FIELD EVALUATION OF V2I CONNECTED VEHICLE DEPLOYMENT IN ADA COUNTY, IDAHO: VALIDATING COMMUNICATION ARCHITECTURE AND CONTROL TECHNOLOGY READINESS

FINAL PROJECT REPORT

by

Umair Mohammad, Fatma Elzahraa Madkour, Ahmed Abdel-Rahim, Sameh Sorour, Mohamed Hefeida, and Mandar Khanal
University of Idaho and Boise State University

Sponsorship
PacTrans, Ada County Highway District (ACHD),
University of Idaho and Boise State University

for
Pacific Northwest Transportation Consortium (PacTrans) USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700

In cooperation with US Department of Transportation- Office of the Assistant Secretary for Research and Technology (OST-R)

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Technical Report Documentation Page

1. Report No.

2. Government Accession No. 01701492

3. Recipient's Catalog No.

4. Title and Subtitle
Field Evaluation of V2I Connected Vehicle Deployment in Ada County, Idaho: Validating Communication Architecture and Control Technology Readiness

5. Report Date

6. Performing Organization Code

7. Author(s)
Umair Mohammad, Fatma Elzahraa Madkour, Ahmed Abdel-Rahim, ORCID# 0000-0001-9756-554X; Sameh Sorour,ORCID# 0000-0002-3936-7833; Mohamed Hefeida, and Mandar Khanal

8. Performing Organization Report No. 2017-S-UI-1

9. Performing Organization Name and Address
PacTrans, Pacific Northwest Transportation Consortium
University Transportation Center for Region 10
University of Washington More Hall 112 Seattle, WA 98195-2700

10. Work Unit No. (TRAIS)

11. Contract or Grant No. 69A3551747110

12. Sponsoring Organization Name and Address
United States of America
Department of Transportation
Research and Innovative Technology Administration

13. Type of Report and Period Covered Research Final

14. Sponsoring Agency Code

15. Supplementary Notes
Report uploaded at www.pactrans.org

16. Abstract

The primary objective of this project was to conduct a field evaluation of a vehicle-to-infrastructure (V2I) connected vehicle traffic signal system deployment in Ada County, Idaho, focusing on validating the communication architecture and control technology readiness for broad implementation. To that end, the reliability of line-of-sight packet exchanges between roadside units (RSUs) and on-board units (OBUs) was extensively tested in the field as a function of the OBU speed and the distance between the OBUs and the RSUs. Two metrics were considered in assessing this V2I communication reliability, the received signal strength indicator (RSSI) and the packet delivery ratio (PDR).

To be able to reliably assess the quality of OBU/RSU communication for OBU/RSU equipment from different vendors, the project focused on developing a vendor-independent reliability testing approach for V2I communications in connected vehicle traffic signal system applications. This was intended to provide an alternative to using the communication data reported by proprietary vendor-supplied interfaces. Our approach was based on building a rigorously tested translation model that uses measured RSSIs from any V2I communication equipment to predict the corresponding PDR values. The results were statistically analyzed and models that predict PDR values were developed. A case study to test and validate this new PDR prediction model was conducted at two intersections in Boise, Idaho.

The developed prediction model will enable transportation system operators to test and validate the efficiency of connected vehicle RSU/OBU communications at signalized intersection approaches under different traffic conditions, independent of vendor-provided tools.

17. Key Words
Roadside unit (RSU), on-board unit (OBU), received signal strength indicator (RSSI), packet drop delivery ratio (PDR)

18. Distribution Statement
No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.		NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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List of Abbreviations

ACHD	Ada County Highway District
CV	Connected vehicle
DSRC	Dedicated Short-Range Communications
GHG	Greenhouse gas
LOS	Line of sight
OBU	On-board unit
PDR	Packet delivery ratio
RSSI	Received signal strength indicator
RSU	Roadside unit
SPaT	Signal performance and timing
USDOT	United States Department of Transportation
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
WAVE	Wireless Access in Vehicle Environment
WSMP	Wave Short Messaging Protocol

Executive Summary

The primary objective of this project was to conduct a field evaluation of a vehicle-to-infrastructure (V2I) connected vehicle traffic signal system deployment in Ada County, Idaho, focusing on validating the communication architecture and control technology readiness for broad implementation. To that end, the reliability of line-of-sight packet exchanges between roadside units (RSUs) and on-board units (OBUs) was extensively tested in the field as a function of the OBU speed and the distance between the OBUs and the RSUs. Two metrics were considered in assessing this V2I communication reliability, the received signal strength indicator (RSSI) and the packet delivery ratio (PDR).

