Evaluation of 5.9 GHz DSRC and 900 MHz Vehicle-to-Vehicle Communication in a Resource Road Environment: Intermediate Trial Results

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Abstract

In the initial trial, 5.9 GHz dedicated short-range communication (DSRC) radio links with 0.2 W transmit power were tested in a resource road environment at UBC's Malcolm Knapp Research Forest. Average non-line-of-sight communication ranges of about 350 m were achieved. Since such ranges are insufficient for resource road safety applications, further tests of 5.9 GHz DSRC radios with higher gain antenna and transmit power were conducted. In addition, the non-line-of-sight communication range of off-the-shelf 900 MHz radio with 10-W transmit power was also evaluated and found to exceed 725 m. The results and findings from this study are presented and further work that would meet the needs of forest resource sectors is proposed.

Acknowledgements

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Introduction

Both the U.S. Federal Communication Commission (FCC) and Innovation, Science and Economic Development (ISED) Canada have allocated 5.9 GHz frequency spectrum to dedicated short-range communication (DSRC)–based intelligent transportation systems (ITS) that will be used primarily to improve road safety, reduce traffic congestion, and support commercial vehicle operations. Fifteen years of research has been conducted to develop DSRC technology that enables broadcasting and receiving of basic safety messages that report a vehicle's speed, heading, brake status, and other information within a range of 300 m. In most countries, 5.9 GHz frequency band has been proposed for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, while in some cases, using 900 MHz frequency band has also been proposed for vehicle-to-infrastructure (V2I) communication. In Japan, 700 MHz frequency band are used for V2V communication along with 5.9 GHz spectrum. Table 1 shows some of the parameters for communication at these frequencies. The National Highway Traffic Safety Administration (NHTSA) is planning to mandate DSRC radios on all vehicles in the near future and NHTSA estimates the cost of V2V equipment to be around $350 per vehicle by 2020.

Some commercial deployment has already taken place. The forest industry could leverage this technology to improve the road safety on resource roads. Initial tests conducted last year at UBC Malcolm Knapp Research Forest (MKRF) showed that the communication range of 5.9 GHz DSRC at 0.2 W transmit power varied from 240 to 500 m in forest environments (Shetty et al. 2017). This range will not be adequate for traffic safety applications on resource roads. As a result, further measurement study on V2V communication with high (allowable) power at different frequencies in the same locations (where the range was limited) was proposed to evaluate possible improvement in the communication range.

Table 1. V2V specification for 5.9 GHz, 900 MHz, and 700 MHz frequency spectrum

Parameter	5.9 GHz DSRC	900 MHz V2I	700 MHz DSRC (Japan)[1]
Frequency band	5.850 to 5.925 GHz	902 to 928 MHz	755.5–764.5 MHz
Number of channels	7	10	1
Channel bandwidth	20 MHz (Control), 10 MHz (Service)	2 MHz	10 MHz
Symbol rate	125 ksymbol/s	40 ksymbol/s	6000 ksymbols/s
Data rate	3 to 27 Mbps	40 kbps	3 to 18 Mbps
Modulation	OFDM (BPSK, QPSK, 16QAM, 64QAM)	BPSK	OFDM

[1] Sevlian et al 2010

Objectives

The long-term objective of this project is the development of a DSRC-based communication system for Canadian resource roads using the established V2V safety framework. The short term objectives of this work are to:

- Investigate the variation in communication range of the off-the-shelf radio systems at different frequencies, transmit powers, and antenna gains in the UBC Malcolm Knapp Research forest.
- Determine the frequency band best suited to meet the needs of V2V communication in forest operations.

Methodology

Instrumentation/hardware

The performance of an off-the-shelf DSRC system, operating at 5.85–5.925 GHz band range with different antenna gains, and an off-the-shelf V2V radio, operating at 902 to 928 MHz band range with different transmit power, were evaluated in the Malcolm Knapp Research Forest (MKRF). Cohda Wireless' 5.9 GHz DSRC MK5 onboard units (OBUs), MK5 roadside units (RSUs), and Rigid Robotics' 900 MHz V2V radios were used for the measurements.

Two pickup trucks that similar to what is commonly used as an industrial vehicle for transporting crews in the forest industry were used for the measurements. One vehicle was used as a stationary transmitter at measurement locations and another vehicle was used as a receiver that was moving around and away from the measurement locations until the radio lost communication with the receiver. The transmitter and receiver antennas were mounted at the same height: 2.44 m from the ground at the back of the pickup truck (Figure 1).

Figure 1. V2V test setup.

During the baseline test, the stationary vehicle had an RSU radio and the moving vehicle had OBU radio; however, this time around, the same radio units (either OSU or RSU on both vehicles) were used during the test to evaluate the performance. ISED has issued radio standards specification RSS-252 establishing the certification requirements for the licence-exempt DSRC OBUs (ISED 2017); however, the DSRC OBU devices should comply with the transmitter power levels described in the ASTM E2213-03 (2010) standard.

Neither the Cohda OBU or RSU units are yet approved for use in Canada; however, a development licence was obtained from ISED prior to testing. Permission from ISED was also obtained for testing the 900 MHz radios using higher transmit power.

Test conditions

Table 2 presents the weather conditions during the testing period. The limited coverage sections from the last tests were selected for performance comparison. There was no snow on the roads near the measurement sites. Table 3 provides the latitude, longitude, and elevation of the stationary vehicle.

Two test passes were made at each measurement location: one experimental vehicle was stationary, and the other was travelling away and toward the stationary vehicle in a long curve (line of sight and non–line of sight) and at the slope (non–line of sight). The average travel speed of the moving vehicle was 15 km/h.

Table 2. Weather data for test period

Test	Date	Mean Temp °C	Max Temp °C	Min Temp °C	Avg Humidity %	Max Humidity %	Min Humidity %	Precipitation mm	Wind Speed km/h	Max Wind Speed km/h
Baseline 5.9 GHz test	Feb 22, 2017	4	7	0	85	100	56	2	3	11
	Feb 23, 2017	4	7	0	81	94	49	4	2	7
5.9 GHz test	Nov 16, 2017	7	9	5	81	95	61	5	5	11
	Nov 17, 2017	6	9	4	84	95	59	1	3	7
900 MHz test	Jan 12, 2018	2	4	1	95	100	89	8	5	11

Table 3. Study locations at Malcolm Knapp Research Forest

Test # (measurement location)	Road	Use case	Transmitter Tx locations		
			Lat	Long	Elevation (m)
1	G	Vehicle awareness/one lane bridge/obstructed	49° 16' 15.61" N	122° 34' 24.38" W	153
2	G	Vehicle awareness/line of sight (LOS) for 225 m and line of sight (NLOS) obstructed	49° 16' 20.44" N	122° 34' 50.79" W	144
3	G	Vehicle awareness/ LOS clearings and LOS semi-obstructed	49° 16' 20.44" N	122° 34' 50.79" W	144
4	G	Vehicle awareness/ LOS clearings and LOS semi-obstructed	49° 16' 17.72" N	122° 35' 02.95" W	141
6	A	Intersection awareness/ LOS obstructed	49° 15' 49.66" N	122° 33' 56.72" W	188
7	A	Intersection awareness/ LOS for 500 m and LOS obstructed	49° 15' 49.66" N	122° 33' 56.72" W	188

Transmit power and antenna gain

As the transmit power of the off-the-shelf 5.9 GHz radios was limited to maximum allowable power, the test of 5.9 GHz DSRC with transmit power of 40 dBm (10 Watt) was not conducted. The transmit powers and antenna gains of 5.9 GHz DSRC radio that were used in the test are listed in Table 4. The overall effective isotropic radiated pattern (EIRP)[1] for 5.9 GHz DSRC radios is limited to 40 dBm. The default transmit power for 900 MHz V2V is 1 W. In this test, the transmit power was amplified to 10 W to evaluate the improved coverage. The antennas used in the test were omnidirectional antennas and their specifications are listed in Table 5. Using high gain antennas could also improve the communication range. However, omnidirectional antennas with higher gains have smaller elevation beamwidths, as suggested by Table 5.

