Evaluation of 5.9 GHz DSRC Vehicle to Vehicle Communication in Resource Road Environment – Initial Trial Results

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ABSTRACT

Connected Vehicles, a part of Intelligent Transportation Systems, is the most promising upcoming technology that will improve safety drastically, address a driver shortage issue and possibly lead to important savings. Dedicated Short Range Communication (DSRC) is a connected vehicle technology mainly designed for urban environment for vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication. However, the operating environment and road conditions on the resources roads are very different than structured roads. Therefore, in this study, the performance of 5.9 GHz DSRC system is evaluated in resources road environment at UBC's Malcom Knapp Research Forest. 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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Table of contents

1. Background 5
2. Introduction 6
3. Objectives 8
4. Methodology 8
5. Results 10
6. Discussions 21
7. Conclusion 22
8. Next Steps 22
9. References 22
10. Appendix A Stand Density Estimates for DSRC Testing Locations (Power 2017) 23
11. Appendix B Free Space Range Estimation Using Friis Equation 25

List of figures

Figure 1. DSRC communication architecture (Campolo et. al. 2015) 6
Figure 2. Measurement locations in MKRF, Maple Ridge BC 10
Figure 3. 5.9 GHz DRSC coverage comparison for different test scenarios at transmit power of 23dBm 12
Figure 4. Topography and vegetation condition around measurement location 1 13
Figure 5. PDR vs. Transmitter Distance for measurement location 1 13
Figure 6. Topography and vegetation condition around measurement location 2 14
Figure 7. PDR vs. Transmitter Distance for measurement location 2 14
Figure 8. Topography and vegetation condition around measurement location 3 15
Figure 9. PDR vs. Transmitter Distance for measurement location 3 15
Figure 10. Topography and vegetation condition around measurement location 4 16
Figure 11. PDR vs. Transmitter Distance for measurement location 4 16
Figure 12. Topography and vegetation condition around measurement location 5 17
Figure 13. PDR vs. Transmitter Distance for measurement location 5 17
Figure 14. Topography and vegetation condition around measurement location 6 18
Figure 15. PDR vs. Transmitter Distance for measurement location 6 18
Figure 16. Topography and vegetation condition around measurement location 7 19
Figure 17. PDR vs. Transmitter Distance for measurement location 7 19
Figure 18. Topography and vegetation condition around measurement location 8 20

Figure 19. PDR vs. Transmitter Distance for measurement location 8 20

List of tables

Table 1. DSRC Parameters (Source - IEEE 802 LAN/MAN Standards Committee) 7

Table 2. Band Plan for Channels (ISED 2007) 7

Table 3. Study locations at Malcolm Knapp Research Forest 9

Table 4. Summary of coverage for 5.9 GHz DSRC at different measurement locations within MKRF area 11

Table 5. Estimated coverage for 5.8 GHz and 700 MHz at different transmit power 21

Table 6. Tree Density: Stems per hectare (>= 10 cm DBH) 23

Table 7. Tree Density: Stems volume (m^3) per hectare (>= 10 cm DBH) 23

Table 8. Description for stratum for each test location.. 24

1. BACKGROUND

Most resource roads are one and half lane wide undivided gravel roads with pull-outs built alongside the main driving surface and in some cases the road width is one lane wide. Mobile (two-way radios) are used on resources roads to communicate location and direction of travel. Communications are made with the use of standardized radio communication signage, a set of dedicated resources radio channels and standardized call procedures. These roads are typically radio assisted while a few are radio controlled. On radio controlled roads, all vehicles are expected to have and use mobile radios, and drivers would rely more heavily on communications of location and direction. In the case of radio assisted roads, radios are generally not mandatory. However, heavy radio traffic volume causes frequent overlapping calls and interference resulting in reducing safety of radio communications systems. In addition other hazards that exist on these roads are narrow lanes and shoulders, excessive speed, high traffic volumes, sharp horizontal and vertical curves, limited passing, stopping and horizontal sight distance, narrow bridge, limited sight distances at intersections, frequent roadsides obstacles, poor visibility due to poor quality aggregate leading to excessive dust thereby obscuring the driver's view of the road and oncoming traffic, changing road surface conditions due to freezing rain and snow, unmarked hazards, other road users failing to follow traffic control procedures and wildlife (BCFSC 2013). There are several Intelligent Transportation System (ITS) safety applications such as approaching emergency vehicle warning, cooperative collision warning system, and cooperative adaptive cruise control that are applicable to resources roads application. However, this ITS safety applications are mainly designed for urban environment and the operating environment and road conditions on resources roads are very different than the structured roads.