To be able to reliably assess the quality of OBU/RSU communication for different vendors, the project focused on developing a vendor-independent reliability testing approach for V2I communications in connected vehicle traffic signal system applications. This was intended to provide an alternative to using the communication data reported by proprietary vendor-supplied interfaces. Our approach was based on building a rigorously tested translation model that uses measured RSSIs from any V2I communication exchange to predict the corresponding PDR values. This was achieved by correlating the signal strength, measured with a generic power meter, to PDR values reported in the communication interface of the equipment of different vendors. Both stationary and in-motion (10 to 40 mph) field data collection tests were conducted at three intersections. These tests were performed over distances of up to 500 meters between the RSUs and the OBUs. In each test, the RSSI values for line-of-sight (LOS) packet exchange between various RSUs and OBUs were collected in the field, using both a generic power meter and vendor-specific tools. Next, the results were statistically analyzed and models that predict PDR values were developed. A case study to test and validate this new PDR prediction model

was conducted at two intersections in Boise, Idaho, as part of the Ada County connected vehicle implementation project.

Our prediction model will enable transportation system operators to test and validate the efficiency of connected vehicle RSU/OBU communications at signalized intersection approaches under different traffic conditions, independent of vendor-provided tools.

Chapter 1. Introduction

1.1 Project Overview

The primary objective of the project was to conduct a field evaluation of a vehicle to infrastructure (V2I) connected vehicle deployment in Ada County, Idaho, focusing on validating the communication architecture and control technology readiness for such implementations. This objective aligns with the V2I Deployment Coalition Goal #1: "*Help to accelerate the deployment of V2I technologies at intersections where the majority of crashes and/or congestion occur*" (1). The ability of vehicles to communicate with controllers and for controllers to communicate signal performance and timing (SPaT) data to users will enhance both intersection safety and operations. In addition, the ability of traffic controllers to sense the number of vehicles approaching from a given direction should, theoretically, improve the operation of signalized intersections by making them more adaptive.

Communication between controllers and vehicles will generate a wealth of data that can be mined to create a database of turning movements at each of the eight signalized intersections. The ability to create such a database as a byproduct of the deployment of the V2I technology will eliminate the need for highway agencies to collect turning movement data at intersections within their jurisdictions. Highway agencies all over the country budget for such expense and schedule turning movement data collection efforts to cycle through all intersections every certain number of years. With the implementation of V2I technology, turning movement data collection will no longer be required.

1.2 Scope of Work

Ada County Highway District (ACHD), the primary agency responsible for operating the Greater Boise Area traffic network, is planning to field test two elements of connected-vehicle V2I traffic signal system applications: 1) priority for heavy vehicles at signalized intersection approaches and 2) traffic signal system V2I and intersection to vehicle (I2V) data exchange.

In order to be able to reliably assess the quality of V2I communication for OBU/RSU equipment from different vendors, this project focused on developing a vendor-independent reliability testing approach for (V2I) communications in connected vehicle traffic signal system applications. This was intended to provide an alternative to using the communication data reported by proprietary vendor-supplied interfaces. Our approach was based on building a rigorously tested translation model that uses measured RSSIs from any V2I communication equipment to predict the corresponding PDR values. This was achieved by correlating the signal strength, measured with a generic power meter, to PDR values reported in the communication interface of the equipment of different vendors. Both stationary and in-motion (10 to 40 mph) field data collection tests were conducted at three intersections. These tests were performed over distances of up to 500 meters between the roadside units (RSUs) and the on-board units (OBUs). In each test, the RSSI values for line-of-sight (LOS) packet exchange between various RSUs and OBUs were collected in the field, using both a generic power meter and vendor-specific tools. Next, the results were statistically analyzed and logistic and linear regression models that predict PDR values were developed. A case study to test and validate this new PDR prediction model was conducted at two intersections in Boise, Idaho.