Table 4. 5.9 GHz DSRC radio effective transmitted power

Radio type	Transmit power dBm	Feeder loss (Cable and connector) dB	Antenna gain dBi	EIRP dBm (Watt)
OBU	26	0.443	5	30.56 (1.13)

[1] Effective isotropic radiated power includes radio trasmit power, antenna gain, and cable losses

OBU	24	0.443	9	32.56 (1.80)
RSU	26	0.243	4	29.76 (0.95)
RSU	26	0.243	12	37.76 (5.97)
RSU	24	0.243	12	35.76 (3.77)

Table 5. 5.9 GHz and 900 MHz omnidirectional antennas specification

Make and model	Type	Frequency	Radio unit	Gain dBi	Length	Elevation beamwidth
Unknown	Vertical monopole	5.9 GHz	RSU	4	8 in (20 cm)	42°
Mobile Mark ECO9	Vertical monopole	5.9 GHz	OBU	9	14 in (35.6 cm)	20° (Appendix A)
Mobile Mark ECO12	Vertical monopole	5.9 GHz	RSU	12	18 in (45.7 cm)	7°
Mobile Mark MGW-312	Shark fine	5.9 GHz	OBU	5	4 in (10 cm)	See Appendix A
Taoglas	Vertical monopole	900 MHz	OBU/Rover	3.5	12.6 in (32 cm)	15° (Appendix A)
Taoglas	Vertical monopole	900 MHz	OBU/Base	3.5	43.1 in (109.4 cm)	15°

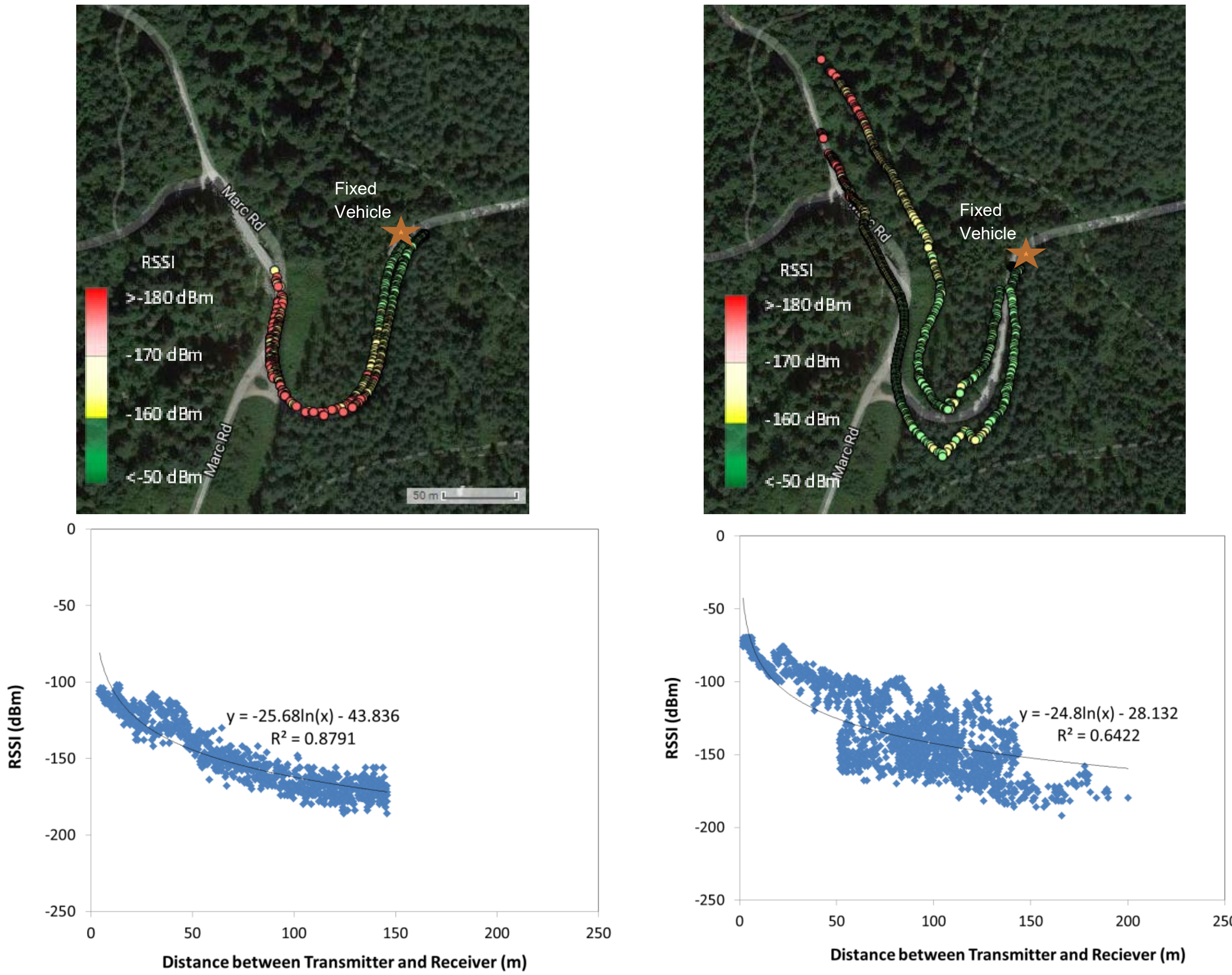
In order to evaluate the communication link between vehicles, a series of basic safety messages (BSMs) was sent from one to the other, with key information such as vehicle location, speed, acceleration, and heading with a time stamp. In the case of 5.9 GHz DSRC, both vehicles were sending and receiving BSMs at 10 messages per second and in the case of 900 MHz V2V, both vehicles were sending and receiving BSMs at 6 messages per second and 3 RTCM (Real Time Correction Messages) messages per second. The moving vehicle would travel until the vehicle completely left the communication range for each test run and then would return back towards the fixed vehicle. In the case of 5.9 GHz DSRC, signal strength and noise were recorded based on which radio signal strength indicator (RSSI) was computed based on the receiver antenna's power signal strength.

Results and discussion

Coverage variation of the off-the-shelf 5.9 GHz and 900 MHz V2V radios

5.9 GHz DSRC coverage

Figure 2 illustrates the coverage range and path loss of 5.9 GHz DSRC at measurement location 1. The signal strength decreased logarithmically as the distance between transmitter and receiver increased. Figure 2 shows the variation of RSSI with the distance between transmitter and receiver. Due to dense vegetation, with stem density of 330 stems/ha and stem volume of 690 m^3/ha, the signal strength for OBU with 5dBi antenna gain dropped considerably after the distance between transmitter and receiver exceeded 50 m.



a) OBU with 5dBi gain antenna on transmitter and receiver vehicles

b) RSU with 12dBi gain antenna on transmitter and receiver vehicles

Figure 2. Coverage range and path loss of 5.9 GHz DSRC at measurement location 1.

The communication range for 5.9 GHz OBU with 5dBi antenna gain was 50% less than the OBU with 9dBi antenna gain. Table 6 depicts the coverage range for OBU with 5 dBi and 9 dBi antenna gain at location 1. Table 7 presents the coverage range for RSU with different antenna gains and arrangements. The coverage range did not vary much between different test setups.

