	Transit_Vehicle_Fare_Payment_Debited	64
76	reservation and fare payment (SMART card)	fare payment and status	Request_Vehicle_Fare_Payment	648
77	reservation and fare payment (SMART card)	schedules, fare info, and request processing	Transit_Vehicle_Fare_Payment_Request	72
78	reservation and fare payment (SMART card)	fare payment and status	Transit_Vehicle_Fare_Payment_Confirmation	64
79	transit vehicle conditions		Transit Vehicle Conditions Request	72
80	transit vehicle conditions	vehicle measures and vehicle probe data	Vehicle measures and vehicle probe data	476

ID	Src	Dst	Data Element 1	Size 1	Data Element 2	Size 2	Data Element 3	Size 3	Data Element 4	Size 4
73	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
74	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
75	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
76	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
77	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
78	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
79	TRMS	TRVS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12
80	TRVS	TRMS	Selsyn	8	Flag	4	Transaction_Type	16	Message_Length	12

ID	Data Element 5	Size 5	Data Element 6	Size 6	Data Element 7	Size 7
73	transit_services_for_corrections	248	transit_services_for_eta	112	transit_services_for_vehicle_fares	4915288
74	request_vehicle_fare_payment	592	CRC	16		0
75	transit_vehicle_fare_payment_debited	8	CRC	16		0
76	request_vehicle_fare_payment	592	CRC	16		0
77	transit_vehicle_fare_payment_request	16	CRC	16		0
78	transit_vehicle_fare_payment_confirmation	8	CRC	16		0
79	Transit Conditions Request	16	CRC	16		0
80	transit_vehicle_eta	216	transit_vehicle_schedule_deviations	192	Agency_Specific_Data	12

ID	Data Element 8	Size 8	Data Element 9	Size 9	Data Element 10	Size 10	Data Element 11
73	transit_vehicle_fare_data	104	CRC	16		0	
74		0		0		0	
75		0		0		0	
76		0		0		0	
77		0		0		0	
78		0		0		0	
79		0		0		0	
80	CRC	16		0		0	

ID	Size 11	Data Element 12	Size 12	Data Element 13	Size 13	Data Element 14	Size 14
73	0		0		0		0
74	0		0		0		0
75	0		0		0		0
76	0		0		0		0
77	0		0		0		0
78	0		0		0		0
79	0		0		0		0
80	0		0		0		0

ID	Data Element 15	Size 15	Data Element 16	Size 16	Data Element 17	Size 17	Data Element 18	Size 18
73		0		0		0		0
74		0		0		0		0
75		0		0		0		0
76		0		0		0		0
77		0		0		0		0
78		0		0		0		0
79		0		0		0		0
80		0		0		0		0

ID	Data Element 19	Size 19	Data Element 20	Size 20	Data Element 21	Size 21	Data Element 22	Size 22
73		0		0		0		0
74		0		0		0		0
75		0		0		0		0
76		0		0		0		0
77		0		0		0		0
78		0		0		0		0
79		0		0		0		0
80		0		0		0		0

ID	Data Element 23	Size 23	Data Element 24	Size 24	Data Element 25	Size 25	Data Element 26
73		0		0		0	
74		0		0		0	
75		0		0		0	
76		0		0		0	
77		0		0		0	
78		0		0		0	
79		0		0		0	
80		0		0		0	

ID	Data Element 27	Size 27	Data Element 28	Size 28	Data Element 29	Size 29	Data Element 30	Size 30
73		0		0		0		0
74		0		0		0		0
75		0		0		0		0
76		0		0		0		0
77		0		0		0		0
78		0		0		0		0
79		0		0		0		0
80		0		0		0		0

ID	Data Element 31	Size 31	Data Element 32	Size 32	Data Element 33	Size 33	Data Element 34	Size 34
73		0		0		0		0
74		0		0		0		0
75		0		0		0		0
76		0		0		0		0
77		0		0		0		0
78		0		0		0		0
79		0		0		0		0
80		0		0		0		0

ID	Data Element 35	Size 35	Data Element 36	Size 36	Data Element 37	Size 37	Data Element 38	Size 38
73		0		0		0		0
74		0		0		0		0
75		0		0		0		0
76		0		0		0		0
77		0		0		0		0
78		0		0		0		0
79		0		0		0		0
80		0		0		0		0

ID	Data Element 39	Size 39	Data Element 40	Size 40
73		0		0
74		0		0
75		0		0
76		0		0
77		0		0
78		0		0
79		0		0
80		0		0