Our prediction model will enable transportation system operators to test and validate the efficiency of connected vehicle RSU/OBU communications at signalized intersection approaches under different traffic conditions, independent of vendor-provided tools.

1.3 Report Organization

This report is organized in five chapters. After the introduction, chapter 2 provides a literature review covering V2I communication testing. Chapter 3 documents the study methodology and research approach. Chapter 4 includes a description of data collection activities and tools used for data collection. Finally, chapter 5 presents the study results, discussion, and conclusions.

Chapter 2. Literature Review

Research on equipping vehicles with communication capabilities has been in progress for more than four decades. It started in the 1980s with basic communications of in-vehicle phones to cell towers, continued with the establishment of the first vehicle-to-vehicle (V2V) and vehicle- to-infrastructure (V2I) standard (a.k.a. Wireless Access in Vehicle Environment, WAVE or 802.11p) using dedicated short-range communications (DSRC), and has reached recent research on vehicular clouds. Initiatives to begin considering such technologies for possible deployment in cities have recently been undertaken by the United States Department of Transportation (USDOT) and a large number of U.S. state departments of transportation. For example, the USDOT recently selected three preliminary locations in New York, Wyoming, and Florida to evaluate the effectiveness of connected vehicle (CV) applications (2). A CV safety pilot platform of 2,800 CVs at 29 locations and 73 miles was started in Ann Arbor, Michigan, in 2012 (3). A safety improvement study of CVs and pedestrians in urban environments was started in New York with 280 RSUs (100 pedestrian-DSRC units) and 10,000 vehicles (4, 5, 6). A Wyoming program included DSRC on-board units (OBUs) in 400 CVs (snowplows and heavy vehicles) (7). Finally, the Florida Expressway Authority deployed V2V and V2I applications (8) to reduce collisions and wrong-way entry using DSRC as the data communications medium for 1,600 cars, ten buses, ten trolleys, 500 pedestrians with smartphone applications, and approximately 40 RSUs along city streets. These initiatives all aimed to provide the U.S. and state DOTs with operational, performance, and reliability studies that can help accelerate the deployment of V2I technologies at traffic intersections, where the most crashes and/or congestion occur. These studies also aimed to test the ability of signal traffic controllers both to communicate SPaT data to users and to sense the numbers of vehicles approaching each side of the intersection in order to enhance both intersection safety and operation.

Among these initiatives were urgent calls from the USDOT (9) and a coalition of state

DOTs (10) to test the reliability of wireless devices designed by different vendors to exchange information in the 5850-5925 MHz (i.e., DSRC) radio spectrum reserved for V2V and V2I applications. The wireless devices referred to are typically the OBU and the RSU. The OBU device is installed in vehicles to enable their inter-communication, as well as their communication to supporting infrastructure through the RSU device. RSUs are usually mounted on traffic light poles to provide line-of-sight (LOS) communications with the vehicles' OBUs for the (typically) four different directions of any intersection.

The CV technologies include SPaT, Geometric Intersection Description (GID) data broadcasting, CV devices (e.g., vehicle awareness devices, aftermarket safety devices, and RSUs), and the USDOT preliminary Security Credentials Management System (11). Two key performance indicators are usually considered in assessing the quality and reliability of V2V (i.e., between OBUs) and V2I (i.e., between OBUs and RSUs) communications, namely the received signal strength indicator (RSSI) and the packet delivery ratio (PDR). The RSSI assesses the level of power with which the signal is received by either device, which highly correlates to the ability of the receiver to detect the content of the signal with no or minimal errors. Conversely, PDR is a measure of the ratio of the number of packets transmitted from a device that are lost or were received with errors by the other, normalized to the total number of sent packets. It is usually expected that both metrics exhibit inverse proportionality trends. Reliability tests for V2V and V2I communications are usually conducted as a function of the distance between the two communicating devices in either LOS or non-LOS scenarios.