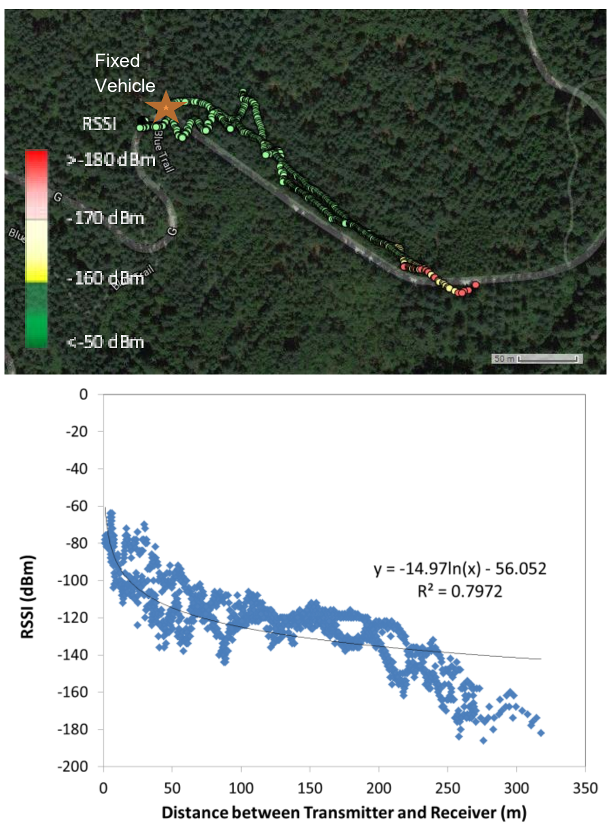
Table 6. 5.9 GHz OBU coverage distance at Test 1 site with different antenna gains

Stationary vehicle		Moving vehicle		Max coverage (m)
Antenna A dBi	Antenna B dBi	Antenna A dBi	Antenna B dBi	
5	5	5	5	145
9	9	9	9	275

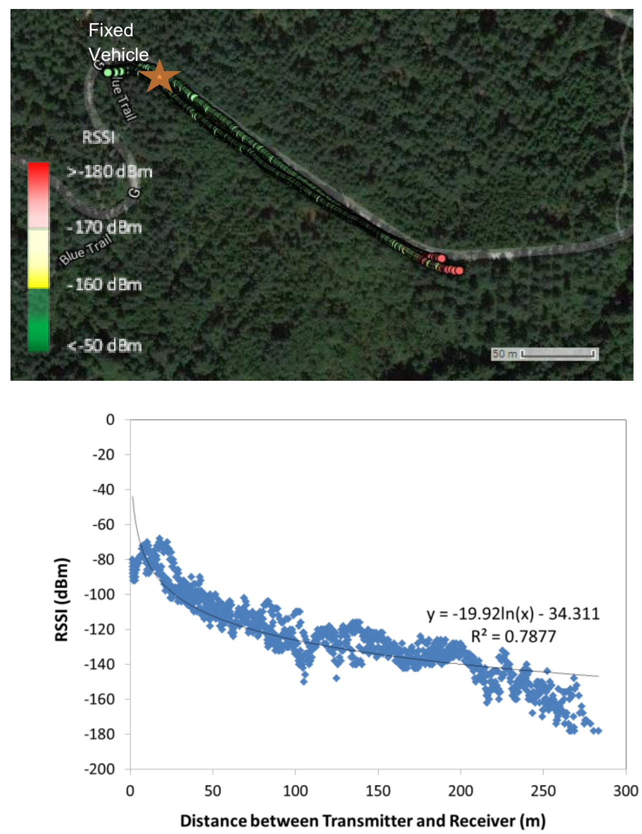
Table 7. 5.9GHz RSU coverage distance at Test Site 1 with antenna gain

Stationary vehicle		Moving vehicle		Max coverage (m)
Antenna A dBi	Antenna B dBi	Antenna A dBi	Antenna B dBi	
4	4	12	12	197
12	4	12	4	207
12	12	12	12	200

Figure 3 shows an aerial view of the vehicle path, and the variation of RSSI with the distance between transmitter and receiver at measurement location 2. The stem density at this location was 293 stems/ha and the volume was 280 m^3/ha, with line of sight up until 150 m having reasonable signal strength for both OBU with 5 dBi antenna gain and RSU with 12 dBi antenna gain. The signal strength drops dramatically at a distance of 200 m between transmitter and receiver.



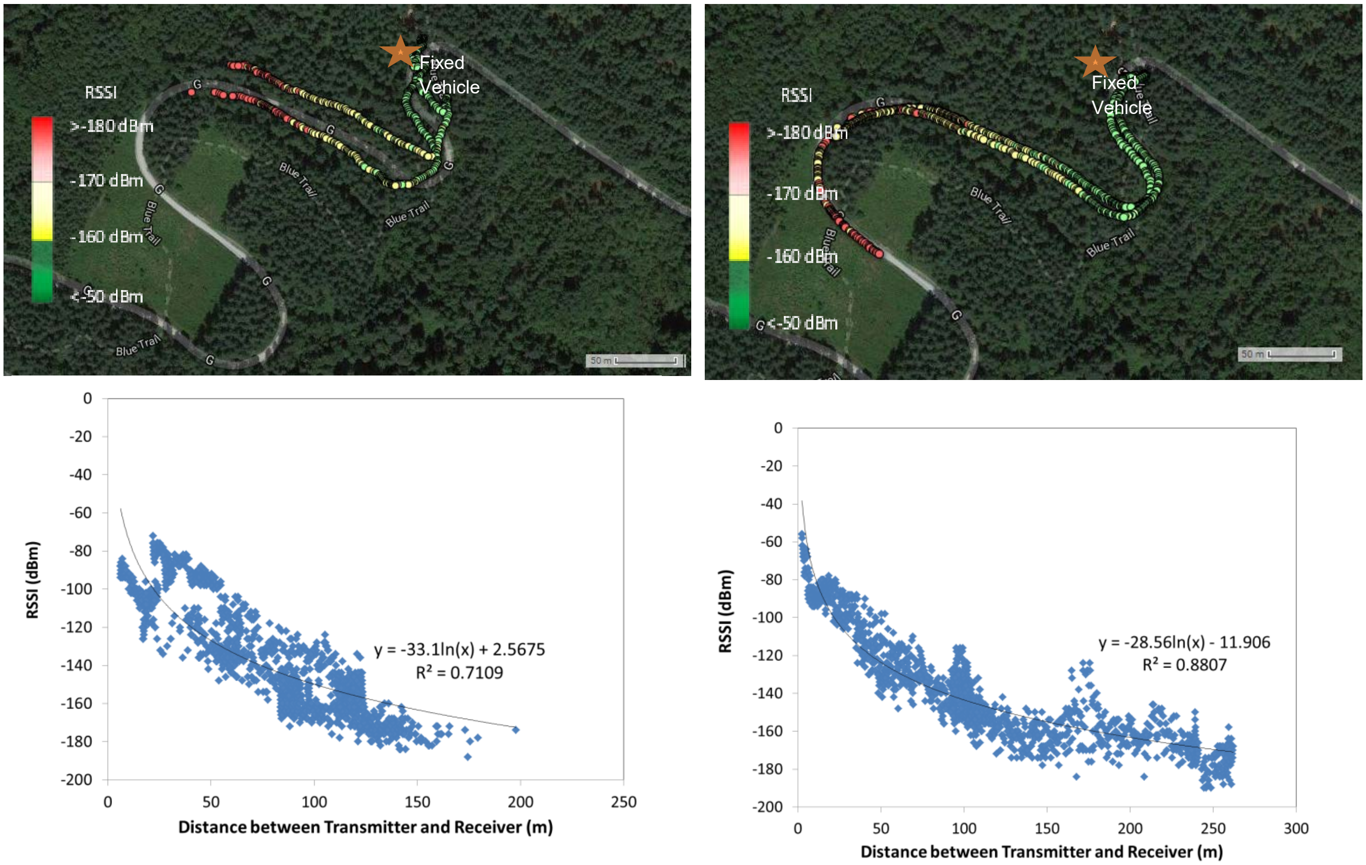
a) OBU with 5 dBi gain antenna on transmitter and receiver vehicles



b) RSU with 12 dBi gain antenna on transmitter and receiver vehicles

Figure 3. Coverage range and path loss of 5.9 GHz DSRC at measurement location 2.