Since 2006, FPInnovations has been part of the BC Radio Communications Working Group (that includes the Ministry of Forests and Range (MOFR), ISED (formerly Industry Canada), BCFSC (formerly Forestry TruckSafe) and the Council of Forest Industries) in creating a comprehensive communications strategy for all of the radio-assisted resource roads in BC with the intent of improving user safety. The strategy had three key parts: refine resource road signage, create standardized radio calling procedures, and establish a bank of radio channels that are dedicated for resource road use in BC (Evans and Bradley 2013). As a result of this study, currently 35 VHF channels are dedicated to resources roads in BC and radio transmitting power is limited to 30 W. With the advancement in communications and US DOT's current rulemaking for connected vehicles, the 5.9GHz DRSC equipped vehicles are expected to be on the road in the near future. The performance of this system is unknown in a Canadian resources road environment where the terrain, topography and traffic density are significantly different than urban environment. Therefore, FPInnovations and UBC have collaborated to evaluate the performance of existing 5.9 GHz DSRC systems and are in a process of developing the DSRC system that will be operating in MHz range for resource road use. Figure 1 shows the DSRC communication architecture with different layers and standards requirement. Any modifications within DSRC systems will require adhering to the appropriate standards and local regulations requirements; for example, any change in the spectrum frequency and bandwidth will require modification in the MAC layer.

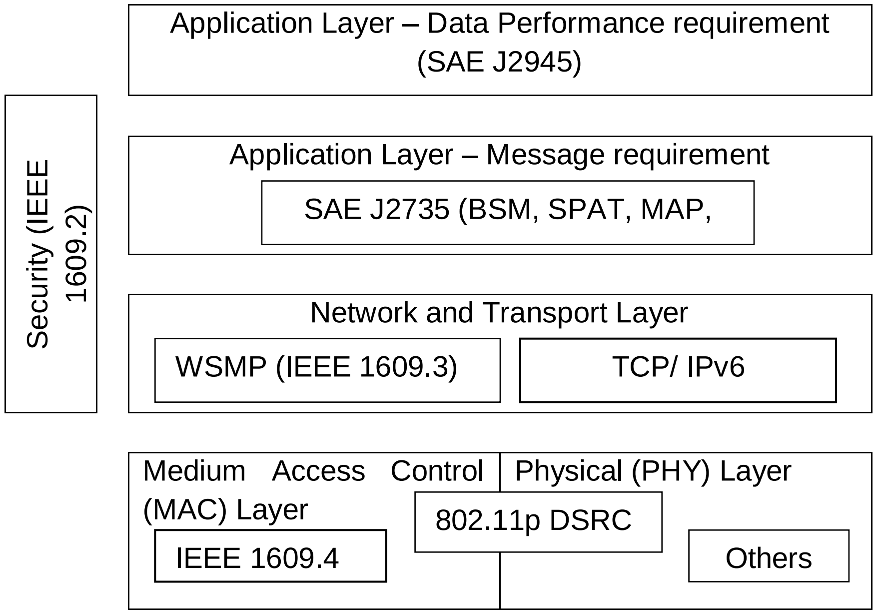


Figure 1. DSRC communication architecture (Campolo et. al. 2015)