Chapter 3. Study Methodology

This chapter introduces field observation tests to investigate the feasibility of future implementation of DSRC technology in connected vehicles. The field tests were performed at three traffic intersections in Moscow, Idaho. DSRC technology is designed to trigger communication from the traffic signal to the CV (one-way) or between two CVs (two-way), or a from traffic signal to pedestrians (one-way). The DSRC is based on short-range to medium-range wireless communication channels specifically designed for automotive use and a corresponding set of protocols and standards.

With Wireless Access in Vehicular Environments (WAVE), the DSRC protocol provides communication between two devices. One of the devices is the communication support for the vehicle, while the other can be any WAVE device, such as in another vehicle, a roadside unit, or a pedestrian device. Per the ASTM E2213-03 (13) standard, the device in the vehicle is defined as the OBU, which is mounted to the vehicle or any portable moving device. The RSU is connected to Power over Ethernet. The Power over Ethernet is connected to a power source and a switch. The switch is also connected to a personal computer, which is used to track the WAVE Short Messaging Protocol (WSMP) sent and received by the RSU by logging to its Web interface and the traffic controller. Figure 3.1 shows the connection between the RSU and the controller, and figure 3.2 is a diagram of the vehicle OBU connection.

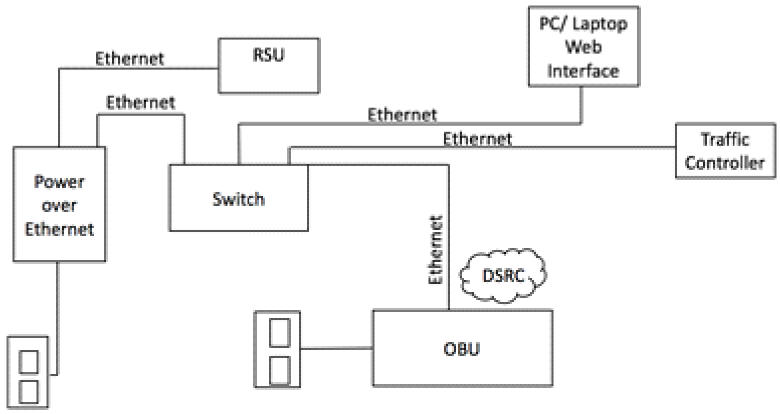

Figure 3.1. Set-up of the RSU with traffic controller

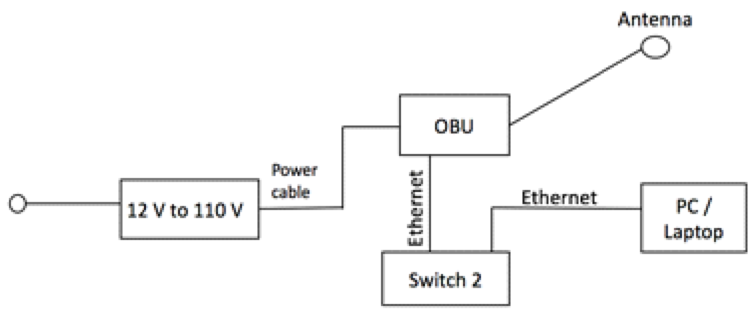

Figure 3.2. OBU vehicle connection diagram

For this project, the RSU was mounted on a pole close to the traffic signal at the intersection and at a height close to the height of a standard traffic signal, as will be discussed in the field data collection section. The OBU was mounted on the car roof. Figure 3.3 shows the RSU and OBU used in this study. Both the RSU and OBU were connected to a power source with variable voltage from (12V to 110V). Two cars were used in the whole testing set-up. The first car was stationary close to the RSU, where it provided the RSU the needed power, and the other car was used to collect the signals at various distances and speeds and to power the OBU mounted on its roof.