The roads at measurement location 3 were winding with some patches of clearcuts. The stem density was 270 stems/ha and the volume was 285 m^3/ha. During the baseline test, the coverage range measured was around 479 m with some sections of the road experiencing dropouts. However, in this test, the measurement range was significantly lower. Figure 4 shows the aerial view of the vehicle path, and the variation of RSSI with the distance between transmitter and receiver at measurement location 3.

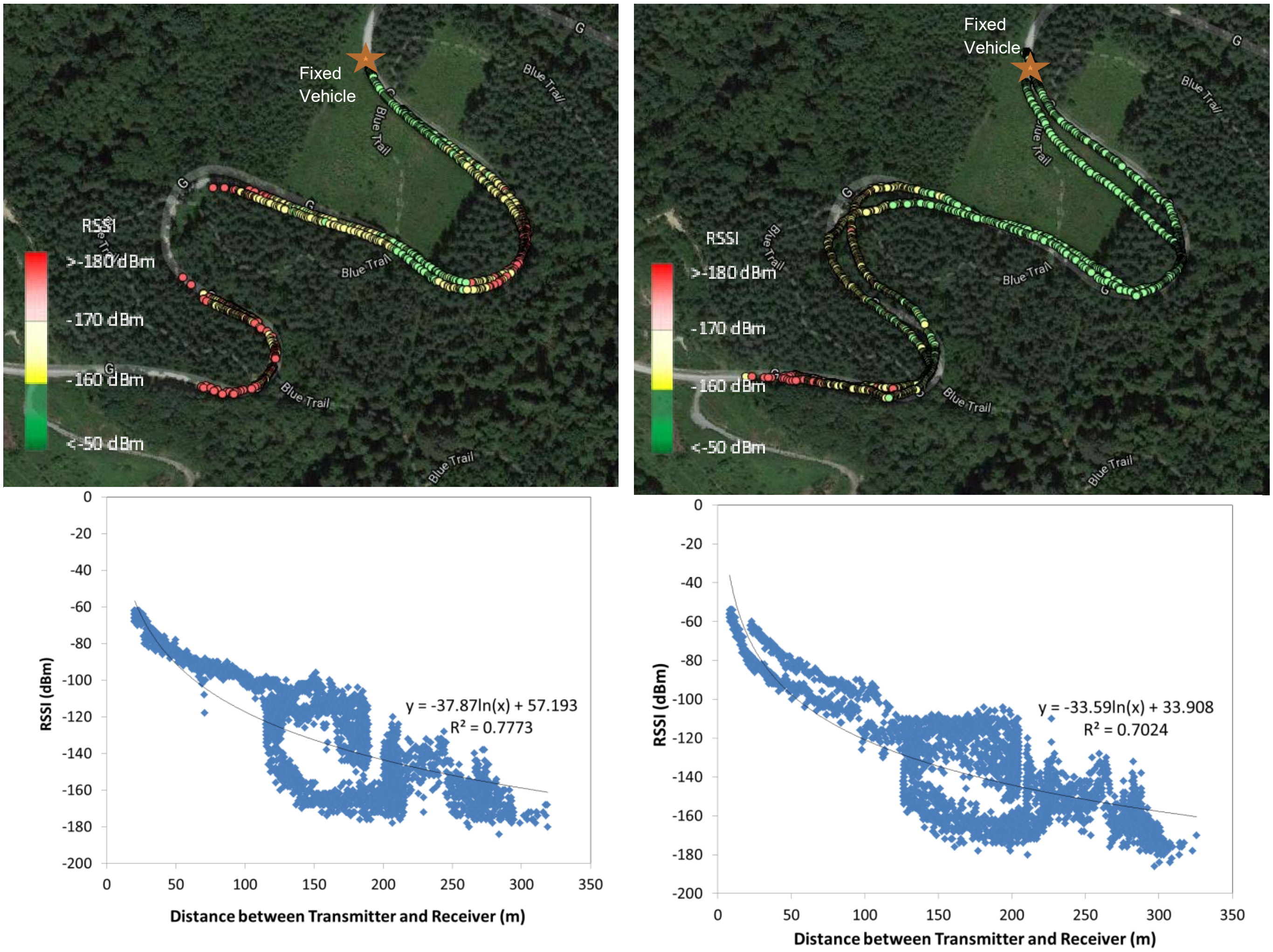


a) OBU with 5 dBi gain antenna on transmitter and receiver vehicles

b) RSU with 12 dBi gain antenna on transmitter and receiver vehicles

Figure 4. Coverage range and path loss of 5.9 GHz DSRC at measurement location 3.

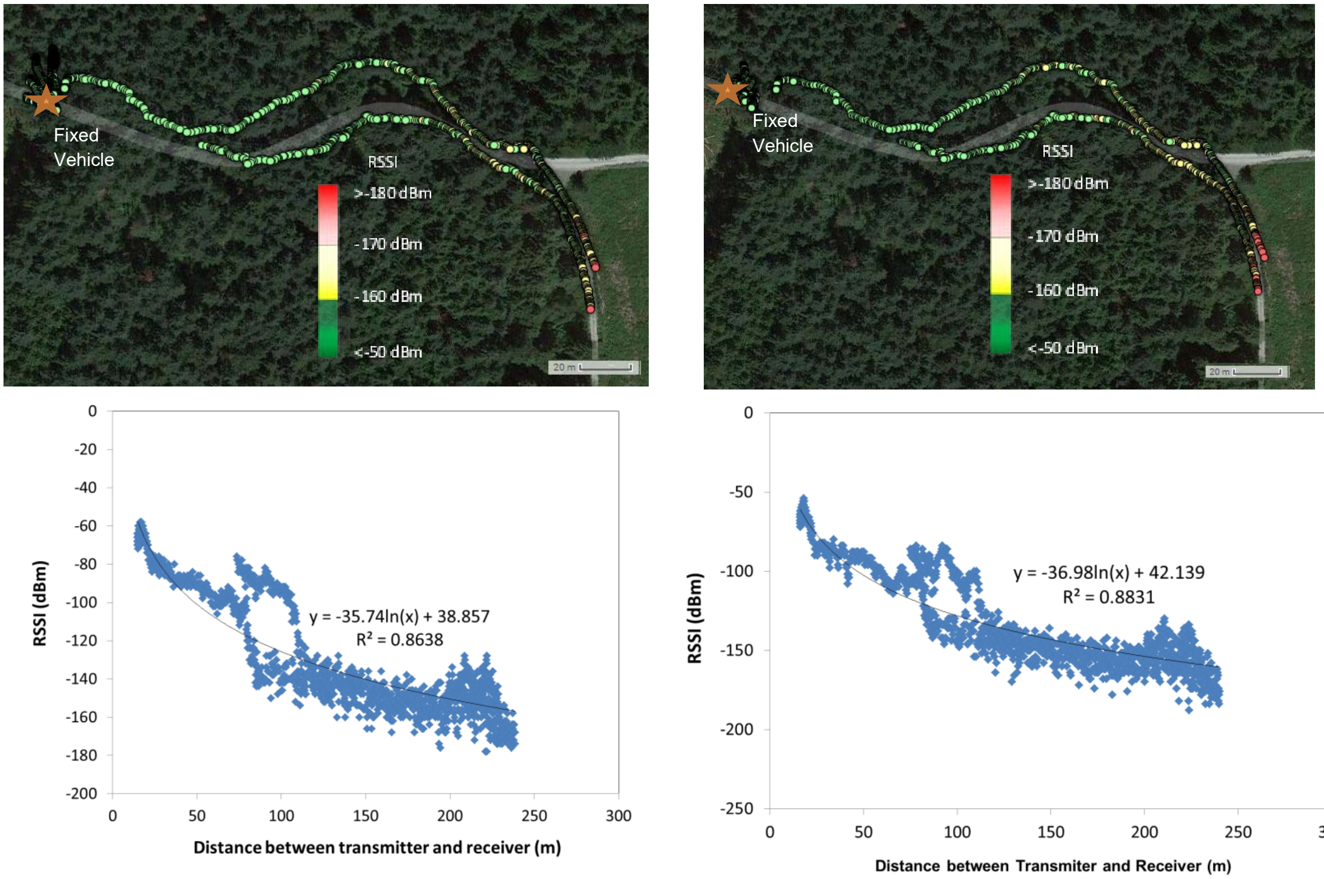
The site of measurement location 4 was another winding road with a cleared stand near the transmitter vehicle. The stem density at this location was 285 stems/ha and the volume was 263 m^3/ha. Figure 5 shows the aerial view of the distance covered, and variation of RSSI with the distance between transmitter and receiver at measurement location 4. The coverage range for this location was the same as the baseline. However, when the OBU was outfitted with a 5 dBi gain antenna, there were some areas of poor coverage where communication was lost.



