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13. ABSTRACT (Maximum 200 words)

The Federal Railroad Administration (FRA) sponsored a project conducted by Transportation Technology Center, Inc. (TTCI) to analyze railroad wireless communication needs and future uses. TTCI examined the railroads' general wireless communication needs and future uses, and analyzed in further detail the railroads' wireless needs in a representative dense urban area. Wireless needs were estimated, gaps were analyzed, and a roadmap for changes, needed developments, and additional spectrum required was developed.

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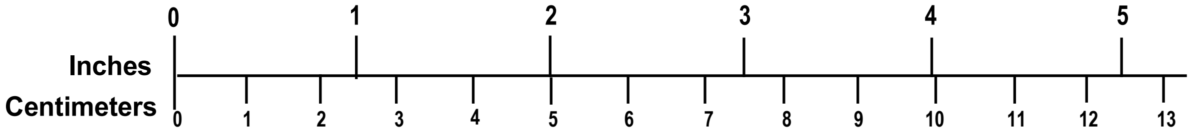

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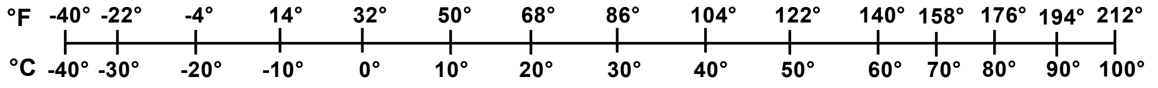

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Executive Summary

From July 2015 to January 2018, Transportation Technology Center, Inc. analyzed the U.S. railroads' current and future wireless data communications needs, predicting significant gaps in available radio frequency (RF) spectrum that will need to be addressed in the coming years, and recommending potential methods to mitigate this shortfall. Specifically, the Federal Railroad Administration (FRA) sponsored TTCI to perform the following tasks:

- To identify the projected future wireless needs of the railroads
- To categorize and quantify these needs
- To identify the gaps between RF spectrum currently available to the railroads and the railroads' predicted needs over time
- To develop a high-level time-phased roadmap to address these gaps

Wireless communication technologies are an important component of a railroad's operations. These technologies enable voice and data communications across a wide range of safety, operational, and business applications that continually become more numerous, complex, and critical. At the same time, global demand and competition for RF spectrum is increasing rapidly.

TTCI, with an industry advisory group (AG):

- Researched wireless applications to assess RF spectrum needs
- Estimated the wireless demand of each application
- Developed a high-level gap analysis of the demand versus available RF spectrum
- Developed a high-level time-phased roadmap to address gaps in the available RF spectrum
- Identified potential tradeoffs associated with assignment of applications to frequency bands
- Identified potential technology developments that may help in addressing the gaps in the available RF spectrum
- Evaluated the additional RF spectrum that may be required to address gaps in the available RF spectrum
- Identified elements to address the railroads' future RF spectrum needs

From the research of railroad applications, estimation of wireless demand, and development of the gap analysis, TTCI and the AG identified a potential deficiency of RF spectrum in the future. Considering only applications that currently use, or are planned to use, railroad spectrum, the currently available spectrum will be exceeded within 5 years. Since the deficit could be large in the outer years, multiple steps will likely be required to close the gap. Therefore, several potential methods to mitigate this growing problem are identified in this report, along with a suggested roadmap of methods when they should be developed.

1. Introduction

The Federal Railroad Administration (FRA) sponsored a project conducted by Transportation Technology Center, Inc. (TTCI) to analyze current railroad wireless data communication needs, identify applications that will require wireless communications in the future, assess currently available radio frequency (RF) spectrum, and develop a roadmap to address gaps between available and needed spectrum over the next 20 years.

1.1 Background

Wireless communication technologies are an important component of a railroad's operations. These technologies enable voice and data communications across a wide range of safety, operational, and business applications that become numerous, complex, and critical. At the same time, global demand and competition for RF spectrum is increasing rapidly.

As the railroads' requirements for additional RF spectrum increase, they will continue to face challenges in obtaining available spectrum to meet their needs. This challenge is underscored by the Federal Communication Commission's intent, stated in its 2010 report titled Connecting America: The National Broadband Plan, "Make 500 megahertz of spectrum newly available for broadband within 10 years."

Without a vision and a strategic plan, additional types of the RF spectrum might not be obtained while still available, resources may be expended on acquiring spectrum that less optimally meets evolving needs, and the limited RF spectrum resources already held by the industry might not be used as efficiently as possible, limiting railroads' capabilities regarding safety, operational, and business applications that increase railroads' efficiency and competitiveness.

1.2 Objectives

The objectives of this project were to:

- Identify the projected future wireless needs of the railroads
- Categorize and quantify these needs
- Identify the gaps between RF spectrum currently available to the railroads and the railroads' projected needs over time
- Develop a high-level time-phased roadmap to address these gaps

1.3 Overall Approach

TTCI conducted this project in close cooperation with an industry advisory group (AG). This AG consisted of representatives from the American Public Transportation Association (APTA), Belt Railway Company of Chicago (BRC), Burlington Northern Santa Fe Railway (BNSF), CSX Transportation, Norfolk Southern Railway (NS), Union Pacific Railroad (UP), Canadian National Railway (CN), and FRA.

To meet the objectives of the project, TTCI, along with the AG, executed the following major tasks.

- Development of a survey, with a list of applications, to assess the current RF spectrum needs for current applications, potential new applications, and expansion of railroad services
- Research on applications identified in the survey
- Review or development of each application's message model
- Review of gathered survey information and generation of a categorized and prioritized list of needs
- Estimation of the wireless demand for each application, in terms of required data rate
- Estimation/categorization of the railroads' total need for RF spectrum, based on required data rates
- Compilation of an inventory of spectrum currently available to the railroads
- Compilation of the utilization of spectrum below 1 GHz in general (not just by railroads)
- Development of a high-level gap analysis on the RF spectrum available to the railroads versus the railroads' predicted needs over time
- Development of a high-level time-phased roadmap to address the gaps in the RF spectrum
- Identification and analysis of potential tradeoffs associated with assigning frequency bands to various applications
- Development of a literature and industry survey to identify potential technology developments that may help in addressing gaps in RF spectrum availability and the railroads' future needs
- Evaluation of the additional RF spectrum that may be required to address gaps in RF spectrum availability and the railroads' future needs
- Identification of elements included in migration plans to address/meet railroads' future RF spectrum needs

1.4 Scope

The scope of this project focused on examining the railroads' general wireless data communication needs and future uses, and analyzed wireless needs in a representative Chicago dense urban area (DUA) where both railroad and other wireless use is the heaviest. Wireless needs from the present to a period of 20 years in the future were estimated, technology gaps were analyzed, a roadmap for changes, needed developments, and additional spectrum required was developed. The project focused on the RF needs of freight and passenger/commuter railroads. The scope of the applications considered was limited to those recommended by the industry AG that supported the effort.

1.5 Organization of the Report

This report is organized into 13 major sections as follows:

- Section 1 provides background information to aid in setting the context for the work performed.
- Section 2 provides an overview of the project tasks.
- Section 3 provides the results of the wireless demand modeling for applications.
- Section 4 provides the forecast for the railroads’ spectrum needs.
- Section 5 categorizes the railroads’ total spectrum needs.
- Section 6 provides an overview of the gap analysis.
- Section 7 provides an overview of potential solutions from new and developing technologies.
- Section 8 identifies the key elements of the mitigation plans.
-
- Section 9 provides an overview of the spectrum owned by the railroads.
- Section 10 provides an overview of the time-phased roadmap.
- Section 11 provides a summary of project findings and recommendations for next steps.

2. Application Identification, Research and Modeling

The following sections summarize the project tasks to identify the applications that require wireless communications, research the communications requirements for these applications, and develop models to quantify the wireless spectrum needs for each.

2.1 Survey of Railroads

TTCI wrote a survey, in the form of a questionnaire, to assess current RF spectrum needs for current applications, potential new applications, and the expansion of railroad services. The survey was composed of an original list of 33 applications that TTCI considered in its assessment of the railroads' wireless needs. Once the survey was developed, TTCI established an AG that consisted of key personnel from each railroad who completed the survey (freight and passenger/commuter). The AG worked with and provided information to TTCI to support the research and modeling of each application's wireless demand. With TTCI working closely with the AG, a consensus was reached pertaining to the anticipated railroad communications needs.

2.2 Application Research

Based on the information provided above, TTCI, together with the AG, researched each application identified in the survey. There were 33 original applications considered, although through coordination with the AG, that number was consolidated to 22 applications.

During the application research, TTCI analyzed and developed:

- A general overview of each application, including actors and key message flows.
- A list and description of each application's primary messages, including origin and destination, approximate message size, and broadcast type.
- Each application's bounce diagram, which describes key message flow or sequence between the different nodes in the system.

The 22 applications that were considered and researched are as follows:

- 01_Interoperable Train Control (ITC) Positive Train Control (PTC)
    - ITC is an interoperable PTC system, with a wireless component, used by freight railroads to prevent train-to-train collisions, overspeed derailments, unauthorized incursions into established work zones, and movement of a train through a mainline switch in the improper position.
- 04_Hi-rail Limits Compliance System (HLCS)
    - The HLCS uses Global Positioning Satellites (GPS) to monitor the locations of hi-rail vehicles when on track, compare the location of the vehicle against the track authorization limits issued to the vehicle, and issue alerts to the operator if the vehicle is operated outside of the authorized limits. The HLCS also uses a Packet Data radio that interfaces with the vehicle's display unit, which also allows the operator of the hi-rail vehicle to notify a dispatcher of emergencies.

- 05_Employee in Charge (EIC) Portable Remote Terminal (PRT)
    - The EIC PRT provides the EIC of railroad roadway workers a wireless, functional interface to a PTC system. The EIC PRT provides a means for the EIC to communicate entry authorization, speed limits, and route for a train approaching Form B protected territory.
- 06_Work Order/Inspection Reporting
    - The work order reporting system uses mobile data terminals installed within a locomotive to enable the crew to report completed work directly from a locomotive to a terminal. The terminal transfers the information from the report to the railroad's host computer system over a data radio network.
- 07_Individual Roadway Worker Protection
    - The roadway worker protection technology is conceived to increase the safety of maintenance-of-way (MOW) workers by improving their situational awareness, and includes worker location monitoring against authorized work zone limits.
- 08_Intra-Loco Consist
    - Intra-loco consist communications refers to the transfer of network data from the computer systems in the lead locomotive to the computer systems in trailing locomotives within the same locomotive consist. This communication takes place on an Ethernet network, currently over the multiple-unit (MU) cables, and possibly wirelessly in the future. The network data being communicated can include vehicle sensor data indicative of vehicle health, commodity condition data, temperature data, weight data, and security data.
- 09_Inter-Loco Consist
    - Inter-loco consist communications refers to the transfer of network data between locomotives in different locomotive consists or other vehicles in the train consist. The communication takes place over a communication channel linking the vehicles in the consist. The communication channel can be implemented using wireless technology or an electric cable system.
- 10_Train Handling Assist-Energy Management and Pacing
    - The train handling assist-energy management system monitors and advises the crew, or controls the speed of a train automatically by controlling the locomotive throttle or dynamic brake. The system serves either as an advisory system or as a cruise control/auto-pilot system. The system monitors the train's position, terrain, train length and weight, speed limits, locomotive performance and braking ability. This information is processed real-time. The pacing system can provide instructions to the train handling assist system in the form of target estimated time of arrivals (ETA) at critical locations for improved schedule adherence and reduced traffic congestion.
- 11_Grade Crossing Monitoring System
    - The grade crossing monitoring system monitors the health and status of the grade crossing, real-time, which includes monitoring the power supply, grade crossing

signals, the presence of train and direction, speed of train, length of train, and crossing gate closures.

- 12_Advance Crossing Activation System
    - The advance crossing activation system is a message-based crossing activation of highway grade crossings in which messages are sent wirelessly from the locomotive to the crossing to indicate the ETA. This system is an overlay for track circuit-based crossings (e.g., to support higher speed trains without increasing track circuit length) or potentially standalone.
- 13_Head-of-Train (HOT)/End-of-Train (EOT) Communications
    - The EOT provides information to the HOT relating to operational conditions and status of the train. This information is provided to the locomotive engineer through the HOT device. This system monitors the brake pipe pressure, arming status, communication status, motion detection, high visibility markers (HVM), brake value, battery state, and battery charge. A newer feature of EOTs can also provide GPS-based location information to help locate missing EOTs and eventually to support rear-of-train protection for train control systems such as moving block.
- 14_Wayside-based Vehicle Monitoring System
    - The wayside-based vehicle monitoring system communicates information from wayside defect detectors to a communication device onboard a rail vehicle. Defect detectors include Wheel Impact Load Detector (WILD), Hot Box, Cracked Wheel Detection, Tread Monitoring, High and Wide, and Dragging Equipment.
- 16_Motes
    - The motes system is a remote-based sensor network that involves mounting “motes,” low-power computers and sensor platforms with a radio, on railcars to monitor operating conditions of the asset being monitored. The motes automatically and dynamically form a “linear mesh” network with multi-hop communications. The motes use this network to communicate with gateways. The gateways can be mounted in the locomotive or at the wayside where the gateway can retrieve both current status and historical measurements from passing motes.
    - The Electronically Controlled Pneumatic (ECP) brake application can send brake control information to rail cars, with locally powered valves, for desired pressure in each cylinder. The ECP brake application allows the locomotive engineer to apply braking force uniformly and near instantaneously to each car in the train. If this application is implemented wirelessly, it may use the motes communication network.
- 17_Centralized Traffic Control (CTC)
    - The CTC system allows control points (CPs) to be operated remotely from a console by one person. The CTC system provides communication between the wayside and the back office for remote control of switches and signals, and monitors the status of the CPs. The CTC system plays a role in preventing conflicting authorities from being granted.
- 19_Multipurpose Onboard Monitoring

    - The Multipurpose Onboard Monitoring application monitors multiple sensor inputs and provides real-time wireless transport. As examples, this application can monitor fuel levels, idle times, train handling, and crew cell phone detection.
- 20_Flexible Operator Location (FOL) for Line of Road
    - The FOL system provides an operator the capability to monitor and control a locomotive from a remote location. The FOL could operate within corridors that have been conditioned with an onboard, wayside, and back office segment providing the FOL systematic monitoring and control of a locomotive over a data communication network.
- 22_Remote Control Locomotive (RCL)
    - The RCL system is installed on locomotives and controls the motive power for the train for use in a yard. A railroad worker, not physically located on the locomotive, operates the train by using a radio transmitter and receiver system.
- 23_Automatic Equipment Identification (AEI) Mobile Reader
    - The AEI mobile reader system scans AEI RF tags mounted to the side of rolling stock. The system detects when a train is present, determines the direction of travel, determines if railcars are missing AEI tags or if the tags no longer work properly, and when the train is out of the system. The system is also used in yards to build a clean train list prior to being sent to other computer systems.
- 24_Yard Fuel Monitoring
    - Yard fuel monitoring is a system used to automatically gauge fuel tanks and report fuel levels over wireless channels.
- 25_Refrigerated Car Management
    - Refrigerated Car Management transmits information about each refrigerated car's location, status, and temperature.
- 30_Drones, Beyond Line of Sight (B-LOS)
    - The Drones B-LOS application allows for B-LOS inspections to support a variety of applications. The B-LOS applications can have a drone flying up to 400 miles away from its operator.
- 31_Differential GPS (DGPS) Correction
    - The DGPS network will use ground-based reference stations that transmit continuously and require data from an array of satellites to calculate corrections. Using the DGPS, locomotive and vehicle location can be precisely calculated.