Figure 3.3. RSU (left) and OBU (right)

The main purpose of this present study was to measure the sent and received WSMP signals by both devices under various distances and vehicle speeds. The data collection had four goals. The first was to calculate the PDR and RSSI communications between the RSU and OBU under different types of traffic intersections (volumes) and conditions (speed limits) to test the reliability and validity of the CV technology and message exchanges for V2V, V2I, and V2P. The second goal was to use the results to develop contour maps showing the different RSSIs at different distances. The third goal was to statistically correlate the RSSI of an impendent tool (power meter) with that of the dedicated vendor's tool. The strength of the correlation obtained would tell how reliable the power meter would be at predicting the RSSI data so that the authors could produce a confidence level for using the power meter to obtain PDR data for other vendors. The fourth goal was to test the performance and validation of various RSUs by different vendors by measuring their PDRs and RSSIs using the logistic model developed in this study. In other words, the authors would use the tools and software of one RSU to measure the reliability and performance of other RSU types. The performance of the equipment of different vendors could be evaluated by measuring transmitted power from the RSU as a function of distance by using a spectrum analyzer.

The collected data were used to build a logistic growth regression model to fit the vendor's RSSI and the PDR values. A dual-band spectrum analyzer was used with the DSRC spectrum, in the range of 5850 MHz to 5925 MHz, analyzed for vendor device. A typical power spectrum, with the RSUs and OBUs of multiple vendors operating, is shown in figure 3.4. The tool provided the power in dBm and a running packet error rate. In addition, time- and location-stamped packet sequence numbers were given in real-time, which could be saved for later analysis.

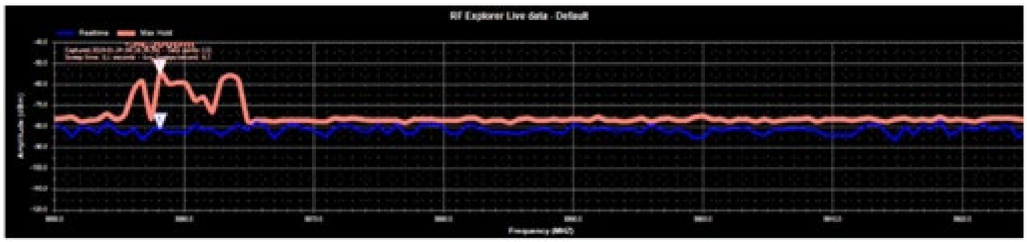

Figure 3.4. Example spectrum snapshot with DSRC devices working

Chapter 4. Data Collection

4.1 Data Collection Overview

Data were collected from field observation in two stages. In the first stage, both the RSSI and PDR from a dedicated vendor's tool were calculated as a function of the LOS distance of the OBU from the RSU (static test) and as a function of the OBU under various speed limits (dynamic test). In the second stage of data collection, RSSI was measuring from the RSU both by the vendor's tool and by a power meter under the same distances, traffic volumes, intersection types, and other conditions.

4.2 Static Test Using the Dedicated RSU

The static tests were done in three different, realistic types of intersections in the city of Moscow, Idaho. The first was a stop sign at a residential, four-leg intersection between 6th and Blaine streets. Each intersection leg had two lanes with a total leg width of 24 ft. The speed limit was 25 mph, as shown in figure 4.1a. This intersection was lined with many trees and houses. The second location was a signalized, commercial, four-leg intersection between Blaine Street and Troy Road (Hwy 8). The intersection had a four-lane approach: the north-south approach had two lanes with a middle left turn lane, and the east-west approach also had two lanes with a middle left turn lane, as shown in figure 4.1b. The speed limit was 35 mph. The second intersection had open terrain, with industrial buildings around. The third location was a rural intersection between Mountain View Road and Darby Road with three legs and two lanes, as shown in figure 4.1c, and a speed limit of 45 mph. The third intersection's terrain was very flat without any obstacles such as trees or buildings or even traffic volumes.

Figure 4.1. Tested intersections

At every intersection, the RSU was mounted on a 12-ft. tripod, as shown in figure 4.2. The 12-ft. height was chosen to ensure safety, as it was found that increasing the height beyond 12 ft. was unstable, and to simulate the height of a standard traffic signal. The OBU was placed inside a vehicle while its antenna was mounted on the vehicle's roof, as shown in figure 4.3. At the residential and commercial intersections, every leg was divided into 50 points (49 segments). The distance between each two points was 5 meters, where each leg was marked at up to 250 meters from the RSU. In contrast, the rural intersection was divided by 10 meters to reach 500 meters away from the RSU. The reason was that the third intersection was very flat and without obstacles, so the broadcast signals were expected to be stronger.