a) OBU with 5 dBi shark fin antenna b) RSU with 12 dBi antenna

Figure 5. Coverage range and path loss of 5.9 GHz DSRC at measurement location 4.

The site of measurement location 6 was an example of intersection awareness with limited sight distance. Figure 6 shows the aerial view of the distance covered, and variation of RSSI with the distance between transmitter and receiver at measurement location 6. The stem density at this location was 340 stems/ha and the volume was 510 m^3/ha. In all cases, due to thick vegetation, the signal dropped dramatically after 200 m and the coverage range was almost the same.



a) OBU with 9 dBi antennas

b) RSU with 12 dBi antenna

Figure 6. Coverage range and path loss of 5.9 GHz DSRC at measurement location 6.

900 MHz V2V radio coverage

At measurement location 1 there was a one-lane bridge at the bottom of a dip. This location demonstrates the coverage when the vehicle is approaching a one-lane bridge on resource roads. Figure 7 presents comparison of 5.9 GHz and 1 W 900 MHz V2V communication range for measurement location 1. The coverage range with the 900 MHz was more than double than 5.9 GHz range. The signal was lost at the end of the road for the 900 MHz; therefore, the coverage range for 10 W 900 MHz V2V was not measured at this location. The signal was a sufficient distance to warn vehicles of the approach to a one lane bridge.

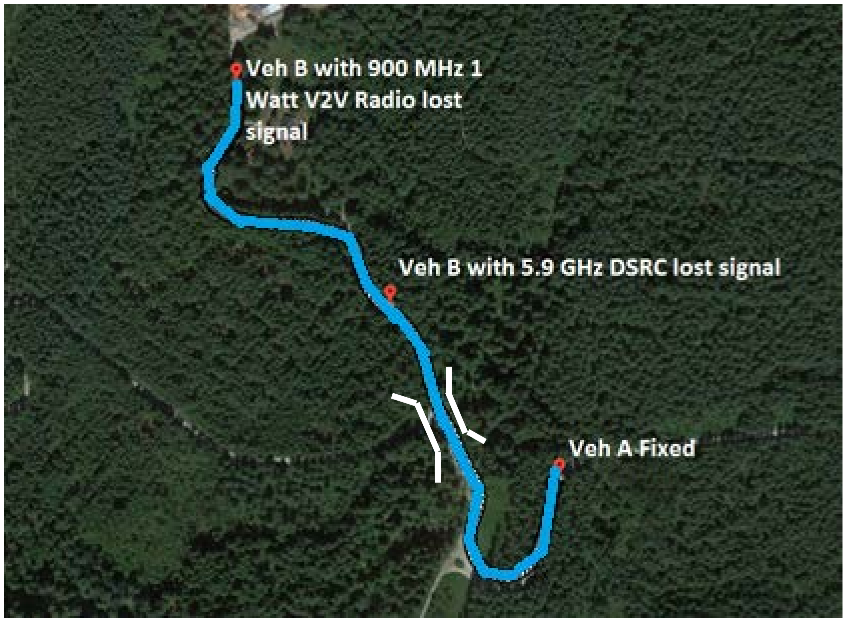


Figure 7. Comparison of 5.9 GHz and 900 MHz V2V communication range for measurement location 1.

Figure 8 shows the comparison of 5.9 GHz DSRC and 900 MHz V2V coverage range at measurement location 2. The road is winding with elevation difference. The packets were received intermittently for 5.9 GHz DSRC in the baseline trial. Although the signal may be lost at certain points on the road it could be reacquired a few meters later, increasing the coverage range of the system. This phenomenon did not occur during the test conducted for this study; as a consequence, the range is lower than the range found during the reference tests. A longer coverage range was obtained with 10 W 900 MHz V2V radios, which is more suitable for resource road safety applications.

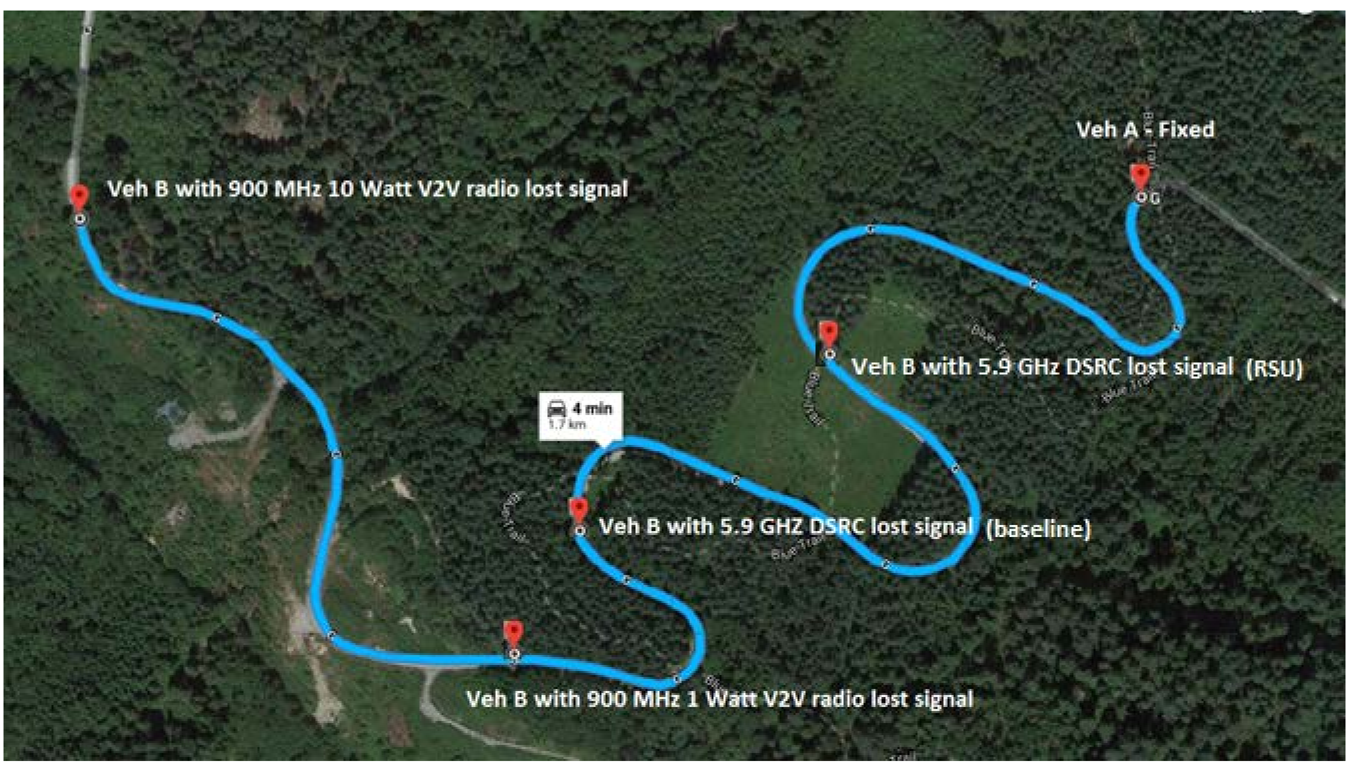


Figure 8. Comparison of 5.9 GHz and 900 MHz V2V communication range for measurement location 3.