2. INTRODUCTION

Canada has more than one million km of road networks; of which, 60% is unpaved roads that are shared between industrial and public traffic. The maintained unpaved road networks with an efficient and safe road transportation system contribute to Canada's economic growth and support its competitiveness in the global economy (Transport Canada 2011). Connected Vehicles technology is one of the ways to make the transportation efficient and safer, which would also support the Canada's Road Safety Strategy 2025's goal that is making the roads in Canada as the safest roads in the world (CCMTA 2016). Connected Vehicles have potential for substantial impact on safety; therefore, Canada will likely mandate this technology in the near future. One of the wireless communication technologies for Connected Vehicles that is extensively studied and standardized is Dedicated Short Range Communications Technology (DSRC). DSRC is a Wi-Fi derivative technology developed to meet specialized needs for secure, low-latency, wireless mobile data communications that facilitate continuous, high-speed, trusted and authenticable data exchange among moving vehicles, and between vehicles and roadway infrastructure or mobile devices, to support safety-critical applications (Bettisworth et. al. 2015). With no other proven standardized wireless technology at present to support Connected Vehicle safety applications, DSRC has gained prominence in ITS applications. However, the frequency used for DSRC vehicle-to-vehicle (V2V) communication is predominantly 5.9 GHz (Spectrum allocation – 5.85 to 5.925 GHz) and DSRC vehicle-to-roadside (V2R) communication is 900 MHz (Spectrum allocation – 902 to 928 MHz) and parameters for 5.9 GHz DSRC systems is presented in Table 1. The band plan for 5.9 GHz DRSC is illustrated in Table 2 with maximum EIRP for each channel. The higher limit of EIRP is permitted only for state or local governmental entities. The FCC has designated Channel 172, a low power, short range communication, exclusively for vehicle to-vehicle safety communications for collision avoidance and Channel 184 is designated exclusively for high-power, longer distance public safety applications involving safety-of-life and property. The typical range for DSRC is 300m with a maximum range of 1000m. The coverage is limited by the allowable power for each channel (US DOT 2015). The height of antenna is restricted to 8 m for Road Side Units (RSU) and in special provision up to 15 m.

Table 1. DSRC Parameters (Source - IEEE 802 LAN/MAN Standards Committee)

PARAMETERS	5850 - 5925 MHz Band
SPECTRUM USED	75 MHz
DATA RATE	6 Mbps - 27 Mbps
COVERAGE	Overlapping communication zones needed and allowed
ALLOCATION STATUS	Primary Status (high protection)
INTERFERENCE POTENTIAL	Sparsely located Military Radars Very Sparsely located Satellite Uplinks
MAXIMUM RANGE	1000 m (~ 3000 ft)
CHANNEL CAPACITY	7 channels
POWER (Downlink)	Nominally less than 33 dBm (2 W)
POWER (Uplink)	Nominally less than 33 dBm (2 W)

Table 2. Band Plan for Channels (ISED 2007)

		Ch 175 Service 20 MHz (23dbm)		Control Channel	Ch 181 Service 20 MHz (23 dbm)		
Channel No.	Ch 172 Service 10MHz	Ch 174 Service 10MHz	Ch 176 Service 10MHz	Ch 178 10MHz	Ch 180 Service 10MHz	Ch 182 Service 10MHz	Ch 184 Service 10MHz
Frequency Range (MHz)	5855-5865	5865 – 5875	5875 – 5885	5885 – 5895	5895 – 5905	5905 – 5915	5915 – 5925
Transmit Power Limit - Max EIRP[1] (dBm)	33	33	33	33/44.8	33/44.8	23	33/40
Application	Collision Avoidance	Med Range Service	Med range Service	Control	Short Range Service	Short Range Service	Intersections
Allocation	Dedicated Public Safety	Shared Public Safety/Private					Dedicated Public Safety
Channel Reservation			Special Licence Zone			Special Licence Zone	

The performance of these DSRC radio channels on the Canadian resources roads is yet to be determined; therefore, having information on the performance of these systems would assist in fine tuning and rulemaking.

[1] Effective Isotropic Radiated Power

3. OBJECTIVES

The overall objective of this project is the development of DSRC system for Canadian resources roads using the established V2V safety framework. To achieve this objective, FPInnovations and UBC conducted the following tests with each test providing the direction for next steps:

- Conducted a series of tests for evaluating the performance of existing 5.9 GHz system at Channel 172 (designated for V2V safety communication – mainly collision avoidance) in Malcolm Knapp Research Forest that represents a typical forest terrain for Lower Mainland in BC
- Investigated the variation in DSRC radio wave propagation and document the circumstance in which the complete breakdown of communication link in the forest occurred

4. METHODOLOGY

The performance of the off-the-shelf DSRC operating at 5.85 - 5.925 GHz band range was evaluated in Malcolm Knapp Research Forest (MKRF) as it represents typical Lower Mainland forest. ARADA Systems' LocoMate DSRC OBU and RSU were used for V2V communication. Two pickup trucks that are commonly used as an industrial vehicle for transporting crews in forest industry were used for the measurements. One vehicle was equipped with RSU with the antenna height of approximately 1.5 m from the ground and was used a transmitter. Another test vehicle was equipped with LocoMate OBUs mounted on top of the roof i.e. 1.6 m from the ground. The ARADA units are not yet approved in Canada; however, the development licence was obtained from ISED (Industry Canada) prior testing. The devices' specs are as follows:

Power: Radio TX out power	23±1 dBm (0.2 Watts)
Receiver Sensitivity	-83±2 dBm for 16QAM modulation
Frequency	5850 MHz to 5925 MHz
Bandwidth and emission designator	10 MHz or 20 MHz (8M 26D1D)
Antenna	Dual antenna diversity system
Default Channel - 172	

The test was performed on February 23 and 24, 2017 to validate the range of an existing 5.9 GHz DSRC system (Ch 172 & Tx of 23 dBm) in a forest environment. Representative sections of the gravel road were selected as test sections, which were surveyed. The average temperature was 3.2ºC. There was no snow on the roads and trees near the measurement sites; however, there was snow accumulation on the side of the roads. Roads covered with snow were not considered in this test. Table 3 provides the latitude, longitude and elevation of the transmitter vehicle. Figure 2 shows the measurement locations at MKRF. Road K30 and G were active logging roads, where logging traffic were observed on K30 road during the test. The speed limit on MKRF roads were 30 km/hr. Two test passes were made at each measurement locations with one experimental vehicle fixed and other travelling away and toward the fixed vehicle in a straight line (line of sight), long curve (line of sight and non-line of sight), at the slope (non-line of sight). The average travel speed of moving vehicle was 15 km/hr.

Table 3. Study locations at Malcolm Knapp Research Forest

Test #	Road	Use Case	Transmitter Tx Locations		
			Lat	Long	Elevation (m)
1	G	Vehicle awareness/ one lane bridge/ Obstructed	49° 16' 15.61" N	123° 34' 24.38" W	153
2	G	Vehicle awareness/ LOS for 225 m and NLOS Obstructed	49° 16' 20.44" N	123° 34' 50.79" W	144
3	G	Vehicle awareness/ LOS Clearings and NLOS Semi Obstructed	49° 16' 20.44" N	123° 34' 50.79" W	144
4	G	Vehicle awareness/ LOS Clearings and NLOS Semi Obstructed	49° 16' 17.72" N	123° 35' 02.95" W	141
5	G	Vehicle awareness/ NLOS – one lane bridge Obstructed	49° 16' 12.45" N	123° 35' 10.18" W	101
6	A	Intersection awareness/ NLOS Obstructed	49° 15' 49.66" N	122° 33' 56.72" W	188
7	A	Intersection awareness / LOS Clearings and Juvenile plantation Semi Obstructed	49° 15' 43.32" N	122° 33' 50.79"W	156
8	K30	Vehicle awareness / LOS UnObstructed for about 450 m	49° 18' 43.92" N	122° 33' 07.97"W	343

Basic Safety Message (BSM) was exchanged between vehicles with the key information such as vehicle location, speed, acceleration and heading with a time stamp. Both vehicles were sending and receiving BSMs at 10 Hz i.e. 10 packets per second. Moving vehicle would travel until the vehicle completely exited the communication range for each test run and then would return back towards the fixed vehicle. The location along the road when no communication is observed between the two vehicles was marked in a georeferenced map for further survey. The Packet Delivery Ratio (PDR), which is one the key performance metrics, was estimated based on packet sent and received. PDR is the ratio of the summation of number of packet receive to the summation of number of packet send.