Figure 4.2. RSU locations at the different test intersections

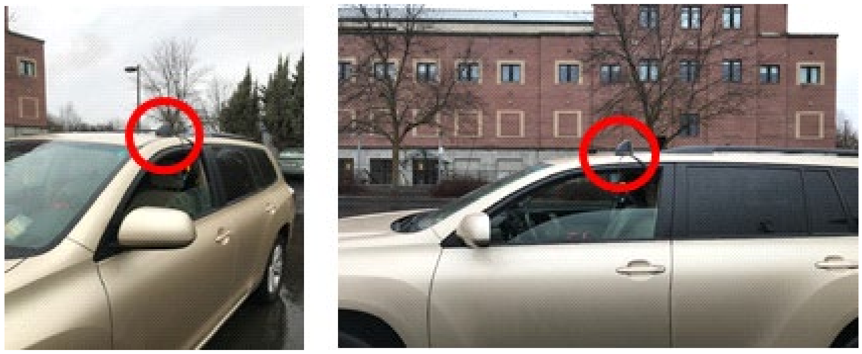

Figure 4.3. The OBU on the vehicle's rooftop

4.3 Power Meter Test

The RF Explore power meter was used in this study. Most of the complexity inherent in full-sized spectrum analyzers was simplified by the automatic functionality provided by the firmware, as the resolution bandwidth (RBW) did not need to be adjusted for each different frequency span:

- General purpose high frequency model: 15-2700 and 4850-6100 MHz
- General purpose wideband model: 15 – 2700 MHz
- Wideband UHF - ISM models: 50 Khz – 960 MHz and 2350 – 2550 MHz
- Narrow band ISM models: 2.4 GHz, 433 MHz, 868 MHz or 915 MHz band.

The test using the power meter was conducted at the McClure building at the University of Idaho; the RSU was placed at a point close to the entrance of the building. That point was elevated enough to simulate the height of a conventional traffic signal. The RSU was powered from the building, and readings were taken every 5 meters for a length of 50 meters (10 stations). The test was conducted in two steps:

1. The RSU was located at a high position, and the readings were taken by the OBU every 5 meters; every reading was taken by making a complete stop at each station.
2. Readings were obtained from the power meter at the same locations as those in the first step. The OBU was turned off during the power meter test to avoid signal interference,

and the power meter was raised to a height similar to that of the OBU mounted on the car roof. Because of sensitivity issues, it took about 5 minutes at each station to get the necessary range of power meter readings.

The two steps were conducted under the same environmental conditions.

Chapter 5. Results and Discussion

Colored contour maps of the RSSI and PDR data were generated for the three different intersections (residential, commercial, and rural) that were considered. The contour maps visualized the data that were collected to determine the power threshold for producing an acceptable PDR, which is associated with limitations on communication exchange operations. Moreover, they helped to identify the signal strength and the covered range. This helped determine the signals' weakest points and to investigate the reasons for them.

Figure 5.1 shows the RSSI and PDR contour maps for the residential area (Blaine with 6th Street). For the west leg of the intersection, the signal decreased slightly when the distance increased from 5 to 110 meters (-60 to -80 dBm), with an average of -74.8 dBm and a PDR of 99.8 percent. The signal strength dropped significantly when the distance was between 110 and 135 meters from the RSU, with an average of -105.175 dBm and a PDR of 15 percent. The power signal started to increase between 140 and 190 meters, with an average of -91.253 dBm and a PDR of 91.7 percent. Then the signal changed again between distances of 190 and 250 meters, where the RSSI average was -105.191 and the PDR 48 percent. The variation in signal strength along the intersection's west leg was possibly due to the large number of trees. On the other hand, the RSSI of the south leg of the intersection decreased slightly from -54.54 to -90.023 dBm between 5 and 160 meters from the RSU, with an average of -80 dBm and a PDR of 99 percent. The RSSI continued to decrease sharply between 160 and 250 meters, where it reached -107.6 dBm with a PDR of 15 percent. For the east leg, the RSSI decreased slightly from -61.2 to -89.6 dBm between 5 and 250 meters, with an average of -85.1 dBm and a PDR of 99.5 percent. Finally, on the north leg, the average RSSI for the whole leg length was -109.9 dBm with a PDR of 0 percent. The reason for this was that the RSU was facing the stop sign and at the same height, so that the signal was blocked in the north direction.