Figure 9 presents the coverage range of 900 MHz V2V at measurement location 6 with the intersection awareness and limited sight distance. Due to thick vegetation, the signal dropped considerably after 200 m for 5.9 GHz DSRC radios. However, 900 MHz V2V radio signal was able to penetrate through this vegetation much better due to the longer wavelength than 5.9 GHz, and the resulting coverage range was more than 500 m. The test until loss of communication couldn't be carried out for the 900 MHz V2V due to the limited road length at this measurement location.

Figure 9. Comparison of 5.9 GHz and 900 MHz V2V communication range for measurement location 6.

Due to the limited road section at measurement location 6, another test was conducted to study the coverage range of 900 MHz V2V in very thick vegetation. Figure 10 illustrates the coverage range of 1-W and 10-W 900 MHz V2V radios at measurement location 7. Table 8 summarizes the coverage range of 900 MHz V2V radios at different measurement locations with 1 W and 10 W transmit powers. The coverage range for 1 W 900 MHz varied from 500 to 551 m in forest environments, whereas the coverage range for 10W 900 MHz varied from 700 to 970 m in forest environments and line-of-sight coverage was more than 4 km.

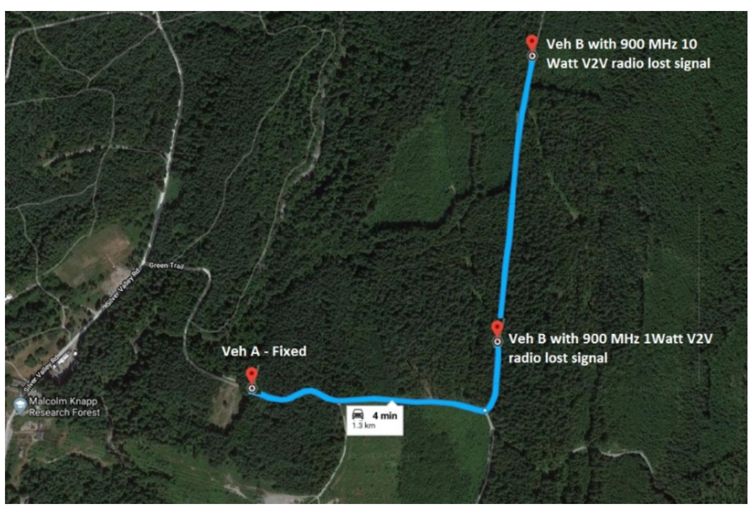


Figure 10. 900 MHz V2V coverage around measurement location 7.

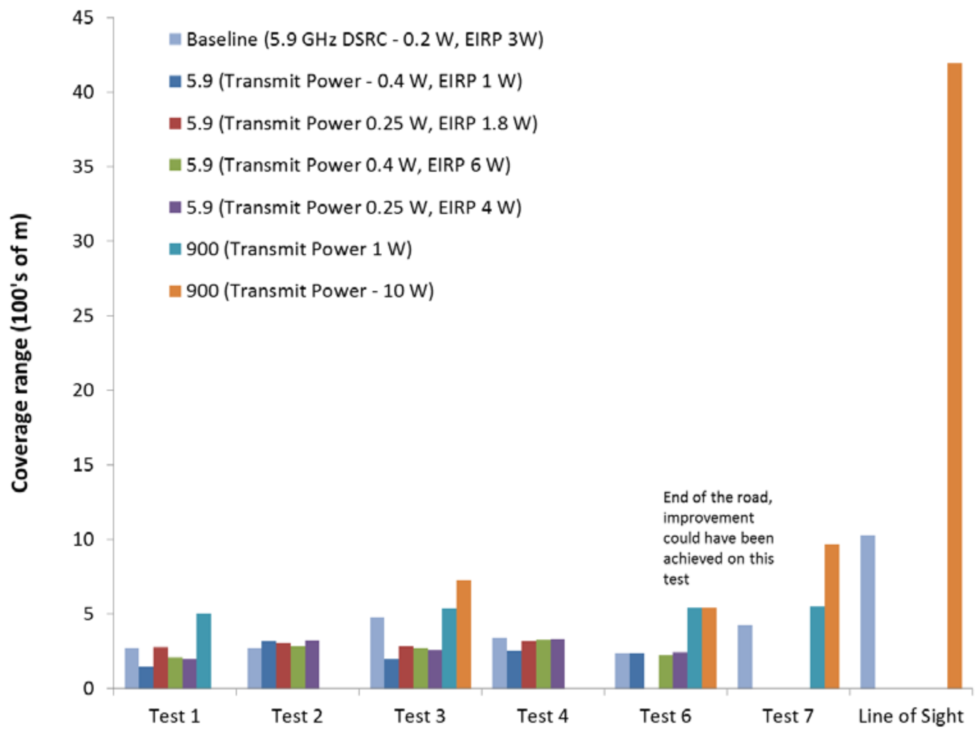
Table 8. 900 MHz V2V coverage range

Test site	Transmit power (W)	Road length (m)	Coverage distance (point to point) (m)
1	1	793	503
3	1	1200	535
3	10	1700	727
6	1	870	540[a]
6	10	870	540 [a]
7	1	650	551
7	10	1300	969
LOS	10	4200	4190

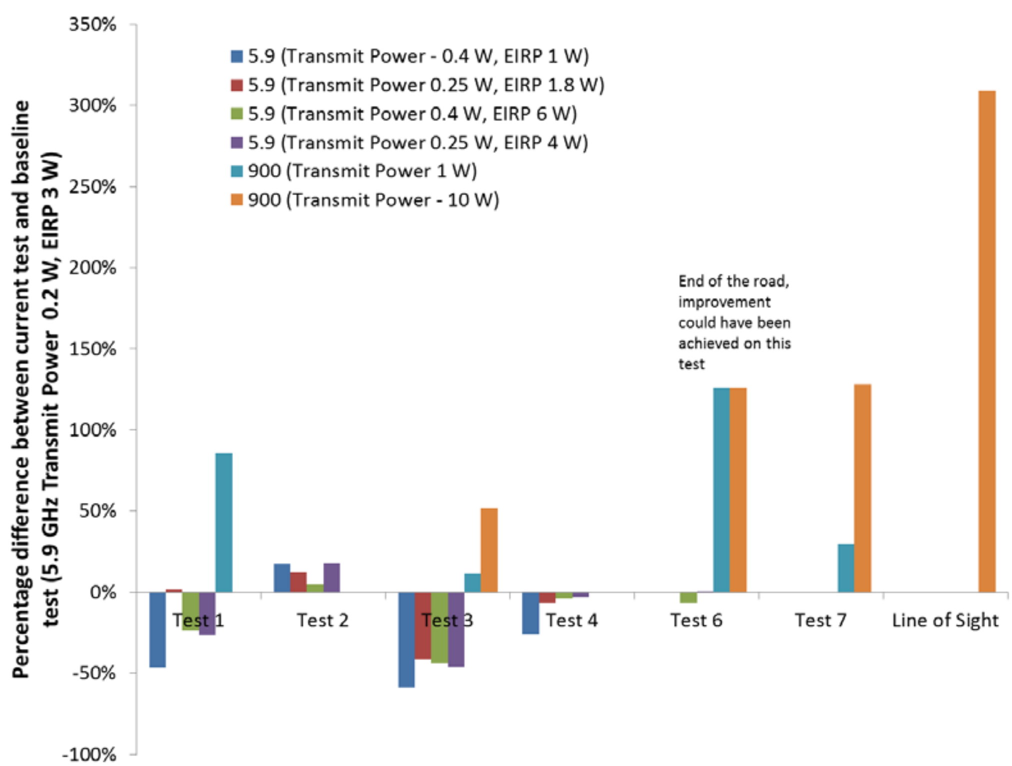
[a] End of the road before loss of signal. More coverage could have been obtained attained in this test