2.3 Review/Validation of Application Message Models

TTCI frequently met and worked with the AG to review each application’s message model. If additional information was needed by TTCI, an AG point of contact was established for each application.

Initially, only applications that use dedicated railroad spectrum were researched, but FRA and TTCI, based on feedback from the AG, subsequently agreed that the research should include applications that use or will likely use non-railroad owned spectrum as well. For purposes of this report, spectrum is considered non-railroad owned if it is not managed and coordinated by the railroads. It was decided that all applications that might possibly use railroad spectrum in the future will be quantified and included, even if they use non-railroad owned spectrum today. The results produced show spectrum needs both with and without use of non-railroad owned spectrum so that the ramifications of either approach can be understood.

Current and future timeframes were considered for each application researched to produce spectrum needs estimates for the present as well as 5, 10, and 20 years in the future. The AG provided feedback and reached a consensus for each message model developed.

2.4 Approach Methodology to Determine Data Rate and Bandwidth

After determining each application's key message flows and approximate message size, each application was analyzed using the "low usage" or "hybrid" models to establish data rates. TTCI, along with the AG, identified which applications would be analyzed in each model. The low model was used for applications that produce low data rates or are not used frequently. The hybrid model analyzed the more complex or frequently used applications.

The hybrid model used information from a Rail Traffic Controller (RTC) simulation in the DUA to determine message triggers and transmission rates. In addition to being the busiest, the Chicago DUA is the most heavily studied and scrutinized area in the rail industry. TTCI has extensive traffic data for this area in RTC simulation and the area provided the worst-case scenario for train traffic and available spectrum. The RTC simulation contains information to determine the busiest base station and average base stations as shown in Figure 1. Peak traffic time was found to be at 7:41 a.m. Currently, 24 trains are active under the busiest base station area, and four trains are active under an average base station.

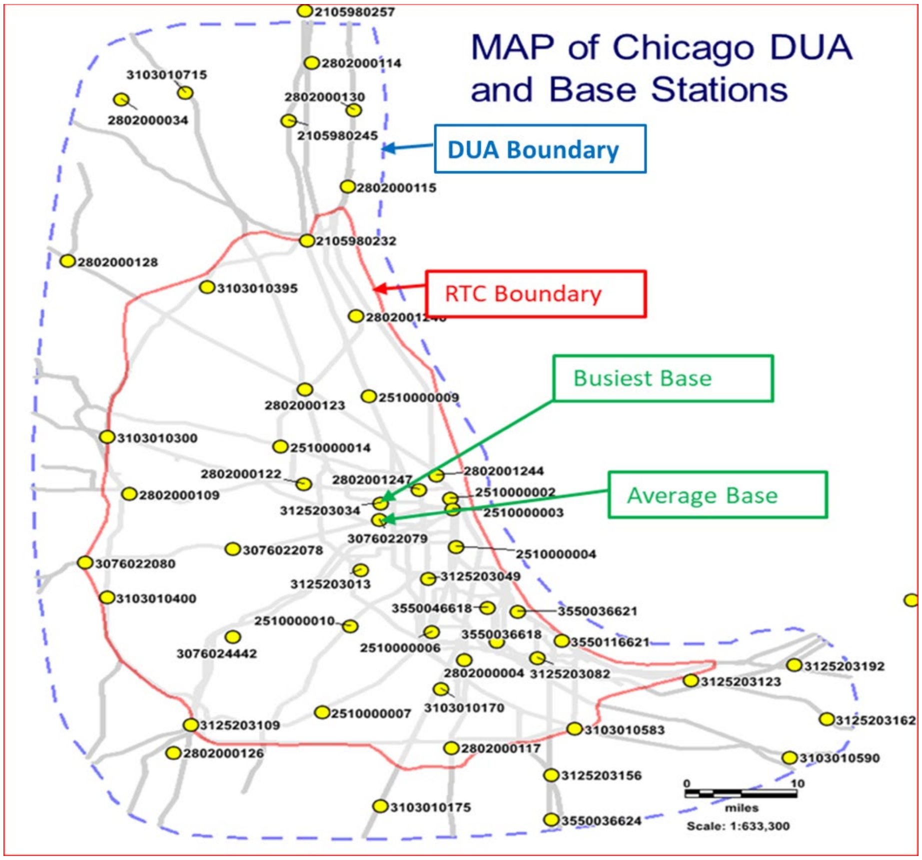


Figure 1. Chicago DUA Base Stations

The RTC simulation provided the number of trains, route miles, grade crossings, CPs, Wayside Interface Units (WIUs), and peak traffic per base station. Figure 2 shows a high-level overview of the two base station coverage areas. A more detailed investigation into the RTC simulation and base station coverage areas resulted in the information in Table 1.

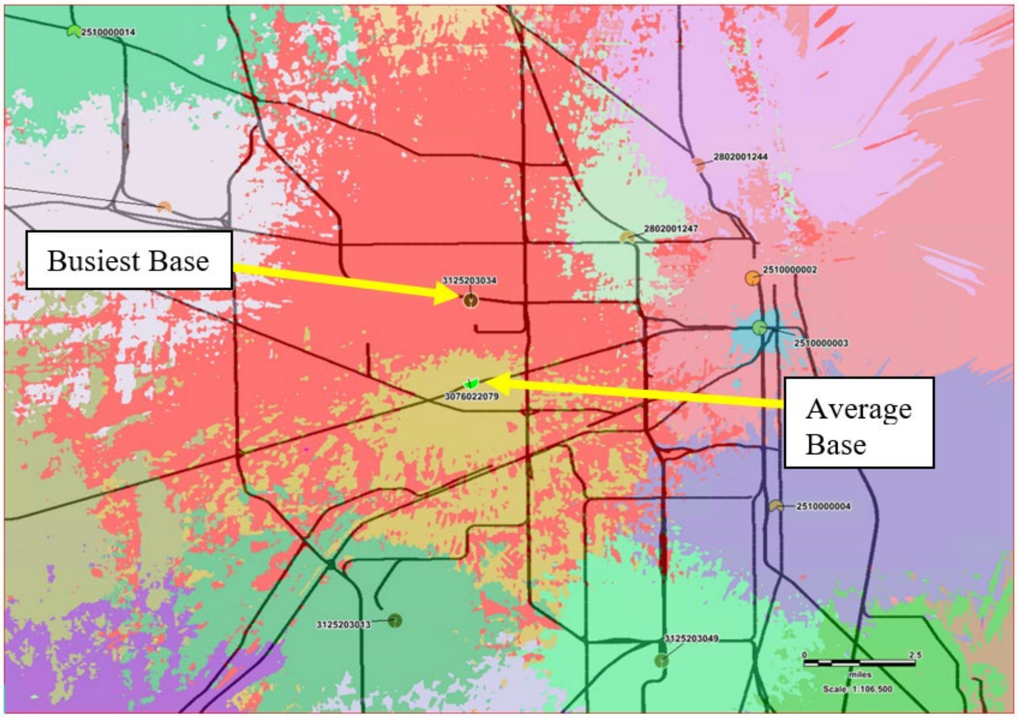


Figure 2. Chicago DUA Base Station Coverage Area

Table 1. Base Stations used in Hybrid Model

Base Station	Average vs. Busiest	Number of Trains	Route Miles	Grade Crossings	CPs	WIUs	Block Size (ft.)
3125203034	Busiest	24	62.7	5	13	45	3,000
3076022079	Average	4	21.7	2	7	17	3,000

The key message flows for each application provide data rates for one instance in the application. The hybrid model used the key message flows and the information from the busiest and average base stations to calculate the data rate during the peak traffic time. The hybrid model considered the current, 5-, 10-, and 20-year timeframes, increases to support more advanced message security, and train traffic. The current timeframe is referenced to the year 2020. Studies have shown that the increase in freight train traffic versus time closely follows the Gross Domestic Product (GDP). For this model, the train traffic was multiplied by an average 1.4 percent per year GDP increase for the 5-, 10-, and 20-year rates. For increased message security, a 96-bit increase every 5 years was assumed. The hybrid model calculated a data rate for each application per timeframe. Whether using the low or hybrid model, the outcome was to determine the overall data rate for all applications. Once the data rates were calculated for each application, the rates were discussed with the AG and agreed upon.

3. Results of Wireless Demand Modeling for Identified Applications

TTCI estimated each application's wireless demand, in terms of required data rate per application, for the busy base station and the average base station scenarios.

Each message in an application was identified, along with its approximate size, message type (broadcast or unicast), and transmission frequency. For the ITC PTC application, the Fixed Frame (F-Frame) and the Dynamic Frame (D-Frame) were considered. To account for the F-Frame, the RTC model was used to determine that Wayside Status Messages (WSM) are transmitted three times every 4 seconds for the busy base and two times every 4 seconds for the average base. This does not include all the WSMs transmitted by waysides, only WSMs transmitted by the busy base station. There are some gaps in the wayside coverage area that require retransmission of WSMs by the base station. All other ITC PTC messages are in the D-Frame.

Table 2 is an example of how a message size was analyzed for applications for which message definitions are documented in the Association of American Railroads' (AAR) Manual of Standards and Recommended Practices (MSRP), in this case MSRP K-4, S-9503.V1.1 [1]. The sizes in red are for variable fields and represent the agreed-upon size that was assumed for the purposes of this project. The additional sizes at the bottom of the table are due to loops in the specified field to account for multiple items and segments.

5.18 (01051) Movement Authority Dataset—Version 4

5.18.1 Description

This message is sent to the locomotive to provide Movement Authority data. This message is sent unsolicited when the office has a new authority to distribute to the locomotive. It also is sent in response to the Request Movement Authority Dataset (02051) message. The locomotive confirms receipt of the message with Confirmation of Movement Authority (02052) message.

5.18.2 Functional Content (see Table 2)

Table 2. ITC PTC Movement Authority Message Analysis

Field	Size (bytes)	Type	Description
Reason for Sending	1	Enumeration	0 = Not used 1 = New authority 2 = Modification of existing authority THIS FIELD IS NOT INCLUDED IN THE CYCLIC REDUNDANCY CHECK (CRC)
Crew Action Required	1	Enumeration	0 = Not used 1 = No crew action required 2 = Crew acknowledge with no response to office 3 = Crew acknowledge with response to office 4 = Crew approval/disapproval THIS FIELD IS NOT INCLUDED IN THE CRC
Railroad Standard Carrier Alpha Code (SCAC)	4	Alphanumeric	Railroad SCAC of the railroad issuing the authority, left-justified space filled

Field	**Size (bytes)**	**Type**	**Description**
PTC Authority Reference Number	4	Numeric	PTC Authority Reference Number
Displayable Movement Authority Reference Number Length	1	Numeric	Length of Displayable Movement Authority Reference Number field
Displayable Movement Authority Reference Number	6	Printable American Standard Code for Information Interchange (ASCII)	Displayable movement authority reference number (see design notes)
Authority Type	1	Enumeration	0 = Not used 1 = Track warrant/track authority 2 = Track and time/track permit 3 = Enter main track 4 = Pass signal at stop 5 = Reserved 6 = Reserved 7 = Reserved 8 = Reserved 9 = Reserved 10 = Reserved 11 = Reserved
Number of PTC Subdivisions/Districts	1	Numeric	Number of PTC subdivisions/districts (1 to 25)
For Each PTC Subdivision/District:			*Repeated as per "Number of PTC Subdivisions/Districts"*
PTC Subdivision/District ID	2	Numeric	PTC subdivision/district identifier (1 to 65,535)
Authority OK Time Stamp	7	Time	Authority OK date and time YYYYMMDDHHMMSS
Number of Authority Void Items	1	Numeric	Number of Authority Void items (0 to 9)
For Each Authority Void Item:			*Repeated as per "Number of Authority Void Items"*
Authority Number to Void	4	Numeric	Movement authority number to void
Number of Authority Segments	2	Numeric	Number of authority segments (0 to 304)
For Each Authority Segment:			*Repeated as per "Number of Authority Segments"*
Authority Segment Direction	1	Enumeration	0 = Not applicable 1 = Unidirectional 2 = Bidirectional
Starting Milepost	4	Numeric	Starting milepost xxxx.xxxx X 10,000
Starting Milepost Prefix Length	1	Numeric	Starting milepost prefix length up to 5 characters
Starting Milepost Prefix	1	Alphanumeric	Starting milepost prefix
Starting Milepost Suffix Length	1	Numeric	Starting milepost suffix length up to 5 characters
Starting Milepost Suffix	1	Alphanumeric	Starting milepost suffix
Ending Milepost	4	Numeric	Ending milepost xxxx.xxxx X 10,000
Ending Milepost Prefix Length	1	Numeric	Ending milepost prefix length up to 5 characters
Ending Milepost Prefix	1	Alphanumeric	Ending milepost prefix