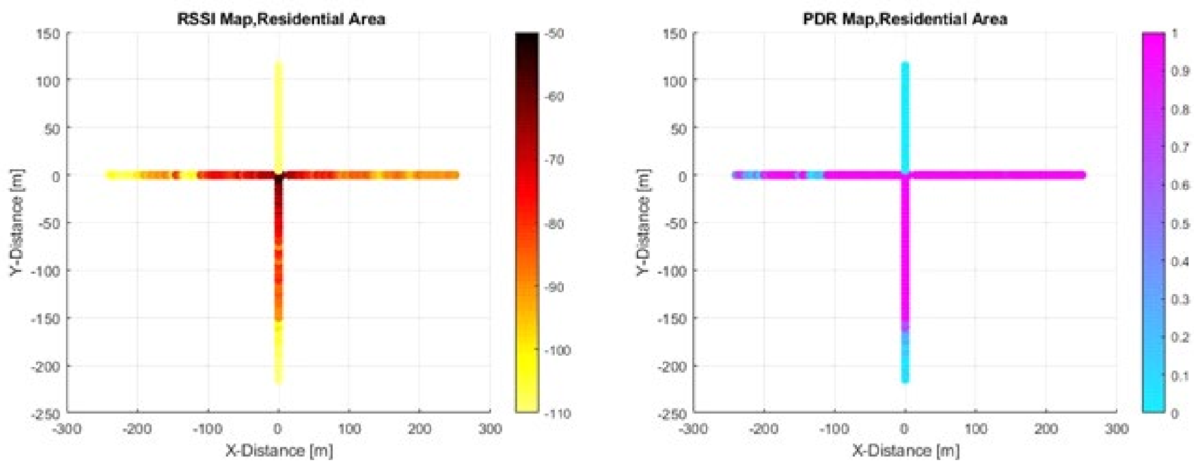

Figure 5.1. RSSI and PDR contour map for the residential area.

Figure 5.2 shows the RSSI and PDR contour maps for the commercial intersection. The RSSI of the west leg decreased slightly for the whole leg length from -64.8 to -98.544 dBm, with an average of -86.4117 dBm and a PDR of 98.57 percent. The RSSI of the east leg changed from -75.041 to -100.205 at distances between 5 to 210 meters from the RSU, with an average of -88.9 dBm and a PDR of 96.53 percent. The RSSI between 210 and 250 meters dropped to -105.76 with a PDR of 39.28 percent. On the north leg, the RSSI average was -84.5 dBm and the PDR was 97.4 percent. Finally, the RSSI of the south leg had an average of -70.46 and a PDR of 98.56 percent, observed for the whole leg length. However, the RSSI values fluctuated (possibly because that branch of the intersection was not straight) along that direction, with an overall PDR of 98 percent.