Comparison of the coverage

Figures 11a and 11 b compare, in relative and absolute terms, the variation in communication range of 5.9 GHz DSRC and 900 MHz V2V to the baseline DSRC system, measured at various locations under different conditions. There was a negative percentage difference between high gain 5.9 GHz DSRC and baseline in most of the measurement locations except in test 2. The coverage range for 900 MHz was effective and a higher percentage gain was found for test 6, test 7, and the line-of-sight tests.



a) Absolute comparison



b) Relative comparison

Figure 11. Comparison of current coverage results with baseline results.

Frequency band for V2V communication in forest operations

On resource roads, the traffic density and vehicle flow are much lower than that found in urban environments; therefore, the extended range with the use of multi-hop will not be applicable in resource roads unless a different routing protocol is used and there are RSUs every 500 m or so. Subsequently, greater communication distance between vehicles is required on resource roads. Figure 12 illustrates the minimum communication range required for V2V communication. Figure 13 is a typical example of V2V communication on resource roads that requires extended coverage. Currently, 5.9 GHz DSRC does not meet this criterion. However, 5.9 GHz DSRC will potentially be mandated in the near future; therefore, 5.9 GHz DSRC or mmWave radar communication would be used in close proximity communication as a fail-safe system for redundancy.

On one-and-a-half–lane or two-lane width resource roads, the current etiquette is that a following vehicle would communicate with the lead vehicle before a passing manoeuver, or the lead vehicle would communicate with the following vehicles to direct them for passing. This etiquette could be adapted in V2V communication with short-range communication such as 5.9 Hz DSRC. Communication used in urban settings such as rear-end collision avoidance using routine 5.9 GHz DSRC safety messages and extended emergency brake lights using event safety messages (Jiang et al., 2006) are also applicable to resource roads.

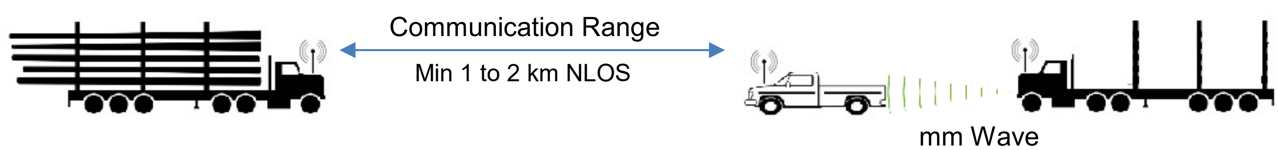


Figure 12. Requirement of V2V communication on resource road

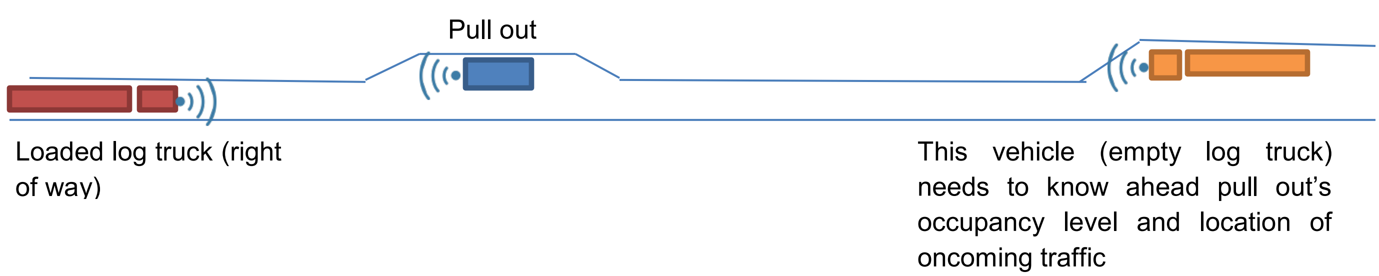


Figure 13. Example of V2V on resource road.

New cellular-based technology, cellular vehicle-to-everything (C-V2X), is being developed that reduces the number of base stations required in vehicle-to-everything (V2X) communication (Uhlemann, 2018), which will be ideal for resource road applications. The traffic flow, traffic density, and driving conditions on the resource roads are quite different than the urban roads and highways. Therefore, the safety and data exchange applications need to be tailored for resource road use with the appropriate vehicular communication technology. Table 9 presents the suitability of radio technology for V2X communication in resource road applications.

Table 9. V2X communication for resource road applications

Communication type	Description	5.9 GHz DSRC	C-V2X	UHF 600-900 MHz radio
Vehicle to network (V2N)	Transmit load info, compliance info on private network	Suitable	Ideal	-
Vehicle to infrastructure (V2I)	Alerts vehicles of bridge's load capacity, pull-out occupancy, road conditions etc.	Suitable	Ideal	Suitable
Vehicle to scale (V2S)	Transmit load info	Suitable	Suitable	Ideal
Vehicle to grader (V2G)	Transmits road roughness info for road maintenance	Suitable	Ideal	Suitable
Vehicle to machine (V2M)	Alerts presence and transmit load information	Ideal	Suitable	Suitable
Vehicle to vehicle (V2V)	Alerts vehicle's presence nearby	Ideal for short range	Suitable	Ideal for long range
Vehicle to worker (V2W)	Alerts worker's presence and vice versa	Ideal	Suitable	Suitable

Figure 15 illustrates some trade-offs that could be made with 5.9 GHz DSRC communication that would address resource road V2V communication. A greater communication range at NLOS is required for resource road operations, due to narrower roads and limited passing locations. Less interference with other frequency bands helps facilitate this. The transmit power of 7 dBm is needed for 150 m coverage range using IEEE802.11p technology (Abdeldime et al., 2014). Currently, the maximum transmit power for 5.9 GHz DSRC is limited to 28 dBm, so the maximum coverage range that could be obtained at this power level is around 600 m. C-V2X technology claims to have extended coverage for the same power level with better link budget (Wang et al., 2017; Misener, 2017; Qualcomm, 2017). However, this claim is based on Qualcomm Research simulation and an Ericsson-Qualcomm trial, which is yet to be verified by a third party. In addition, this technology has not yet been tested in resource road environments.

DSRC operating in the UHF 600–900 MHz range, which uses white space spectrum (over-the-air analog TV signals) holds promise with its longer range capability and suitability for reliable communication in remote locations, as the radio waves at this frequency can penetrate through obstacles more easily and thereby achieve greater range. For longer range, the latency and throughput requirement can be relaxed. In the future, for platooning and automation, higher latency and throughput would be required, which could be addressed with the use of dual-band V2V radios (one operates in SHF or EHF range for higher latency and throughout, and another operates in UHF range for longer coverage distance.)