Field	**Size (bytes)**	**Type**	**Description**
Ending Milepost Suffix Length	1	Numeric	Ending milepost suffix length up to 5 characters
Ending Milepost Suffix	1	Alphanumeric	Ending milepost suffix
Track Name Length	1	Numeric	Track name length up to 32 characters
Track Name	1	Alphanumeric	Track name
PTC Subdivision/District ID	2	Numeric	PTC subdivision/district identifier (1 to 65,535)
Track Limit CRC	4	CRC-32	The CRC around the transformation of the authority segments
Number of in Effect After Arrival Items	1	Numeric	Number of In Effect After Arrival Items (0 to 1)
For Each in Effect after Arrival Item:			*Repeated as per "Number of In Effect After Arrival Items"*
At Milepost	4	Numeric	At milepost xxxx.xxxx X 10,000
At Milepost Prefix Length	1	Numeric	At milepost prefix length, up to 5 characters
At Milepost Prefix	1	Alphanumeric	At milepost prefix
At Milepost Suffix Length	1	Numeric	At milepost suffix length, up to 5 characters
At Milepost Suffix	1	Alphanumeric	At milepost suffix
At Track Name Length	1	Numeric	At track name length, up to 32 characters
At Track Name	1	Alphanumeric	At track name
PTC Subdivision/District ID	2	Numeric	PTC subdivision/district identifier (1 to 65,535)
Number of Trains	1	Numeric	Number of trains (1 to 3)
For Each Train:	N/A	N/A	*Repeated as per "Number of Trains"*
Identifying Locomotive ID	10	Alphanumeric	Identifying Locomotive ID
Locomotive Direction	1	Alphanumeric	N, S, E, W
Number of Do Not Foul Limits Ahead/In Effect Behind Items	1	Numeric	Number of Do Not Foul Limits Ahead/In Effect Behind Items (0 to 1)
For Each Do Not Foul Limits Ahead/In Effect Behind Item:	N/A	N/A	*Repeated as per "Number of Do Not Foul Limits Ahead/In Effect Behind Items"*
Number of Trains	1	N/A	Number of trains (1 to 3)
For Each Train:	N/A	N/A	*Repeated as per "Number of trains"*
Identifying Locomotive ID	10	Alphanumeric	Identifying Locomotive ID
Locomotive Direction	1	Alphanumeric	N, S, E, W
Number of Authority Restriction Segments	2	Numeric	Number of authority restriction segments (0 to 308)
For Each Authority Restriction Segment:			*Repeated as per "Number of Authority Restriction Segments"*
Starting Milepost	4	Numeric	Starting milepost xxxx.xxxx X 10,000
Starting Milepost Prefix Length	1	Numeric	Starting milepost prefix length up to 5 characters
Starting Milepost Prefix	1	Alphanumeric	Starting milepost prefix

Field	Size (bytes)	Type	Description
Starting Milepost Suffix Length	1	Numeric	Starting milepost suffix length up to 5 characters
Starting Milepost Suffix	1	Alphanumeric	Starting milepost suffix
Ending Milepost	4	Numeric	Ending milepost xxxx.xxxx X 10,000
Ending Milepost Prefix Length	1	Numeric	Ending milepost prefix length up to 5 characters
Ending Milepost Prefix	1	Alphanumeric	Ending milepost prefix
Ending Milepost Suffix Length	1	Numeric	Ending milepost suffix length up to 5 characters
Ending Milepost Suffix	1	Alphanumeric	Ending milepost suffix
Track Name Length	1	Numeric	Track name length up to 32 characters
Track Name	1	Alphanumeric	Track name
PTC Subdivision/District ID	2	Numeric	PTC subdivision/district identifier (1 to 65535)
Authority Restriction Type	1	Enumeration	0 = Not used 1 = Joint with train 2 = Joint with men and equipment 3 = Joint (unspecified) 4 = Speed restriction
Speed	1	Numeric	Maximum authorized speed for restriction in mph
Number of Stop Short Items	1	Numeric	Number of Stop Short Items (0 to 1)
For Each Stop Short Item:			*Repeated as per "Number of Stop Short Items"*
Milepost	4	Numeric	Milepost xxxx.xxxx X 10,000
Milepost Prefix Length	1	Numeric	Milepost prefix length up to 5 characters
Milepost Prefix	1	Alphanumeric	Milepost prefix
Milepost Suffix Length	1	Numeric	Milepost suffix length up to 5 characters
Milepost Suffix	1	Alphanumeric	Milepost suffix
Track Name Length	1	Numeric	Track name length up to 32 characters
Track Name	1	Alphanumeric	Track name
PTC Subdivision/District ID	2	Numeric	PTC subdivision/district identifier (1 to 65,535)
Signal PTC Subdivision/District ID	2	Numeric	PTC subdivision/district ID where the signal is located (0 to 65,535); see design notes below
Site Name	40	Printable ASCII	Wayside site name where the signal is located
Site Device ID	40	Printable ASCII	Wayside site device ID of the signal where authority is granted
Device Type	1	Enumeration	0 = Not used 1 = Signal
Size of Summary Text	1	Numeric	Size of summary text following up to 80 characters
Body of Summary Text	10	Printable ASCII	Summary text
Number of Lines	1	Numeric	Number of lines of text following 0 to 100
Text Lines:			*Repeated as per "Number of Lines"*
Size of Text	1	Numeric	Size of text following up to 80 characters

Field	Size (bytes)	Type	Description
Body of Text	10	Printable ASCII	Text message to crew
CRC	4	CRC-32	This is the CRC around all the fields from the "Railroad SCAC" through the last field in the message
N/A	245	Subtotal	N/A
N/A	22	Additional Authority Restriction Segment	N/A
N/A	21	Additional Authority Segment	N/A
Message Total	**288**	**Bytes**	N/A

If the message was not defined in the MSRP, then input was gathered from the AG or technical experts to determine the appropriate message sizes. Once the message total was established, the message transmission frequency was determined from the MSRP message description or from input from the AG and technical experts. If a message has more than one trigger, then the individual transmission frequencies were added together. Only messages that appreciably contribute to spectrum use were included in the model. For example, in ITC PTC, the WIU Status Message (msg# 5100) was included since it is transmitted at regular, frequent intervals while the Train Handling Exception Report message (msg# 02085) was not included since it is not regularly nor frequently sent.

In addition to the message payload, the message header size was also included. The Edge Messaging Protocol (EMP), defined in MSRP K-4, S-9354.V1.1, defines the message envelope (header, footer) used to communicate between the various ITC applications. EMP is also used by interoperable non-train control applications (e.g., energy management) [2]. The use of a common envelope facilitates an interoperable infrastructure for message transmission, reception, decoding, and routing. Table 3 shows the EMP Analysis with the assumed message sizes in red. If an application message uses an unknown protocol, then EMP was assumed as the default.

Table 3. Edge Messaging Protocol Analysis

EMP Header Summary			
	Header Field	Field Size (bits)	Definition and Notes
Common	Protocol (header) Version	8	Version of EMP header Each version of the EMP message format specification will define the header version number applicable to that version of the specification
	Message Type (ID)	16	Application message ID The messaging specifications will assign unique Message Type (ID)s
	Message Version	8	Application message version The messaging specifications will define the valid versions of each message and its content
	Flags	8	Flags indicating what options were used in constructing the header
	Data Length	24	Size of message body
Optional	Message Number	32	Application level message sequence number
	Message Time	32	Time of message creation 0 if not supported
	Variable header size	8	Size of the variable portion of the header Time To Live
Variable	Time to Live	16	Message time to live (seconds) Used to aid in routing and bridging
	Source	5	Message source address Null terminated string (Bytes)
	Destination	6	Message destination address Null terminated string (Bytes)
		Message Body	
	Data Integrity	32	CRC or application-specific frame check sequence (e.g., Hash-based Message Authentication Code) 0 if not supported
	Total	32	Bytes

The size of the message payload (in bytes) was added to the size of the EMP overhead. If the message type was broadcast then only one instance of the message was considered during each transmission. If the message type was unicast then the message and overhead were multiplied by the number of receiving nodes for each transmission. For example, in the busy base station scenario, the base station can send a message to 24 trains at the same time with a single broadcast transmission, while a unicast message must be transmitted one at time to each of the 24 trains.

Broadcast message:

(message payload + EMP header) x transmission frequency = required data rate

Unicast message:

(message payload + EMP header) x # nodes x transmission frequency = required data rate

For a low-power application that only communicates within a single train, sharing bandwidth but not going through a base station, a frequency re-use multiplication factor (number of nodes) of 6/20 for a busy base and 3/20 for an average base area was used. The ratio was based on the assumption that six trains could operate relatively close to each other under a busy base station, three trains could operate relatively close to each other under an average base station, and there are 20 PTC channels available in the Chicago DUA. For example, in the 62.7 route miles covered by the busy base station, the assumption is made that only six of the 24 trains would be close enough together to require unique channels for wireless applications that only communicate within a single train and do not use a base station. This adjustment was made due to the shorter transmission range and possibility of efficient channel reuse.

Table 4 through Table 7 show the model results for each base station coverage area over the current, 5-, 10-, and 20-year time periods. All 22 applications are included in the tables below. However, note that some applications are introduced or phased out at different times. Also, some applications evolve over time. For example, the ITC PTC application is assumed to have added capability in 10 and 20 years. Currently, certain factors that can significantly affect future data rate requirements have not been resolved. For example, future PTC implementations will likely use some method for dependably determining train integrity and end of train location. One potential method is the use of PTL technology. Although it may change before being widely deployed, the current PTL design requires a relatively high data rate between end of train and front of train, due to messages being sent every second. Other methods for train integrity and end of train location are conceivable that do not require as much RF bandwidth. For example, if the end of train sent a message with its GPS coordinates to the front of train only at the times when needed to support PTC, a much lower data rate would be required. Realizing that RF spectrum is a precious commodity, the tables and plots shown in this report assume that this lower data rate approach is used for future PTC applications, rather than assuming PTL is used. The analysis tool developed on this project, however, includes models of both approaches so that the higher data rate alternative can be assessed as well, if desired.

Table 4. Wireless Data Rate Demand—Current

Applications	**Sum of Required Data Rate per Transmitting Node (bps) (Busy Base Coverage Area)**	**Sum of Required Data Rate per Transmitting Node (bps) (Avg. Base Coverage Area)**
Advance Crossing Activation	1,680	424
AEI Mobile Reader	1,200	1,200
Centralized Traffic Control	79	21
Crossing Monitoring	14	2
Energy Management System (EMS)/Pacing	71	20
EOT/HOT	12	12
Hi-rail Limits Compliance System	88	88
Inter-Loco Consist (within same train)	394	131
ITC PTC	1,487	611
Multipurpose Onboard Monitoring Applications	445	74
Refrigerated Car Management	1	0
Remote Control Locomotives	9,600	9,600
Wayside-based vehicle monitoring	80	28
Work Order Reporting	1,200	1,200
Yard Fuel Monitoring	1,200	1,200
Grand Total	17,552	14,612

Table 5. Wireless Data Rate Demand—5 Year

Applications	**Sum of Required Data Rate per Transmitting Node (bps) (Busy Base Coverage Area)**	**Sum of Required Data Rate per Transmitting Node (bps) (Avg. Base Coverage Area)**
Advance Crossing Activation	2,063	487
AEI Mobile Reader	1,200	1,200
Centralized Traffic Control	97	23
Crossing Monitoring	15	2
Differential GPS	860	860
Drones	9,400	9,400
EIC PRT Communications	43	26
EMS/Pacing	77	22
EOT/HOT	16	16
Hi-rail Limits Compliance System	97	97
Individual Roadway Worker Protection	31	31
Inter-Loco Consist (within same train)	44,896	14,965
ITC PTC	1,864	691
Multipurpose Onboard Monitoring Applications	565	87
Refrigerated Car Management	2	0
Remote Control Locomotives	9,600	9,600
Wayside-based vehicle monitoring	121	38
Work Order Reporting	1,200	1,200
Yard Fuel Monitoring	1,200	1,200
Grand Total	73,346	39,947

Table 6. Wireless Data Rate Demand—10 Year

Applications	**Sum of Required Data Rate per Transmitting Node (bps) (Busy Base Coverage Area)**	**Sum of Required Data Rate per Transmitting Node (bps) (Avg. Base Coverage Area)**
Advance Crossing Activation	2,482	630
Centralized Traffic Control	115	32
Crossing Monitoring	15	2
Differential GPS	362	362
Drones	305,400	305,400
EIC PRT Communications	50	32
EMS/Pacing	617	179
EOT/HOT	19	19
Hi-rail Limits Compliance System	431	431
Individual Roadway Worker Protection	47	47
Inter-Loco Consist (within same train)	44,998	14,999
Intra-Loco Consist (Coupled Locos)	180,000,000	90,000,000
ITC PTC	6,742	2,031
Motes	137,257	68,459
Multipurpose Onboard Monitoring Applications	698	125
Refrigerated Car Management	2	1
Remote Control Locomotives	9,600	9,600
Wayside-based vehicle monitoring	148	47
Yard Fuel Monitoring	1,200	1,200
Grand Total	180,510,185	90,403,597

Table 7. Wireless Data Rate Demand—20 Year

Applications	**Sum of Required Data Rate per Transmitting Node (bps) (Busy Base Coverage Area)**	**Sum of Required Data Rate per Transmitting Node (bps) (Avg. Base Coverage Area)**
Advance Crossing Activation	3,425	772
Centralized Traffic Control	158	39
Crossing Monitoring	16	2
Differential GPS	410	410
Drones	305,400	305,400
EIC PRT Communications	64	38
EMS/Pacing	659	191
EOT/HOT	26	26
FOL	280,156,041	43,774,381
Hi-rail Limits Compliance System	478	478
Individual Roadway Worker Protection	63	63
Inter-Loco Consist (within same train)	60,269	60,269
Intra-Loco Consist (coupled locos)	180,000,000	90,000,000
ITC PTC	8,346	2,251
Motes	145,397	72,491
Multipurpose Onboard Monitoring Applications	1,003	157
Refrigerated Car Management	3	1
Remote Control Locomotives	9,600	9,600
Wayside-based vehicle monitoring	205	63
Yard Fuel Monitoring	1,200	1,200
Grand Total	460,692,763	134,227,832

4. Forecast of Railroads' RF Spectrum Needs

To determine the bandwidth required for each application, the data rates were converted to spectrum requirements using the approved current ITC PTC spectral efficiency. Rate 1/2 convolutional forward error correction coding was assumed and accounted for by using 16 kbps as the data rate, given a 32-kbps symbol rate. ITC PTC uses π/4-shifted Differential Quadrature Phase Shift Keying (DQPSK) modulation, over 25 kHz channels at 32 kbps symbol rate. This was a reasonable middle-of-the road assumption, since it is used for a major application today (i.e., PTC), it is more efficient than most other applications today, but is less efficient than what might be used for future applications.