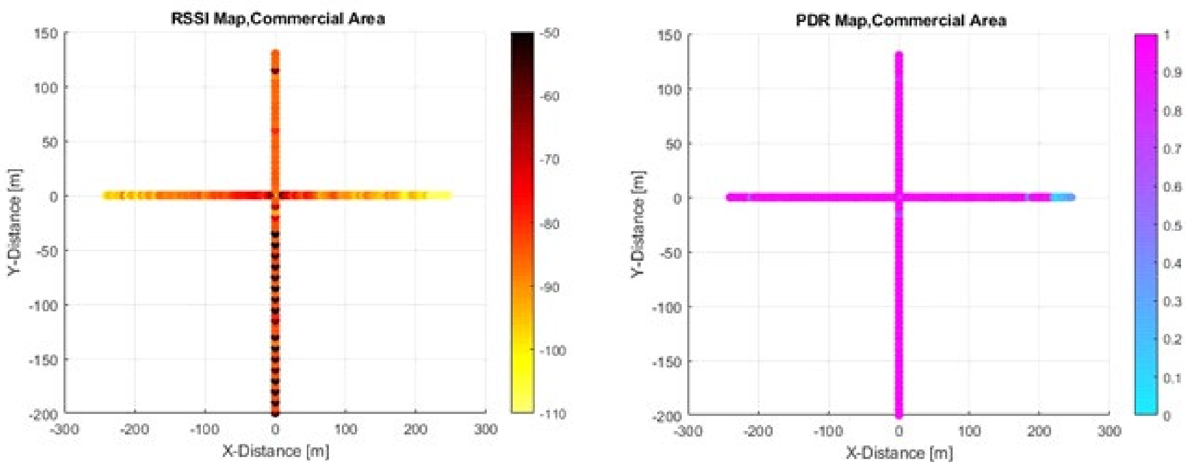

Figure 5.2. RSSI and PDR contour map for the commercial area.

Figure 5.3 shows the contour maps for the rural intersection. The RSSI of the north leg decreased slightly, with an average of -80 dBm between 10 to 240 meters and a PDR of 97 percent. Between 240 and 250 meters, the RSSI dropped sharply to -104.157 dBm with a PDR of 68 percent. Then the RSSI increased again between 250 and 500 meters (-92.9 dBm) with a PDR of 99.9 percent, probably because of topography. The RSSI of the south leg decreased slightly from -68 to -100 dBm until 220 meters with an average of -88 dBm and a PDR of 99.8 percent. Then the RSSI was very low (-109.44 with a PDR of 66 percent) between 220 and 260 meters because of road curvature at that section. From 260 to 500 meters, the RSSI increased again to -96.8 with a PDR of 92 percent. Finally, on the east leg, the RSSI decreased slightly from 10 to 240 meters (from -63.48 to -100.23 dBm) with an average PDR of 99 percent, and between 240 and 500 meters the RSSI average was-108.448 with a PDR of 19 percent.

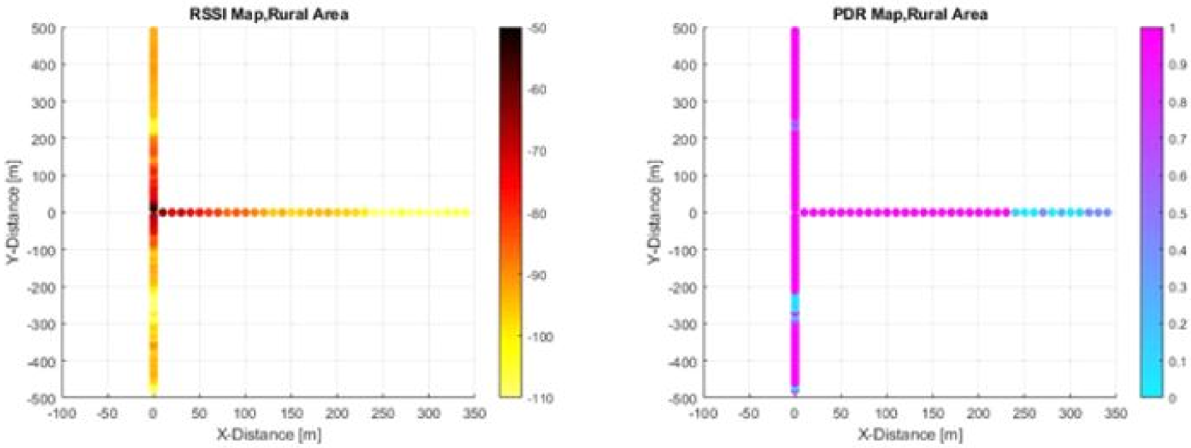

Figure 5.3.RSSI and PDR contour map for the rural area.

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