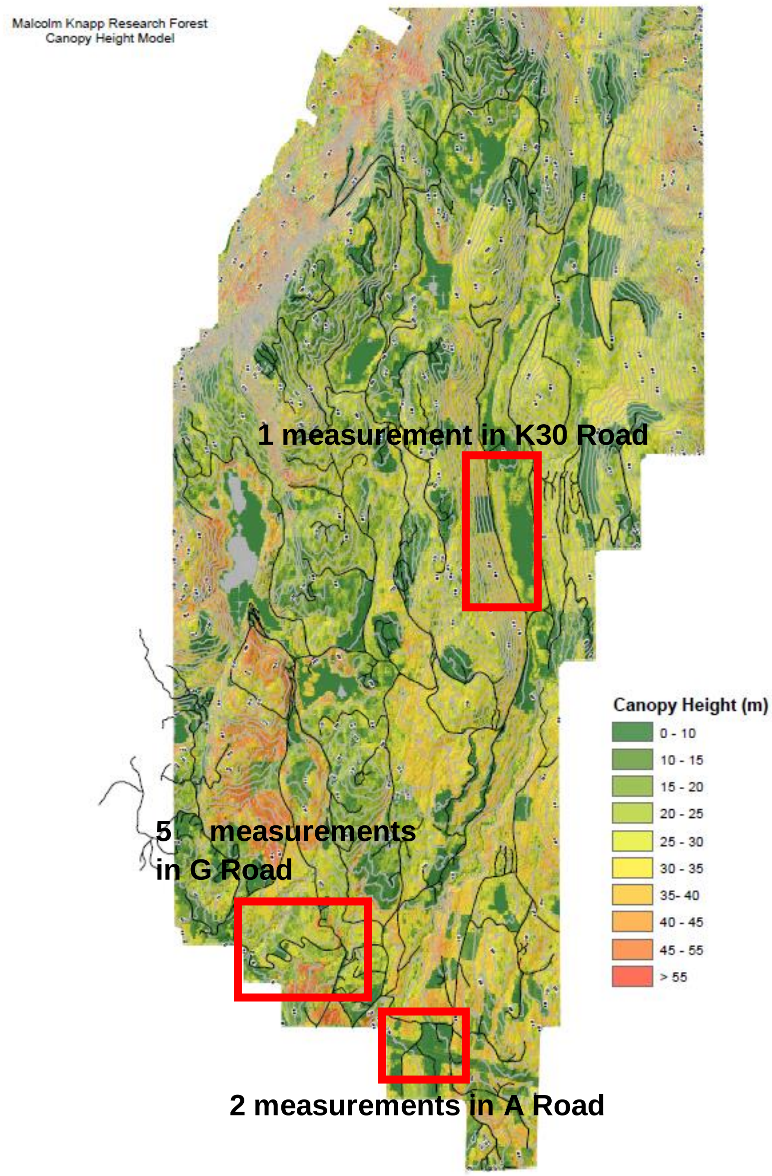


Figure 2. Measurement locations in MKRF, Maple Ridge BC

5. RESULTS

Measurements from eight different locations with different stem density and elevation, which represents the typical condition that the vehicles would encounter on resources road, are presented in Table 4. The stem density was weighted averaged by stratifying the area around the measurement locations and the detailed calculations are presented in Appendix A. The average communication range at 10% PDR is 346 m with one vehicle moving. Figure 3 illustrates the variation in communication range measured at different locations under different conditions. Assuming antenna gain and cable loss as -3 dBi for channel 172 Tx and Rx, the maximum theoretical free space coverage is estimated to be 1.6 km using Friis equation. The actual average communication coverage in forest condition is approximately 20% of the free space value.

Table 4. Summary of coverage for 5.9 GHz DSRC at different measurement locations within MKRF area

Test #	Vegetation description	Elevation difference [2] (m)	Road Length (m)/ Curvature	Max Observed Coverage [3] (m)	Max Range for 10% PDR[4] (m)
1	Old growth mixed with Douglas-fir plantation thinned and some road clearing stand with avg stem density of 330 stems/ha and avg stem volume of 690 m^3/ha.	-5	505/ C curve	279	271
2	Second growth Douglas fir thinned, mixed plantation unthinned and some road clearing stand with avg stem density of 293 stems/ha and stem volume of 280 m^3/ha,	18	361/ J curve	327	270
3	Douglas fir plantation thinned, mature mixed plantation unthinned and reforested plantation with stem density of 270 stems/ha and stem volume of 285 m^3/ha	60	850/ S curve	466	479
4	Douglas fir plantation thinned, mature mixed plantation unthinned and reforested plantation with stem density of 285 stems/ha and stem volume of 263 m^3/ha	48	849/ S curve	359	339
5	Douglas fir plantation thinned, mature mixed plantation unthinned and reforested plantation with stem density of 293 stems/ha and stem volume of 270 m^3/ha	17	651/ C curve	267	243
6	Mixed mature plantation and some reforested stems long roadside with avg stem density of 340 stems/ha and stem volume of 510 m^3/ha	1	283/ J curve	232	239
7	Mixed young plantation, mixed natural and right of way stems with avg stem density of 420 stems/ha and stem volume of 180 m^3/ha	-30	742/ U curve	423	414
8	Mature mixed natural and reforested trees with avg stem density - 360 stems/ha and avg stem volume - 585 m^3/ha	1	523/ level light of sight	513	514
Average Coverage				**358**	**346**