One issue to account for in the process of converting data rate to spectrum is contention. The factor (25 kHz/16 kbps) is suitable for anything transmitted from a base station (i.e. "outbound"). However, for anything transmitted to a base station or sent peer-to-peer, contention will reduce the effective throughput. If everything on the channels with contention were sent via carrier-sense multiple access (CSMA), it could be assumed that contention reduces the throughput by a factor of approximately 2 (i.e., 1/2 of the ideal available throughput). However, some of the messages are regular/periodic, which allows the base station to schedule them, improving the throughput. Considering the mix of CSMA and scheduled traffic on those links, it was assumed that the throughput is about 2/3 of what is achievable in the same bandwidth for transmissions from a base that do not incur contention. Therefore, the hybrid model used 25 kHz/16 kbps as the spectral efficiency for the outbound base station traffic and 3/2 x 25 kHz/16 kbps spectral efficiency for all other transmissions.

For transmissions from a base, to determine the amount of spectrum required, the data rate was multiplied by (25 kHz/16 kbps). For all other transmission, to determine the amount of spectrum required, the data rate was multiplied by (3/2)*(25 kHz/16 kbps).

Table 8 through Table 11 show the progression of spectrum demand for each time interval. The below totals for spectrum need may seem large, but note that the applications include all optional heavy bandwidth message traffic such as video and Wireless MU. Also, this section only addresses spectrum demand for a single base station (busy and average), and does not account for frequency reuse throughout the entire DUA. The Chicago DUA total need is addressed in Section 6.

Table 8 and Table 9 are low estimates since the calculated bandwidth assumes $\pi/4$ shifted DQPSK modulation when some of the current and 5-year applications actually use a 2-ary modulation scheme, which requires more bandwidth to transmit the same data as the $\pi/4$ shifted DQPSK modulation. A single modulation scheme was used for simplicity and the assumption that all applications will move towards more efficient modulation schemes in the future.

Table 8. Spectrum Demand – Current

Applications	**Sum of Required Bandwidth (Hz) per Transmitting Node (Busy Base Coverage Area)**	**Sum of Required Bandwidth (Hz) per Transmitting Node (Avg. Base Coverage Area)**
Advance Crossing Activation	3,220	762
AEI Mobile Reader	2,813	2,813
Centralized Traffic Control	124	32
Crossing Monitoring	22	4
EMS/Pacing	157	46
EOT/HOT	29	29
Hi-rail Limits Compliance System	188	188
Inter-Loco Consist (within same train)	923	308
ITC PTC	2,621	1,009
Multipurpose Onboard Monitoring Applications	963	160
Refrigerated Car Management	3	1
Remote Control Locomotives	12,500	12,500
Wayside-based vehicle monitoring	125	43
Work Order Reporting	2,813	2,813
Yard Fuel Monitoring	2,813	2,813
Grand Total	29,311	23,518

Table 9. Spectrum Demand – 5 Year

Applications	**Sum of Required Bandwidth (Hz) per Transmitting Node (Busy Base Coverage Area)**	**Sum of Required Bandwidth (Hz) per Transmitting Node (Avg. Base Coverage Area)**
Advance Crossing Activation	3,960	874
AEI Mobile Reader	2,813	2,813
Centralized Traffic Control	151	36
Crossing Monitoring	23	4
Differential GPS	2,016	2,016
Drones	14,688	14,688
EIC PRT Communications	102	61
EMS/Pacing	169	49
EOT/HOT	37	37
Hi-rail Limits Compliance System	208	208
Individual Roadway Worker Protection	74	74
Inter-Loco Consist (within same train)	105,224	35,075
ITC PTC	3,382	1,158
Multipurpose Onboard Monitoring Applications	1,205	185
Refrigerated Car Management	4	1
Remote Control Locomotives	12,500	12,500
Wayside-based vehicle monitoring	196	60
Work Order Reporting	2,813	2,813
Yard Fuel Monitoring	2,813	2,813
Grand Total	152,374	75,462

Table 10. Spectrum Demand – 10 Year

Applications	**Sum of Required Bandwidth (Hz) per Transmitting Node (Busy Base Coverage Area)**	**Sum of Required Bandwidth (Hz) per Transmitting Node (Avg. Base Coverage Area)**
Advance Crossing Activation	4,769	1,143
Centralized Traffic Control	180	50
Crossing Monitoring	23	4
Differential GPS	848	848
Drones	708,438	708,438
EIC PRT Communications	117	76
EMS/Pacing	1,284	373
EOT/HOT	45	45
Hi-rail Limits Compliance System	829	829
Individual Roadway Worker Protection	111	111
Inter-Loco Consist (within same train)	105,463	35,154
Intra-Loco Consist (coupled locos)	421,875,000	210,937,500
ITC PTC	12,615	3,819
Motes	321,697	160,450
Multipurpose Onboard Monitoring Applications	1,473	263
Refrigerated Car Management	5	2
Remote Control Locomotives	12,500	12,500
Wayside-based vehicle monitoring	242	75
Yard Fuel Monitoring	2,813	2,813
Grand Total	423,048,452	211,864,492

Table 11. Spectrum Demand – 20 Year

Applications	**Sum of Required Bandwidth (Hz) per Transmitting Node (Busy Base Coverage Area)**	**Sum of Required Bandwidth (Hz) per Transmitting Node (Avg. Base Coverage Area)**
Advance Crossing Activation	6,595	1,401
Centralized Traffic Control	247	60
Crossing Monitoring	24	4
Differential GPS	961	961
Drones	708,438	708,438
EIC PRT Communications	150	89
EMS/Pacing	1,365	396
EOT/HOT	62	62
FOL	656,615,720	102,596,206
Hi-rail Limits Compliance System	925	925
Individual Roadway Worker Protection	148	148
Inter-Loco Consist (within same train)	141,255	141,255
Intra-Loco Consist (coupled locos)	421,875,000	210,937,500
ITC PTC	15,659	4,227
Motes	340,774	169,900
Multipurpose Onboard Monitoring Applications	2,083	326
Refrigerated Car Management	8	2
Remote Control Locomotives	12,500	12,500
Wayside-based Vehicle Monitoring	337	100
Yard Fuel Monitoring	2,813	2,813
Grand Total	1,079,725,064	314,577,312

5. Available Spectrum

According to the National Economic Research Associates, Inc. at the 3rd Annual Asia Pacific Spectrum Management conference, there is an ever-increasing demand for radio spectrum, from railroads and emergency services to businesses and consumer cellular users. The high demand and dwindling availability is driving up the price to purchase and maintain spectrum. "Both reserve prices and final prices for spectrum have been trending upwards since 2008. Average final prices are up 250% from 2008 to 2016" [3].

Available spectrum is a finite resource that is governed by the Federal Communications Commission (FCC) to provide the most efficient use of the frequencies. Radio frequencies are broken down into bands, which can span a few kilohertz up to several megahertz. The bands usually designate a type of licensee or specific usage. For instance, one commonly used band is the Business Pool (150–174 MHz), which includes frequencies designated for railroad use, as well as emergency services and other commercial businesses. Bands may have coordinators assigned by the FCC that work to prevent congestion and provide the most efficient use of their frequencies. The FCC may also apply limiting factors to the bands such as maximum power output, allowing only mobiles to be licensed, or limiting the types of users allowed to acquire licenses on the frequencies. Depending on the intended usage and FCC rules, there may be further limitations. Also, to limit attenuation, there is a maximum effective radiated power (ERP) placed on antennas that exceed certain height above average terrain (HAAT) values.

Radio spectrum was analyzed in its entirety from 30 MHz to 10 GHz to help the rail industry identify spectrum segments where expansion may be possible in the future. Radio spectrum for Chicago was chosen as the basis for this study to represent a DUA. To facilitate the analysis of the DUA, TTCI developed a metric to assess the various spectrum usages by band. This metric was used to evaluate areas of underutilized frequencies and assess other frequency bands for expansion in the future.

For this analysis, the Chicago Mass Transit Area was selected as the area of interest, covering a 180-mile radius around downtown Chicago. This DUA hosts both freight and commuter railroads, and has extensive interchange due to Canadian, eastern, and western railroads meeting in the area to pick up and transfer freight. This DUA was used as the standard to see that the future implementation plans will work in any area. This analysis did not consider the number of mobiles in use, or the licenses that are authorized for nationwide, statewide, or countywide use. The non-site-based licenses are difficult to quantify since they are only searchable by frequency or where the company is located and, being such a large and congested area, this would have required significant time and effort to determine. Mobiles were not included since the reported numbers are not always accurate, just an estimate of the maximum that could be used in the 10-year timeframe. It is not uncommon for 100 mobiles to be licensed on 1 frequency for each base station.

It was determined that information from active FCC licenses would provide the most complete data. When reviewing active licenses, several pieces of information were extracted from each license:

- A count of active base stations on each license (up to six).
- The number of frequencies licensed for each base station to broadcast on.

- The licensed maximum ERP for each frequency.
- The service codes associated with each frequency.

Service codes are helpful to identify frequencies that may have more active use. For instance, "Y" indicates a trunked channel that could have several hundred users at one location. "P" indicates public safety use and is limited to emergency responders and government agency licensing.

After the bands were identified, further research showed that some frequencies would not be available to the railroads due to regulations from the FCC and other factors. Table 12 shows the availability of the frequency bands, as well as the type of users that obtain the licenses. The red bands were not considered further in the analysis. The black bands were the areas of focus.

Table 12. Frequency Band Information and Availability

Frequency Band	Licensed Users
30–50 MHz	Utility, railroads, county, businesses
50–54 MHz	Not Available - Amateur
54–72 MHz	Not Available - TV broadcast
72–73 MHz	Available - Mobile only, low power
73–75 MHz	Not Available - Radio astronomy
75–76 MHz	Available - Mobile only, low power
76–150 MHz	Not Available - TV Broadcast, Aviation, Satellite Communication
150–174 MHz	Railroads, businesses, public safety
174–217 MHz	Not Available - TV broadcast, aviation, satellite communication
217–222 MHz	Petroleum, railroads, businesses
222–450 MHz	Not Available - TV broadcast, aviation, satellite communication, amateur
450–470 MHz	Business, petroleum, public safety, railroads low power
470–512 MHz	Businesses, public safety
512–788 MHz	Not Available - public safety, radio astronomy, TV broadcast
787–788 MHz	28 licenses being auctioned
788–805 MHz	Not Available - public safety, radio astronomy, TV broadcast
805–806 MHz	Mobile only
806–810 MHz	Not Available - public safety, radio astronomy, TV broadcast
810–849 MHz	Business, public safety
849–851 MHz	Not Available - nationwide mobiles (high power)
851–862 MHz	Business, public safety, utilities
862–896 MHz	Not Available - public safety
896–902 MHz	Waiver Availability - limited
902–928 MHz	Railroads, businesses
928–935 MHz	Not Available - nationwide (high power), personal communications (unlicensed)
935–940 MHz	Available - businesses, utilities

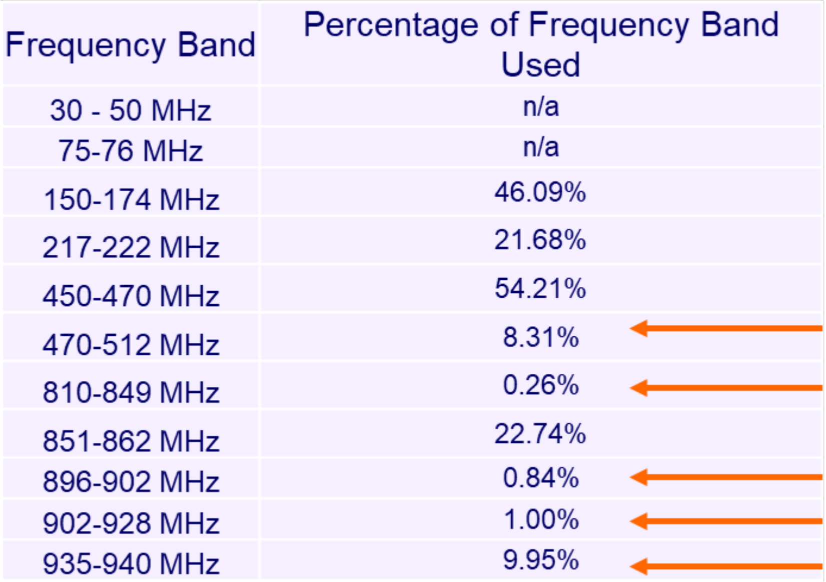
Frequency Band	Licensed Users
940–3.8 GHz	Not Available - weather radar, aviation, satellite communications, TV broadcast, wireless communications
3.8–4 GHz	Point to point microwave
4–5.3 GHz	Not Available - satellite, aviation
5.3–5.406 GHz	Not useable - weather radar
5.406–5.725 GHz	Not Available - satellite, maritime, aviation
5.725–5.925 GHz	Intelligent transportation service - nationwide
5.925–7 GHz	Not Available - satellite communications, TV broadcast
7–7.3 GHz	TV studio transmitter links
7.3–8.5 GHz	Satellite, space exploration
8.5–10 GHz	Not useable - weather radar

Examining frequency bands both numerically and visually helped determine if there were areas available for expansion. However, several factors played a key role and could not be ignored. For instance, the FCC license database was considered to be accurate and complete, but there were occurrences where the licenses were old and were missing information. Some licenses were missing the values for maximum power, or the location information was not precise. The FCC has an ongoing task to update the earlier licenses as they are renewed.