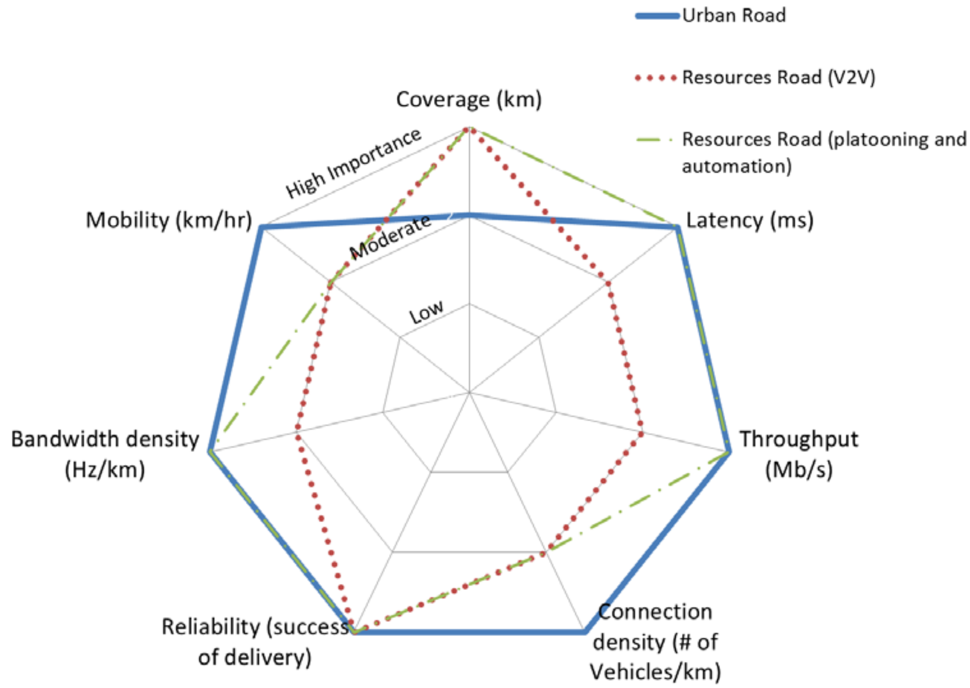


Figure 14. Requirements for V2V communication in different scenarios.

Summary and conclusion

To determine the operating frequency and transmit power best suited for resource road safety applications, FPInnovations and the UBC Radio Science Lab have collaboratively tested the performance of V2V radios at different frequencies, transmit powers, and antenna gains in the UBC Malcolm Knapp Research Forest.

The 5.9 GHz DSRC testing with different allowable transmit powers and antenna gains did not exceed the 1-km (line-of-sight) and 350-m (non-line-of-sight) coverage ranges found in the baseline study. The line-of-sight (LOS) coverage for 10-W 900 MHz was about 4.2 km, which is four times greater than 5.9 GHz DSRC LOS coverage. The coverage range for 1 W 900 MHz varies from 500 to 551 m in forest environments, which is 60% more than 5.9 GHz DSRC coverage, whereas the coverage range for 10-W 900 MHz varied from 700 to 970 m in forest environments, which is 170% more than 5.9 GHz DSRC coverage. Environmental factors such as vegetation and topography have a strong influence on the coverage, and the losses and sensitivity may differ for different transmit power levels, vegetation, frequencies, and environmental factors.

Considering the requirement for the V2V safety applications, the results obtained for 900 MHz communication systems with 10 W transmit power is promising for resource-road connected-vehicle safety applications such as collision avoidance. Performance at other frequencies in the 600–900 MHz range remains to be tested. The requirements for certain parameters such as latency and throughputs could be relaxed for longer-coverage V2V communication on resources road. Considering the possibility of platooning and automation on resource roads, the use of 5.9 DRSC is still recommended for lower latency and higher throughput. Thus, the use of dual-band V2V radios (one operates in SHF or EHF band for lower latency and higher throughout and another operates in UHF frequency band for longer coverage distance) could potentially meet the resource roads' ITS application needs.

Next steps

More testing in the 600–900 MHz spectrum band and 5.9 GHz with C-V2X radio is needed. The following steps are recommended for testing:

- Test off-the-shelf 900 MHz V2V radio with in-cab dashboard in typical forest working conditions to study its effectiveness in increasing resource road safety.
- Study the performance of other off-the-shelf radios in the 600–900 MHz band at the same measurement locations for ITS application.
- Test any coverage improvement made with the off-the-shelf C-V2X radios.
- Seek feedback from ISED and the ITS community on the possibility of using dual-band radios for resource road applications.
- Study the possibility of using dual-band radios and integration of the 900 MHz and 5.9 GHz communication data.
- Test radio systems in additional forest environments and different weather conditions.

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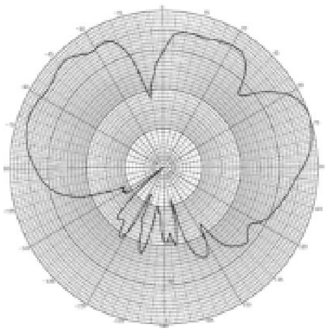
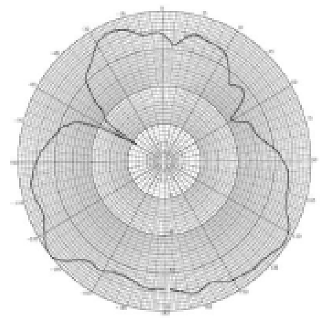
Appendix A – Antenna radiation pattern

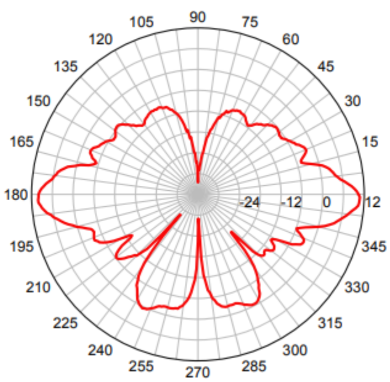
Elevation plot

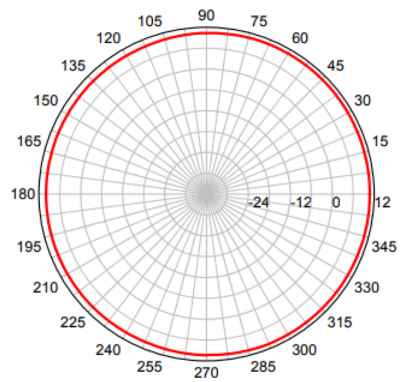


Azimuth plot



a) 5dBi shark fin antenna

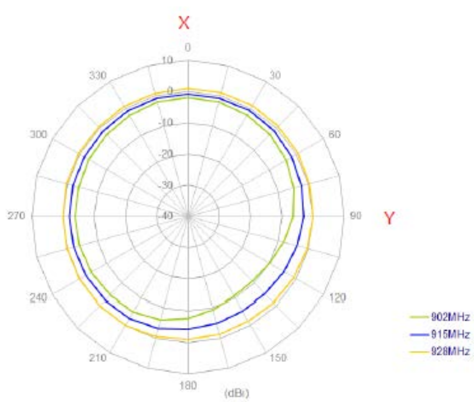




b) 9dBi vertical pole antenna

Figure 15. OBU 5.9 GHz antenna radiation pattern.

Elevation plot



Azimuth plot

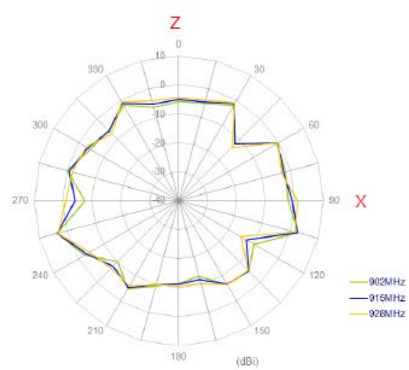


Figure 16. 900 MHz V2V 3.5dBi antenna radiation pattern.

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