This study focused on stations with an “F” class, indicating that they were a fixed base station, but there are other designators that also indicate a non-moving transmitter, such as repeaters. Licenses that were not fixed location-based, such as nationwide authorizations, were not included in this analysis. Using the Hata equation, an initial guideline was developed to measure the percentage of frequency being used by the fixed base stations in each of the bands. Examining the frequencies with less than 10 percent usage provided an initial area of focus for future consideration. Further research would be required to determine if there are any other factors that would limit the use by railroads of lightly loaded non-railroad frequency bands or frequencies, such as FCC rules and guidelines for each channel and frequency band, physical locations of stations, or other characteristics of the transmissions and equipment. Adjacent channel interference may also be a consideration depending on the emission designators.

As shown in Table 13, the most attainable bands (the ones with arrow pointing) appear to be 470–512 MHz, 810–849 MHz, 896–902 MHz, 902–928 MHz, and 935–940 MHz. As stated above, the analysis considered only base stations using the “F” designator and licensed to specific locations. The 902–928 MHz band has over 3,000 licenses that are “LR” use code that indicates radiolocation land base stations, and were not counted in the metric. Furthermore, the railroads have ribbon licenses for bands that allow them to use set frequencies around any train tracks across the nation. These licenses are not displayed in the FCC database.

Table 13. Frequency Usage



Frequency Band	Percentage of Frequency Band Used
30 - 50 MHz	n/a
75-76 MHz	n/a
150-174 MHz	46.09%
217-222 MHz	21.68%
450-470 MHz	54.21%
470-512 MHz	8.31%
810-849 MHz	0.26%
851-862 MHz	22.74%
896-902 MHz	0.84%
902-928 MHz	1.00%
935-940 MHz	9.95%

Using these findings, the railroads can focus on current and future technologies and the need to obtain available spectrum.

6. Gap Analysis

The gap analysis focused on the wireless needs of the Chicago DUA. It was based on the results from Section 3 and estimates the spectrum need for each time interval. The data rates were tallied and compared to determine the gap between the spectrums needed, what is currently available to date, and what will potentially be available in the future. Table 14 shows the total railroad-owned spectrum available in each frequency band.

Table 14. Current Railroad Owned Spectrum in Chicago DUA

Currently Available Amount of Spectrum				
220 Band (Hz)	ATCS Band (Hz)	450 Band (Hz)	RCL Band (Hz)	Total Spectrum Available
550,000	150,000	325,000	80,000	1,105,000

There are 14 nationwide PTC channels (25 kHz each) and an additional 8 channels used in the Chicago DUA, providing a total of 22 PTC channels or 550 kHz of spectrum. There are 6 ATCS (900 MHz) channel pairs totaling 150 kHz of available spectrum. There are 13 ultra-high frequency (UHF) (450 MHz) channel pairs totaling 325 kHz of available spectrum. There are eight 5 kHz RCL (220 MHz band) channel pairs totaling 80 kHz. Altogether, the railroads have access to 1,105 kHz of available spectrum.

To account for the spectral efficiency and frequency reuse, ITC PTC was used as the "baseline" conversion factor. In Chicago, 20 of the ITC PTC channels are presently needed, i.e., 500,000 Hz, and each channel can support up to 16 kbps data rate due to 1/2 rate convolutional coding for Forward Error Correction. The factor for converting data rate to spectrum required then becomes 500,000 Hz/16,000 bps. This conversion factor was applied to the application data rates to determine the DUA bandwidth need.

The available spectrum was then subtracted from the DUA bandwidth need to find the gap, in Hz, for each particular timeframe. Notice that a negative gap indicates a surplus of spectrum. In fact, there is no actual surplus (despite what is shown), since most railroad wireless applications today use conventional modulations that are less spectrally efficient than $\pi/4$ DQPSK by a factor of 2 or more. For comparison purposes, the gap analysis tables were shown for busy and average base stations, with and without the heaviest spectrum consumers (i.e., video and Wireless MU). Several potential applications will use real-time video such as drones, FOL, and Inter-Loco Consist. Wireless MU is a wireless option for MU cables that connect coupled locomotive networks and has very high data rate.

In the tables below, spectrum requirements are displayed to show the requirements with and without Wireless MU, the video component of certain applications and applications that may use non-railroad spectrum. Command and control for FOL is included in the analysis as it approximates other methods of remote/automated train operation that may be developed in the future. The Wireless MU application spectrum requirements are also removed in some tables due to practicality. The communication requirements between coupled locomotives are large and a need to override has not been identified to justify moving this communication link from hardwired to wireless transport.

Table 15 through Table 20 show the spectrum gap at each timeframe (now, 5 years, 10 years, and 20 years). Table 15 shows the gap for the busiest base station, including all applications. The applications responsible for the largest increase in spectrum use in Table 15 are the introduction of video at 5 years and FOL command and control at 20 years.

Table 15. Gap Analysis of Busiest Base Station (All Applications Included)

Busiest Base Station in Chicago DUA (All Applications Included)			
	DUA Data Rate (bps)	**DUA Bandwidth Need (Hz)**	**GAP (Hz)**
Total data rate at busiest base Now	17,552	548,485	-556,515
Total data rate at busiest base 5 years	73,346	2,292,073	1,187,073
Total data rate at busiest base 10 years	180,510,185	5,640,943,275	5,639,838,275
Total data rate at busiest base 20 years	460,692,271	460,692,271	14,395,528,482

Note that the bandwidth required *today* is higher than shown, since most applications currently use 2-ary modulation, which is of lower order than the π/4 DQPSK assumed. This will likely be true of the 5-year predictions as well, since it is unlikely that all the current applications will have migrated to π/4-shifted DQPSK (or higher order modulation) by then.

Table 16 shows the spectrum gap for the busiest base station without the video components and Wireless MU applications, for the reasons cited above. The applications responsible for the largest increase in spectrum use in Table 16 are the introduction of the command and control function of drones in 5 years, mote-to-mote traffic in 10 years, and FOL command and control in 20 years.

Table 16. Gap Analysis of Busiest Base Station without Video or Wireless MU

Busiest Base Station in Chicago DUA (without Video or Wireless MU)			
	DUA Data Rate (bps)	**DUA Bandwidth Need (Hz)**	**GAP (Hz)**
Total data rate at busiest base Now	17,552	548,485	-556,515
Total data rate at busiest base 5 years	28,946	904,573	-200,427
Total data rate at busiest base 10 years	169,785	5,305,775	4,200,775
Total data rate at busiest base 20 years	337,071	10,533,482	9,428,482

Table 17 shows the spectrum gap for the busiest base station without the video components and Wireless MU applications or any of the applications that currently use non-railroad owned spectrum, for the reasons cited above. The application responsible for the largest increase in spectrum use in Table 17 is the introduction of FOL command and control in 20 years. This is a significant overall reduction in overall spectrum need when compared to Table 16.

Table 17. Gap Analysis of Busiest Base Station without Video, Wireless MU, or Non-Railroad Owned Spectrum

Busiest Base Station in Chicago DUA (without Video, Wireless MU, or Non-Railroad Owned Spectrum)			
	DUA Data Rate (bps)	**DUA Bandwidth Need (Hz)**	**GAP (Hz)**
Data rate of busiest PTC base Now	14,705	459,545	-645,455
Data rate of busiest PTC base 5 years	25,980	811,865	-293,135
Data rate of busiest PTC base 10 years	31,156	973,638	-131,362
Data rate of average PTC base 20 years	190,073	5,939,792	4,834,792

Table 18, Table 19, and Table 20 show the same progression of removal of high bandwidth need applications for an Average Base Station. The main difference between the Busy Base and Average Base Stations is the decrease in train traffic under the Average Base.

Table 18. Gap Analysis of Average Base Station (All Applications Included)

Busiest Base Station in Chicago DUA (without Video, Wireless MU, or Non-Railroad Owned Spectrum)			
	DUA Data Rate (bps)	**DUA Bandwidth Need (Hz)**	**GAP (Hz)**
Data rate of busiest PTC base Now	14,612	456,619	-648,381
Data rate of busiest PTC base 5 years	39,947	1,248,334	143,334
Data rate of busiest PTC base 10 years	90,404,089	2,825,127,770	2,824,022,770
Data rate of average PTC base 20 years	134,227,832	4,194,619,750	4,193,514,750

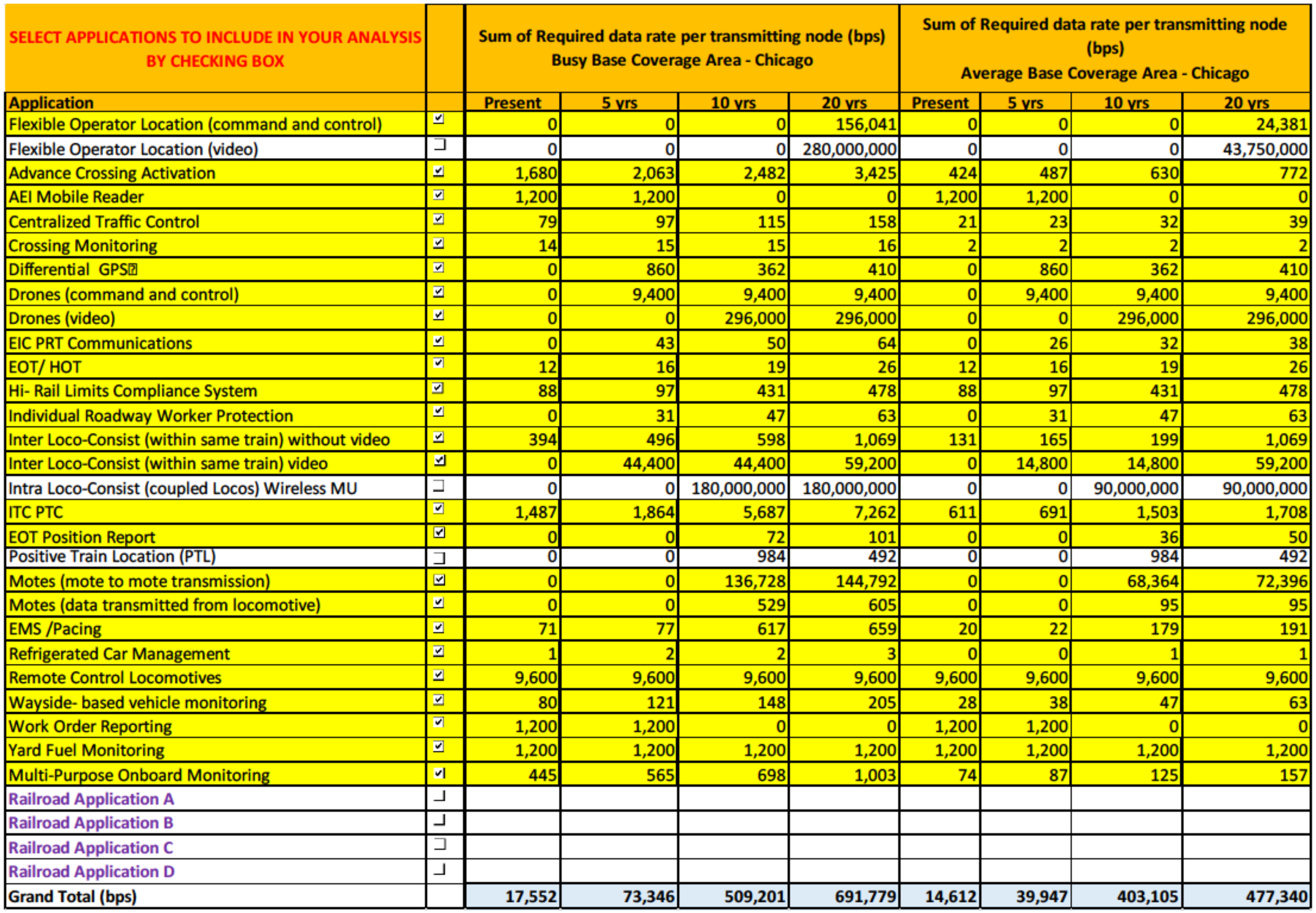
Table 19. Gap Analysis of Average Base Station without Video or Wireless MU

Average Base Station in Chicago DUA (without Video or Wireless MU)			
	DUA Data Rate (bps)	**DUA Bandwidth Need (Hz)**	**GAP (Hz)**
Data rate of busiest PTC base Now	14,612	456,619	-648,381
Data rate of busiest PTC base 5 years	25,147	785,834	-319,166
Data rate of busiest PTC base 10 years	93,289	2,915,270	1,810,270
Data rate of average PTC base 20 years	122,632	3,832,250	2,727,250

Table 20. Gap Analysis of Average Base Station without Video, Wireless MU, or Non-Railroad Owned Spectrum

Average Base Station in Chicago DUA (without Video, Wireless MU, or Non-Railroad Owned Spectrum)			
	DUA Data Rate (bps)	**DUA Bandwidth Need (Hz)**	**GAP (Hz)**
Data rate of busiest PTC base Now	12,137	379,295	-725,705
Data rate of busiest PTC base 5 years	22,660	708,109	-396,891
Data rate of busiest PTC base 10 years	23,599	737,480	-367,520
Data rate of average PTC base 20 years	48,878	1,527,453	422,453

Since every combination of desired application cannot be displayed efficiently in this report, a Gap Analysis Tool that allows user-selectable applications was developed. The user can simply check the box next to the desired application and the gap is calculated and displayed for each time period for both the busy and average base stations. There are also blank rows included for additional future applications, if needed. Applications previously excluded from the gap analysis are included in the Gap Analysis Tool to allow for additional analyses including these applications. Figure 3 below shows an example of the Gap Analysis Tool output without the Wireless MU, FOL (video), or Non-Railroad Owned Spectrum application boxes selected. As each application box is checked, the entire row is highlighted and the DUA Need and Gap are tabulated separately without video, with video assuming π/4-shifted DQPSK modulation, and with video assuming 64-ary quadrature amplitude modulation (64 QAM) modulation. Table 21 and Table 22 show the tabulated output from the Gap Analysis Tool for the Busy Base and Average Base, respectively.



SELECT APPLICATIONS TO INCLUDE IN YOUR ANALYSIS BY CHECKING BOX		Sum of Required data rate per transmitting node (bps) Busy Base Coverage Area - Chicago				Sum of Required data rate per transmitting node (bps) Average Base Coverage Area - Chicago			
Application		**Present**	**5 yrs**	**10 yrs**	**20 yrs**	**Present**	**5 yrs**	**10 yrs**	**20 yrs**
Flexible Operator Location (command and control)	☑	0	0	0	156,041	0	0	0	24,381
Flexible Operator Location (video)	☐	0	0	0	280,000,000	0	0	0	43,750,000
Advance Crossing Activation	☑	1,680	2,063	2,482	3,425	424	487	630	772
AEI Mobile Reader	☑	1,200	1,200	0	0	1,200	1,200	0	0
Centralized Traffic Control	☑	79	97	115	158	21	23	32	39
Crossing Monitoring	☑	14	15	15	16	2	2	2	2
Differential GPS	☑	0	860	362	410	0	860	362	410
Drones (command and control)	☑	0	9,400	9,400	9,400	0	9,400	9,400	9,400
Drones (video)	☑	0	0	296,000	296,000	0	0	296,000	296,000
EIC PRT Communications	☑	0	43	50	64	0	26	32	38
EOT/ HOT	☑	12	16	19	26	12	16	19	26
Hi- Rail Limits Compliance System	☑	88	97	431	478	88	97	431	478
Individual Roadway Worker Protection	☑	0	31	47	63	0	31	47	63
Inter Loco-Consist (within same train) without video	☑	394	496	598	1,069	131	165	199	1,069
Inter Loco-Consist (within same train) video	☑	0	44,400	44,400	59,200	0	14,800	14,800	59,200
Intra Loco-Consist (coupled Locos) Wireless MU	☐	0	0	180,000,000	180,000,000	0	0	90,000,000	90,000,000
ITC PTC	☑	1,487	1,864	5,687	7,262	611	691	1,503	1,708
EOT Position Report	☑	0	0	72	101	0	0	36	50
Positive Train Location (PTL)	☐	0	0	984	492	0	0	984	492
Motes (mote to mote transmission)	☑	0	0	136,728	144,792	0	0	68,364	72,396
Motes (data transmitted from locomotive)	☑	0	0	529	605	0	0	95	95
EMS /Pacing	☑	71	77	617	659	20	22	179	191
Refrigerated Car Management	☑	1	2	2	3	0	0	1	1
Remote Control Locomotives	☑	9,600	9,600	9,600	9,600	9,600	9,600	9,600	9,600
Wayside- based vehicle monitoring	☑	80	121	148	205	28	38	47	63
Work Order Reporting	☑	1,200	1,200	0	0	1,200	1,200	0	0
Yard Fuel Monitoring	☑	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200
Multi-Purpose Onboard Monitoring	☑	445	565	698	1,003	74	87	125	157
Railroad Application A	☐								
Railroad Application B	☐								
Railroad Application C	☐								
Railroad Application D	☐								
Grand Total (bps)		17,552	73,346	509,201	691,779	14,612	39,947	403,105	477,340

Figure 3. User-Defined Gap Analysis Selection

Table 21. User-Defined Gap Analysis Tool Output Display for Busy Base

Busy Base – Chicago	**Bandwidth without Video**			**Video**			**Overall GAP**	
	DUA need (bps)	**DUA bandwidth Need (Hz)**	**GAP for non-video applications (Hz)**	**Data Rate required for Video (bps)**	**Bandwidth needed for video using pi/4 DQPSK (Hz)**	**Bandwidth needed for video using 64 QAM (Hz)**	**Overall GAP (with video at pi/4 DQPSK) (Hz)**	**Overall GAP (with video at 64 QAM) (Hz)**
Present Status	17,552	548,485	-556,515	0	0	0	-556,515	-556,515
Status in 5 Years	28,946	904,573	-200,427	44,400	1,387,500	462,500	1,187,073	262,073
Status in 10 Years	168,801	5,275,025	4,170,025	340,400	10,637,500	3,545,833	14,807,525	7,715,858
Status in 20 Years	336,579	10,518,107	9,413,107	355,200	11,100,000	3,700,000	20,513,107	13,113,107

Table 22. User-Defined Gap Analysis Tool Output Display for Average Base

Average Base – Chicago	**Bandwidth without Video**			**Video**			**Overall GAP**	
	DUA need (bps)	**DUA bandwidth need (Hz)**	**GAP for non-video applications (Hz)**	**Data Rate required for video (bps)**	**Bandwidth needed for video using pi/4 DQPSK (Hz)**	**Bandwidth needed for Video using 64 QAM (Hz)**	**Overall GAP (with video at pi/4 DQPSK) (Hz)**	**Overall GAP (with video at 64 QAM) (Hz)**
Present Status	14,612	456,619	-648,381	0	0	0	-648,381	-648,381
Status in 5 Years	25,147	785,834	-319,166	14,800	462,500	154,167	143,334	-164,999
Status in 10 Years	92,305	2,884,520	1,779,520	310,800	9,712,500	3,237,500	11,492,020	5,017,020
Status in 20 Years	122,140	3,816,875	2,711,875	355,200	11,100,000	3,700,000	13,811,875	6,411,875

Figure 4 shows the Gap Analysis Tool output for the Busy Base with and without applications currently using non-railroad owned spectrum and with and without video, using π/4-shifted DQPSK modulation. Note that Wireless MU and FOL video are not included in the graphs. The brown and orange bars show the DUA need without video and compare with and without non-railroad owned spectrum. The blue bars show the DUA need with video and also compare it with and without non-railroad owned spectrum. The horizontal red line indicates the current available total bandwidth of 1,105,000 Hz. Note that the bandwidth required by today's applications is higher than shown, since most applications currently use 2-ary modulation, which is of lower order than the π/4-shifted DQPSK assumed. This will likely be true of the 5-year predictions as well, since it is unlikely that all the current applications will have migrated to π/4-shifted DQPSK or higher by then.

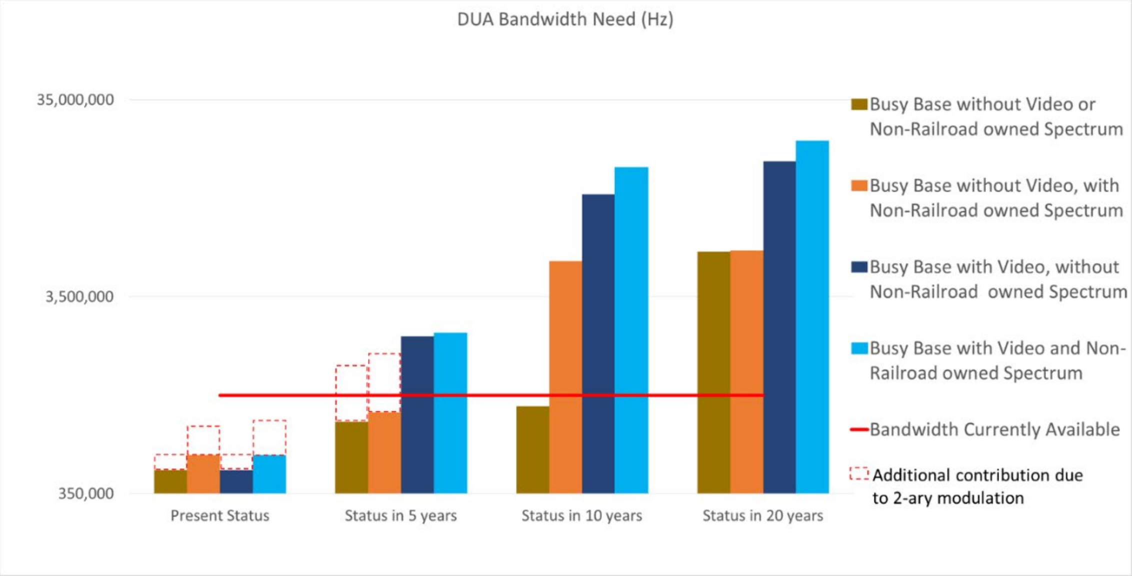


Figure 4. Busy Base DUA Need Bar Chart

Figure 5 shows the same information as Figure 4 for the Average Base. Figure 4 and Figure 5 are useful because they show, at a glance, the simplified breakdown of the DUA spectrum need over time while showing differences in spectrum with and without non-railroad owned spectrum and video. Focusing on the brown bar in both graphs, the increase in bandwidth need from the 5- to 10-year timeframes is attributed to the ITC PTC introduction of Quasi-Moving Block and Full Moving Block messages. The increase in bandwidth from the 10- to 20-year times is attributed to the introduction of FOL command and control messages.

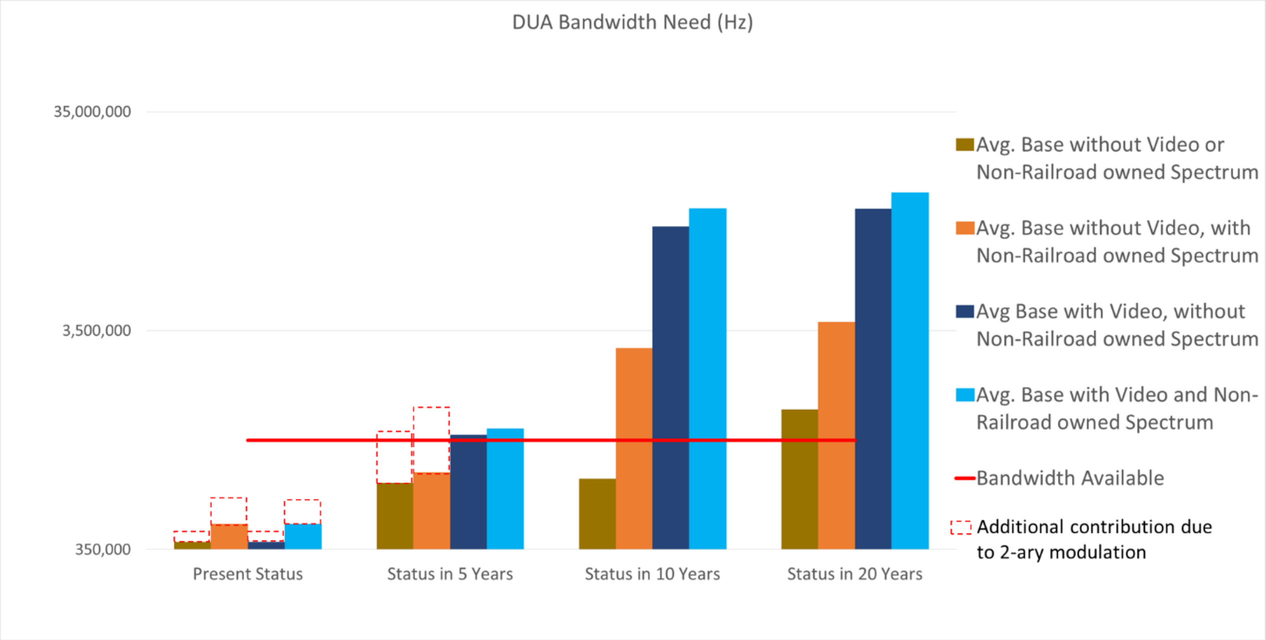


Figure 5. Average Base DUA Need Bar Chart

7. Potential Solutions from New and Developing Technology

Advanced wireless communications technologies can be applied to increase the throughput capacity or efficiency of the limited amount of spectrum available. The following are descriptions of technologies recommended for further consideration to achieve this objective.

High Order Modulations (HOM) – This achieves higher data rate over a given amount of channel bandwidth than the widely used frequency-shift keying (FSK) and binary phase-shift keying (BPSK) modulations. HOM achieves this by encoding more than 1 bit of (binary) information per transmitted symbol. This is done by selecting each symbol to be transmitted from more than two possible frequencies, phases and/or amplitudes. For example, instead of only being able to select either 0 or 180 degrees for each binary symbol as done with BPSK, 3 bits can be transmitted per symbol by having eight different phases from which to choose (e.g., 0, 45, 90, 135 degrees, etc.). Even higher order modulations are typically achieved by using amplitude in addition to phase in order to convey more bits per symbol. For example, 64 QAM communicates 6 bits per symbol, increasing the data rate by a factor of approximately 6 as compared with BPSK for a given channel bandwidth. Modern cellular systems now commonly use 64 QAM, which has increased the availability and lowered the cost of components. The increased spectral efficiency of HOM comes at a cost, however, due to several compounding factors. HOM requires higher signal-to-noise ratio (SNR) and greater power amplifier linearity than lower order modulations, both of which increase the cost of transmitters. Higher SNR thresholds increase the number of channels required for frequency reuse. The higher SNR requirements necessitate higher ERPs, which might require FCC waivers in some bands. Nonetheless, the cost/benefit ratio of HOM versus other solutions makes it almost inevitable that HOM will be used increasingly by railroads as total throughput demand increases and available spectrum decreases.

Higher Frequencies – Today's dedicated railroad spectrum is at frequencies below 1 GHz. In general, spectrum above 1 GHz is not as heavily used as that below 1 GHz, although spectrum up to 2.6 GHz is now becoming widely used. This is because the cost of components increases and propagation distance decreases as frequency increases. Certain frequencies have especially short propagation range, due to absorption by certain molecules in the atmosphere. As industrial and consumer throughput demand increases and available spectrum decreases, there will be greater incentive to develop less expensive components to exploit higher frequency spectrum. Higher frequencies should be seriously considered for new railroad standards associated with short-range wireless links, such as those to be used only within station areas and also those for communication among locomotives and/or cars within the same train. Not only do the costs of components increase with frequency, the number of base stations needed also increases with the square of frequency (all else equal), due to the reduced propagation with increasing frequency.

A particular area of the spectrum that is gaining significant interest in the wireless communications industry is in the 30 to 300 GHz range, also known as millimeter-wave (mmW) frequencies. These frequencies open the opportunity for orders of magnitude greater bandwidths than today's existing systems. Industry studies have shown that mmW systems can offer more than an order of magnitude increase in capacity over current state-of-the-art 4G cellular networks at current cell densities [4]. To get all the benefits of mmW, however, current communication systems would need to be significantly redesigned. Specifically, cell sizes would need to be smaller, highly directional and adaptive transmissions would be needed, and directional isolation between links would be required.

Dynamic Message Assignment to Spectrum (Cognitive Radio) – As conditions change, different channels may become available. Availability of licenses for the same channels nationwide are becoming rare. For example, PTC 220 LLC owns additional local channels (beyond their 14 nationwide 220 MHz channels) in certain urban areas. When a train is in those areas, it may use the additional channels. In other bands, certain regions have more unassigned channels than others. At a particular location, some channels may only be used at certain times of day or during certain events and may be free at other times. The ability of an intelligent controller to dynamically assign excess communications load to whatever spectrum is available at the time of transmission could more efficiently match supply with demand and reduce interference. This can be done based on static information (predefined tables of available channels versus track location) or information broadcast by base stations about channels available in their local area. Alternatively, it can be done dynamically by continually scanning to sense channel utilization and assigning messages to be transmitted on channels according to availability at the time of transmission. This concept is referred to as "cognitive radio." Cognitive radio has the advantage of being more adaptable and not requiring maintenance of tables identifying available spectrum versus location and/or time. However, it is susceptible to and a potential cause of message collisions in situations when a channel is free while being sensed, but then becomes occupied by another user while the cognitive radio transmits. Cognitive radio performance could be likened to that of CSMA, including its well-known hidden-terminal issues. Other radio features can also be adaptable to conditions, such as data rate, modulation, and transmit power level.

Spectrum Aggregation – Spectrum aggregation techniques allow adding carriers that are dispersed either within the same band and/or different bands (intra/inter-band), as well as combination of carriers having different bandwidths. It is considered as one of the factors that will provide a boost to the user throughput in next generation wireless systems [5]. Aside from an improvement in user data rates, spectrum aggregation can offer advantages such as better resilience to path loss and fading (due to different bands experiencing different propagation losses or fading effects) and enhanced interference control. It also provides a means to utilize non-contiguous bits of spectrum that cannot be or is in the process of being re-farmed.

Software Defined Radio – A Software Defined Radio (SDR) allows different waveforms, protocols, data rates, and potentially frequency bands to be handled by the same radio hardware, according to which software modules are operating on the radio at the time. This flexibility can be useful in implementing the capabilities described above. The radio can also be updated as needs change over time, with ability to use legacy waveforms as well as new ones in the same radio to facilitate smooth migration from the former to the latter. An SDR's flexibility comes at some cost, especially for broadband or multi-band RF components, so it may not be cost-effective for all applications or frequency bands. An SDR must be designed to protect against the threat of an unauthorized user reprogramming the radio in a way that might pose a security concern.

Increased Processor and Memory Capacity – For more than a half century, a solid trend has been seen of ever-increasing processor and memory capacity and decreasing cost and size. This trend can be applied in many cases to compensate for the problematic supply versus demand trend of radio spectrum. In particular, applications that wirelessly communicate raw or minimally processed data to a location where it is processed into less voluminous information, alerts, and conclusions may be amenable to migrating more of the data processing to the source, resulting in less data requiring wireless communications. Many applications involving sensors communicating to an office or to a train should be prime targets for use of increased processing at the sensor to reduce wireless load.

Massive Multiple Input, Multiple Output (MIMO) – As the name indicates, MIMO systems consist of multiple antennas at both the transmitter and receiver. This results in an additional degree of freedom (aside from time and frequency) to accommodate more data throughput. Advantages of MIMO include better reliability, spectral efficiency, and energy efficiency [6]. Massive MIMO uses this concept and applies it to cases where the transmitter and/or receivers are equipped with many (tens or even hundreds) of antenna elements. In massive MIMO, fast fading and intracell interference can be mitigated with linear precoding and detection methods.

8. Key Elements of Migration Plans

Key migration trends anticipated to meet the ever-growing needs of railroad wireless communications are described in Table 23.

Table 23. Key Elements of Migration

From (today):	To (future):
Traditional Use of Spectrum	**More Efficient Use of Available Spectrum**
Low Order Modulation	Higher Order Modulations
Half-Rate Forward Error Correction Coding	Higher Rate Codes
Standard Protocols	Lower Overhead and Packet Aggregation
Transmitting Raw Data	Transmitting Processed Information
Dedicated Links	Dynamic Assignment of Packets to Media
Large Cell Sizes	Smaller Cell Sizes
Omni Antennas	Directional Antennas for Spatial Reuse
Dedicated Railroad Bands	**Additional or Liberated Spectrum**
Very High Frequency (VHF) and UHF	Higher Frequencies
Wireless Stationary Links	Landline and Optical Stationary Links
Narrowband Channels	Re-farming and Channel Aggregation
Dedicated Railroad Spectrum	Greater Use of Non-Railroad Owned Spectrum

Traditionally, binary modulation (2-ary frequency-shift keying [FSK] and binary phase-shift keying [BPSK]) have been used for communicating data over railroad wireless channels. While these modulations are inexpensive to implement and do not require such high SNR as their higher order counterparts, as spectrum demand and cost increase while improved technologies become less expensive, links will need to migrate to higher order modulations such as 64 QAM and multi-carrier versions thereof, such as orthogonal frequency-division multiplexing (OFDM). In some cases, the maximum effective radiated power (ERP) limits allowed by FCC will need to be increased.

For decades, rate 1/2 convolution forward error correction (FEC) coding has been preferred for many applications, due to its significant coding gain. Since the late 1990s, low-density parity check codes (LDPCC) and turbo codes have become affordable to implement. These are very powerful codes that can come within a fraction of a dB of the Shannon capacity limit on additive white Gaussian noise (AWGN) channels. These high-rate codes can nearly double the data rate obtainable with rate 1/2 coding.

Standard protocols (e.g., those developed for the Internet) are mature and readily available in commercial off-the-shelf (COTS) equipment. They tend to have very high overhead (e.g., large headers) that use excessive bandwidth. Radios dedicated to railroad use typically do not require all the features of these standard protocols and therefore will need to be streamlined to maximize throughput versus available channel bandwidth.

Applications such as remote sensing may send raw sensor data over wireless links today to be processed at the back office. For some of these applications, the processing of raw data into much less voluminous information (e.g., alerts) could be moved to the source. Processing performance and memory capacity continually increase while cost and size decrease. This will lead to a migration of processing from the destination to the source (e.g., from the office to the wireless remote sensors) as spectrum becomes more expensive and less available.

Traditionally, each dedicated RF channel is assigned to a particular application. Since not all applications need to communicate simultaneously, more efficient use of spectrum can be achieved by dynamically assigning messages or packets to whatever spectrum is most available at the time of transmission and location where needed. Software such as the Interoperable Train Control Messaging (ITCM) system is evolving such capability for the railroads.

As seen in the cellular phone industry, wireless networks that employ frequency reuse can generally increase capacity by reducing cell coverage size. An exception in some scenarios is the PTC 220 MHz network, since wayside status relay service (WSRS) traffic increases as cell size decreases. However, if/when a cellular network is deployed for railroad applications other than PTC, reducing the size of the cells as demand increases can increase the capacity of a given amount of spectrum.

Spatial reuse of spectrum can be increased by employing narrow-beam antennas instead of the omni-directional and near-omni antennas widely used today. This is another technique (e.g., sector antennas or MIMO) used by the cellular phone industry to increase capacity. Since mobile platforms can have any orientation relative to a base station, fixed narrow-beam antennas are less amenable for use at mobiles than at base stations (e.g., pointed along track). However, dynamic and adaptive antenna arrays or sectored antennas could ultimately be employed on mobile platforms.

While spectrum below 1 GHz is becoming very crowded, availability generally increases as frequency increases above 2.6 GHz. This is because hardware costs increase and propagation decreases as frequency increases. The ever-increasing demand for spectrum, however, is driving a reduction in cost and an increase in availability of higher frequency radio components. Railroads will need to migrate applications to higher frequencies, especially those applications that do not require long-range omnidirectional communications.

Today, many links between fixed sites are wireless (e.g., codeline, some backbones). As spectrum becomes costly and as fiber and other optical communication technologies become more cost effective, railroads will increasingly benefit from migrating fixed sites to these alternative media.

As spectrum needs change, railroads will find opportunities to re-farm existing spectrum use to more efficiently meet evolving needs. In some cases, multiple channels (contiguous or non-contiguous) may be aggregated to accommodate higher data rate applications.

Spectrum acquisition and the often-accompanying FCC waiver process can be lengthy and costly. As more commercial services become available that use auctioned spectrum, railroads will likely find certain applications (especially those that are not safety-critical nor mission-critical) that are suitable for use of commercial services.

Many of the migrations discussed above will require a significant amount of time from start to completion. There will be a mix of legacy and new communications systems both handling the same applications during the migration period. A SDR can facilitate a smooth migration by handling both legacy and new waveforms/protocols during the transition period.

9. Assignment of Bands to Applications

TTCI analyzed the assignment of railroad frequency bands to various railroad applications, as mentioned in Section 8. This analysis produced a tool to assist railroads in choosing a frequency band that is best suitable for each new application and potentially moving some current railroad applications to more optimal frequency bands.

The following are the criteria used for this band rating analysis.

- **Propagation Distance Required** – This criterion evaluates how propagation characteristics of each frequency band scores against the RF link range requirement of each application.
- **Coordination Requirements and Noise Susceptibility** – This criterion evaluates the overall coordination required with non-railroad licensed users and the noise susceptibility of railroad radio systems due to the non-railroad licensed radio operations. As mentioned in Section 5, the frequencies owned by the railroads include both nationwide and regional. FCC has put in place some rules for those frequencies which require coordination with the non-railroad licensed users. For this band rating analysis, the assumption is that the amount of coordination required is directly proportional to the number of non-railroad licensed users. Also, a higher number of non-railroad licensed users may contribute to the increase of overall noise floor. For the example analysis performed, this criterion was considered insignificant and therefore given zero weighting. It was included in the tool, however, in case railroads subsequently determine to weight it differently.
- **Spectrum Availability vs. Demand** – This criterion evaluates how each railroad frequency band scores against the spectrum needs of the railroad wireless applications. The spectrum demand for each application is based on the highest bandwidth requirement over the next 20 years. Availability versus demand was determined based on the gap analysis in Section 6.
- **Antenna Size** – This criterion evaluates how the frequency bands can affect the antenna size and to what extent the application requires the antenna to be small. Antenna physical size is directly proportional to wavelength (λ) and inversely proportional to frequency. As a result, if the frequency increases, antenna size decreases for the same radiation pattern.
- **Directional Link** – This criterion defines the requirement of the RF communication link in terms of mobility and directionality. Specifically, it identifies whether a very directional link can be used or if omnidirectional antennas must be used.

Table 24 is an example scoring output of the tool, using the criteria explained above and the ratings on a scale of 1, 2, and 3. A spreadsheet table was developed for each application in which a score is computed for each frequency band by multiplying the rating times the weight assigned and summing that for all the criteria. The weight assignments to the criteria differ from one application to another. For many applications, the RF link range requirement is the most heavily weighted criterion. Note that the rating for 'Spectrum Availability versus Demand' criterion is based on the 'Spectrum Availability versus Demand Ratio.' The ratio is calculated using the spectrum needs for each application and spectrum available in each frequency band.

Although the band rating analysis identifies the most ideally suited frequency band for various applications, there are other factors beyond the scope of this tool that must be considered. For example, some applications cannot use any existing railroad frequency band. This is because of the disproportionately high spectrum needs. Those applications include future enhanced ITC PTC, Inter-Loco Consist with video, Drones with video and Flexible Operator Location (command and control).

Besides the amount of spectrum available in each band, another factor that should be considered in optimally assigning a band to each application is the business value of that application to the railroad. A critical application that might result in stopped trains if its wireless signal does not propagate reliably may be a stronger candidate for a lower frequency band (e.g., 220 MHz) than a less critical application that also needs good propagation. It was not practical for this project to meaningfully assess the relative availability of spectrum by band in the future nor the business value of the various applications. So, the results presented here must be taken as one of multiple inputs to the ultimate assignment of bands to applications. The costs (direct or indirect) of moving an application that is already designed to operate in a particular band were not considered in these tables; rather it weights the bands in terms of operating each application.

Table 24. Example Band Rating of the Three Railroad Bands for a Sample Application

Criteria	**Frequency Bands (MHz)**			**Weight**	
	220	450	900	in %	
Propagation Required	3	2	1	50	Scale: 1, 2, 3
Coordination Requirements & Noise Susceptibility	2	1	3	0	3- Very Good
Spectrum Availability vs. Demand	3	2	1	30	2- Moderate
Antenna Size	1	2	3	20	1- Very Bad
Directional Link	1	2	3	0	
Total				100	
Score	260	200	140		
Available Spectrum (kHz)	550	325	150		
Spectrum Availability vs. Demand Ratio	0.4	0.2	0.1		

Table 25 is the band scoring result for ‘Inter-Loco Consist with Video’ application. Note that ‘Spectrum Availability versus Demand Ratio’ is significantly low for all the frequency bands due to high spectrum demand to facilitate video data. In this case, the spectrum demand was on the order of tens of megahertz whereas the available spectrum is in kilohertz.

Table 26 is the band scoring result for ‘Drones’ with video application. Although the ratings for the criteria remain the same across Table 25 and Table 26, the values for the weights are different. This is because of the difference in the RF link range requirements between the applications. Inter-loco consist is a medium range (less than 5 miles) application whereas Drones is a long range (greater than 5 miles) application.

Table 25. Rating Analysis for Inter-Loco Consist with Video Application

Criteria (with Video)	Frequency Bands (MHz)			Weight	
	220	450	900	in %	
Propagation Required	3	2	1	10	Scale: 1, 2, 3
Coordination Requirements & Noise Susceptibility	2	1	3	0	3- Very Good
Spectrum Availability vs. Demand	3	2	1	25	2- Moderate
Antenna Size	1	2	3	50	1- Very Bad
Directional Link	1	2	3	15	
Total				100	
Score	170	200	230		
Available Spectrum (kHz)	550	325	150		
Spectrum Availability vs. Demand Ratio	0.009	0.005	0.002		

Table 26. Rating Analysis for Drones with Video Application

Criteria (with Video)				Weight	
	220	450	900	in %	
Propagation Required	3	2	1	45	Scale: 1, 2, 3
Coordination Requirements & Noise Susceptibility	2	1	3	0	3- Very Good
Spectrum Availability vs. Demand	3	2	1	35	2- Moderate
Antenna Size	1	2	3	20	1- Very Bad
Directional Link	1	2	3	0	
Total				100	
Score	260	200	140		
Available Spectrum (kHz)	550	325	150		
Spectrum Availability vs. Demand Ratio	0.04	0.02	0.01		

Table 27 is a summary of scores for all railroad applications based on the individual scoring analyses such as that shown in Table 24. Note that the 220 MHz frequency band scored highest for more than half of the applications as it is the band with highest spectrum availability and best propagation characteristics. If sufficient additional spectrum cannot be obtained at 220 MHz to accommodate all applications for which that band scored highest, the *relative* 220 MHz scores can be used as input to help decide which applications might be assigned to a higher frequency. As noted previously, the results presented in Table 24 are not the sole criteria to be considered in assigning new applications to bands or re-farming existing applications to bands. Other criteria, such as relative amount of spectrum available in each band (or other potential bands and non-railroad spectrum) at the time of the assignment must be also considered. And the business value of each application should also be considered.

Table 27. Summary of Final Scores for All the Railroad Applications

Applications	Score – Frequency Band (MHz)		
	Score 220	Score 450	Score 900
ITC PTC	260	200	140
Hi-Rail Limits Compliance System	260	200	140
EIC PRT Communications	260	200	140
Work Order Reporting	260	200	140
Individual Roadway Worker Protection	160	200	240
Inter-Loco Consist (within same train) Video	170	200	230
Inter-Loco Consist (within same train) w/o Video	190	200	210
Crossing Monitoring	200	200	200
Advance Crossing Activation	260	200	140
EOT/HOT	240	200	160
Wayside-Based Vehicle Monitoring	160	200	240
Centralized Traffic Control	200	200	200
Multipurpose Onboard Monitoring Applications	260	200	140
Remote Control Locomotives for Line of Road	260	200	140
AEI Mobile Reader	160	200	240
Yard Fuel Monitoring	160	200	240
Refrigerated Car Management	260	200	140
Drones w/o Video	230	180	130
Drones w/ Video	260	200	140
Differential GPS	260	200	140
Motes (between cars)	170	200	230
Motes (loco to base)	260	200	140
Pacing	260	200	140
Flexible Operator Location	260	200	140

10. Time-Phased Roadmap

As can be seen from previous sections, depending on various factors, a shortfall in spectrum to support railroad applications in a DUA like Chicago could occur in a timespan as short as 5 years. In order to address this shortfall, a number of actions, developments, and changes are advised to be implemented by the railroads. In this section, a high-level roadmap of these actions and changes is presented and discussed.

Table 28 shows the recommended chronological roadmap. The table outlines the recommended actions to be taken by the railroads, and the timeframes in which these actions need to start occurring or being researched/developed (indicated with an "X" symbol). Table 29 shows the railroad applications, sorted chronologically as a function of the timeframe when they are estimated to become operational (indicated with an "X" symbol). As indicated in previous sections, certain applications are planned to be phased-out. In those cases, the phase-out time for those applications is indicated in the table with an "O" symbol.

Table 28. Roadmap of Recommended Actions

RECOMMENDED ACTIONS	Timeframe to Start Developing/Acquiring			
	ASAP	5 years	10 years	20 years
Spectrum Acquisition (Below 1 GHz)	X			
Higher Order Modulations	X			
Spectrum Aggregation	X			
Dynamic Message Assignment to Spectrum	X			
Software-Defined Radio	X			
Security Improvements	X			
Maximize Data Reduction at Source	X			
Alternatives to Wireless where Feasible	X			
Maximize Data to Overhead Ratio		X		
Re-Farm Existing Railroad Bands		X		
Higher Frequencies – Above 1 GHz (Acquisition and Implementation)			X	
Smaller Base Station Cell Sizes			X	
Spatial Re-Use (Directional Antenna, Phased Array)			X	
Massive MIMO			X	

Table 29. Application Implementation Timeline

APPLICATION	Application to Become Operational			
	Present	5 years	10 years	20 years
ITC PTC	X			
Centralized Traffic Control	X			
Crossing Monitoring	X			
EOT/HOT	X			
Hi-Rail Limits Compliance System	X			
Inter-Loco Consist (within same train) without Video	X			
Refrigerated Car Management	X			
Remote Control Locomotives	X			
Wayside-Based Vehicle Monitoring	X			
Yard Fuel Monitoring	X			
Multipurpose Onboard Monitoring	X			
Advance Crossing Activation	X			
AEI Mobile Reader	X		O	
Work Order Reporting	X		O	
EIC PRT Communications		X		
Differential GPS		X		
Drones (command and control)		X		
Individual Roadway Worker Protection		X		
Inter-Loco Consist (within same train) Video		X		
Pacing			X	
Motes (mote-to-mote transmission)			X	
Motes (data transmitted from locomotive)			X	
Drones (video)			X	
Flexible Operator Location (command and control)				X
Flexible Operator Location (video)				X
Intra-Loco Consist (coupled locos) Wireless MU				

It is worth noting that the shortfall will likely not be addressed by a single technology or action, but instead a combination of them. Some of the key recommendations will be discussed next.

A general recommendation for the short term is the acquisition of additional spectrum. This should be leveraged with some of the technological developments outlined in Section 7, particularly spectrum aggregation and dynamic message assignment to spectrum. This combination would allow a better overall utilization of spectrum. In contrast to the current scheme, where certain applications are restricted to specific bands, spectrum aggregation and dynamic message assignment would allow applications to dynamically use one or multiple bands simultaneously. The band selection would be done dynamically depending on factors such as current utilization and link quality. One of the key advantages of these aggregation technologies is better resilience to path loss and fading (due to different bands experiencing different propagation losses or fading effects) and enhanced interference control.

Unsurprisingly, the applications that require the highest bandwidth are those that require video transmissions, which are: video for inter-loco consist (video on the end of the train), video for flexible operator location, and video for drones. By the year 2040, a total of 8.8 GHz is predicted to be needed to support these video applications alone (assuming a π/4-shifted DQPSK modulation). Naturally, supporting this would not be feasible using the currently-owned railroad spectrum. As such, various actions may be needed, of which, the use of higher modulations schemes is a key one. To illustrate, the use of 64 QAM for video applications would reduce the video bandwidth need by 18.5 MHz in 5 years, and by 5.86 GHz in 20 years on a busy base. Similarly, the bandwidth need would be reduced by 6.2 MHz in 5 years and 923.8 MHz in 20 years on an average base. To support higher order modulations, a sufficiently high signal-to-noise ratio would be required, and as such, careful link design and frequency allocations would be needed.

An additional solution/recommendation to partially reduce the spectrum shortfall would be the use of commercial services and non-railroad owned spectrum, e.g., cellular, wherever possible. This would be especially beneficial for video applications, but its extension to other applications should be considered. Depending on the criticality (operational or safety) of the messages to be transmitted or sensitivity to failure, not all applications may be well suited for non-railroad owned spectrum use, or if they are, a secondary (backup) transmission path may be needed.

The above-mentioned technologies and actions, are some of the key recommendations for the railroads to start developing in the short term. In a period of 5 to 10 years, additional technologies and actions are recommended, including data-to-overhead ratio and re-farming of existing railroad bands. For more details on these strategies, see Section 8. Furthermore, the findings of Section 9 should serve as a guide for the re-farming, as they indicate, on an application-by-application basis, the bands that are most ideally suited for each application.

Finally, to support railroad technologies that are predicted to be needed in 20 years, railroads are advised to adopt technologies that will be key enablers to 5G cellular networks. This adoption should start occurring no later than 10 years from now. The key enablers are the use of millimeter wave technologies and massive MIMO, as described in Section 7. To successfully achieve the implementation of these technologies, a re-design of base station networks will likely be needed. A key driver for this is the need for smaller cell sizes, mostly due to the higher path loss suffered by signals at higher frequencies. To overcome this, a higher number of base stations with smaller footprints may be needed. An advantage of this is the increased collective capacity of base stations.

As shown in Table 28, a combination of multiple technologies and strategies are recommended to address the predicted shortage in spectrum to support railroad applications. Existing technologies need to be leveraged with some of the future technologies addressed in Section 7. Furthermore, certain key elements of migration plans outlined in Section 8 should begin to be implemented now to ensure that the spectrum available is enough to support the needed applications in time for their implementation.

11. Conclusion

TTCI analyzed the railroads' general wireless data communication needs and future uses, and analyzed their wireless needs in Chicago, a representative DUA where both railroad and other wireless use is the heaviest. TTCI, together with an industry AG:

- Researched wireless applications to assess RF spectrum needs
- Estimated the wireless demand of each application
- Developed a high-level gap analysis on the demand versus available RF spectrum
- Developed a high-level time-phased roadmap to address gaps in the RF spectrum
- Identified potential tradeoffs associated with assignment of applications to frequency bands
- Identified potential technology developments that may help in addressing the gaps in the RF spectrum
- Evaluated the additional RF spectrum that may be required to address gaps in the RF spectrum
- Identified elements to address railroads' future RF spectrum needs

From the research of railroad applications, estimation of wireless demand, and development of the gap analysis, TTCI and the AG identified a potential deficiency of RF spectrum in the future. The amount of predicted gap varies significantly depending upon the assumptions made. Figure 4 and Figure 5 summarizes the predicted spectrum needs versus time for a few different sets of assumptions. These figures also show the amount of dedicated spectrum currently available to railroads for comparison with estimated demand to assess the predicted spectrum gap.

Since the deficit could be large in the outer years, multiple steps will likely be required to close the gap. Some of those steps should be started very soon. Therefore, several potential methods to mitigate this growing problem are shown in this report along with a suggested roadmap.

12. References

References

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Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AWGN	Additive White Gaussian Noise
ATCS	Advanced Train Control System
AG	Advisory Group
APTA	American Public Transportation Association
ASCII	American Standard Code for Information Interchange
AAR	Association of American Railroads
AEI	Automatic Equipment Identification
BRC	Belt Railway Company of Chicago
B-LOS	Beyond Line of Sight
BPSK	Binary Phase Shift Keying
bps	Bits per Second
CN	Canadian National Railway
CSMA	Carrier-sense Multiple Access
CTC	Centralized Traffic Control
COTS	Commercial Off-the-shelf
CP	Control Point
CRC	Cyclic Redundancy Check
DUA	Dense Urban Area
DGPS	Differential Global Positioning Satellite
DQPSK	Differential Quadrature Phase Shift Keying
D-Frame	Dynamic Frame
EMP	Edge Messaging Protocol
ERP	Effective Radiated Power
ECP	Electronically Controlled Pneumatic
EIC	Employee in Charge Portable Remote Terminal
EOT	End-of-Train
EMS	Energy Management System
ETA	Estimated Time of Arrival
FCC	Federal Communications Commission

ACRONYMS	EXPLANATION
FRA	Federal Railroad Administration
F-Frame	Fixed Frame
FOL	Flexible Operation Location
FEC	Forward Error Correction
FSK	Frequency Shift Keying
GPS	Global Positioning Satellite
GDP	Gross Domestic Product
HOT	Head-of-Train
HAAT	Height Above Average Terrain
HOM	High Order Modulation
HLCS	Hi-rail Limits Compliance
HVM	High Visibility Marker
ICD	Interface Control Document
ITC	Interoperable Train Control
ITCM	Interoperable Train Control Messaging
LIG	Locomotive Interface Gateway
LDPCC	Low-Density Parity Check Codes
MSRP	Manual of Standards and Recommended Practices
MOW	Maintenance-of-Way
mmW	Millimeter-Wave
MIMO	Multiple Input Multiple Output
MU	Multiple-Unit
NERA	National Economic Research Associates, Inc.
NS	Norfolk Southern Railway
OFDM	Orthogonal Frequency-Division Multiplexing
PRT	Portable Remote Terminal
PTC	Positive Train Control
PTL	Positive Train Location
RF	Radio Frequency
RTC	Rail Traffic Controller
RCL	Remote Control Locomotive

ACRONYMS	EXPLANATION
SNR	Signal-to-Noise Ratio
SDR	Software-Defined Radio
SCAC	Standard Carrier Alpha Code
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
UHF	Ultra-High Frequency
UP	Union Pacific Railroad
VHF	Very High Frequency
WIU	Wayside Interface Unit
WILD	Wheel Impact Load Detector
WSRS	Wayside Status Relay Service