[2] Difference between transmitter (fixed) and reciever (lost connection); positive means transmitter is at higher elevation than reciever.
[3] Coverage range between transmitter and receiver measured using georeference map
[4] Coverage range measured used PDR data

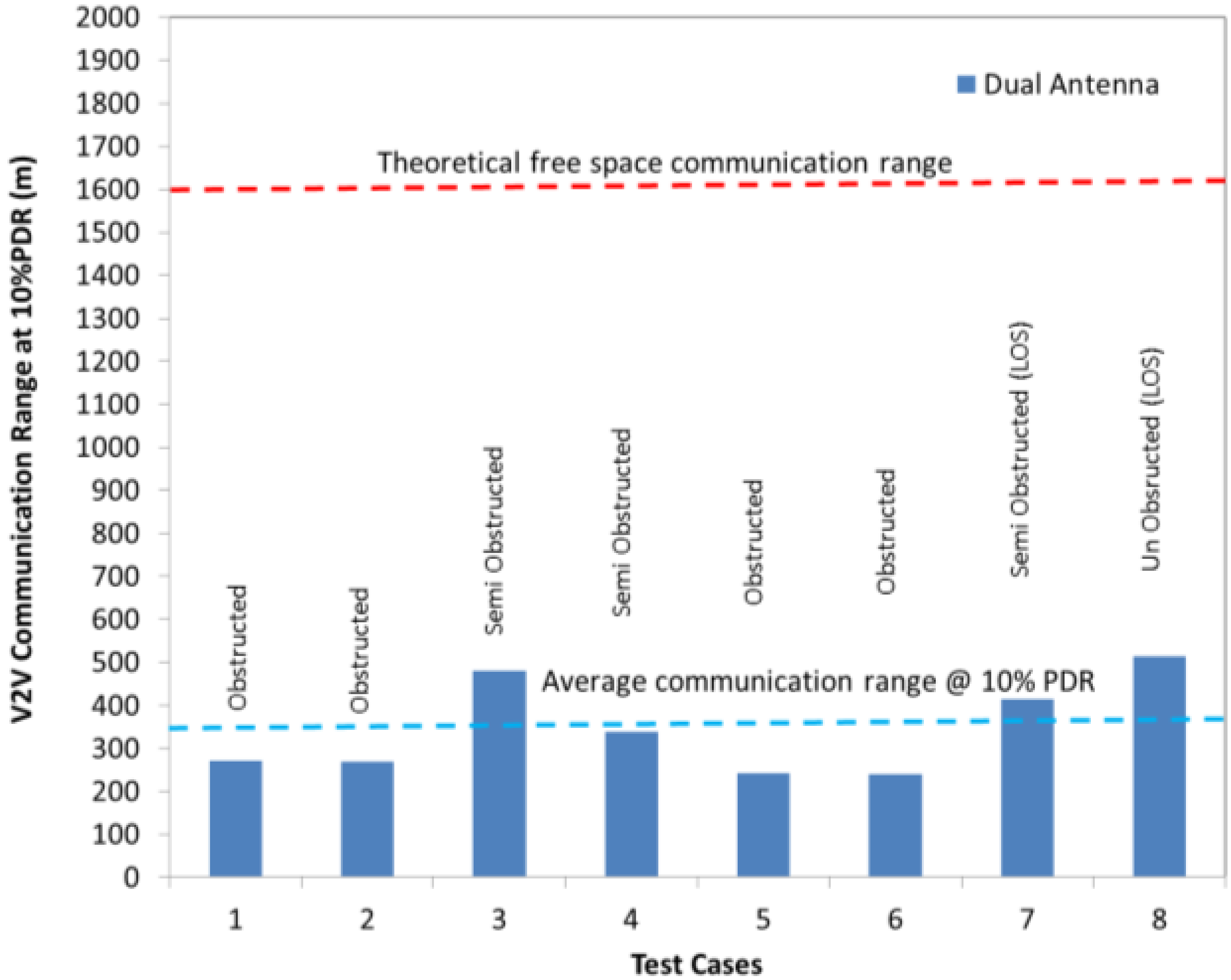
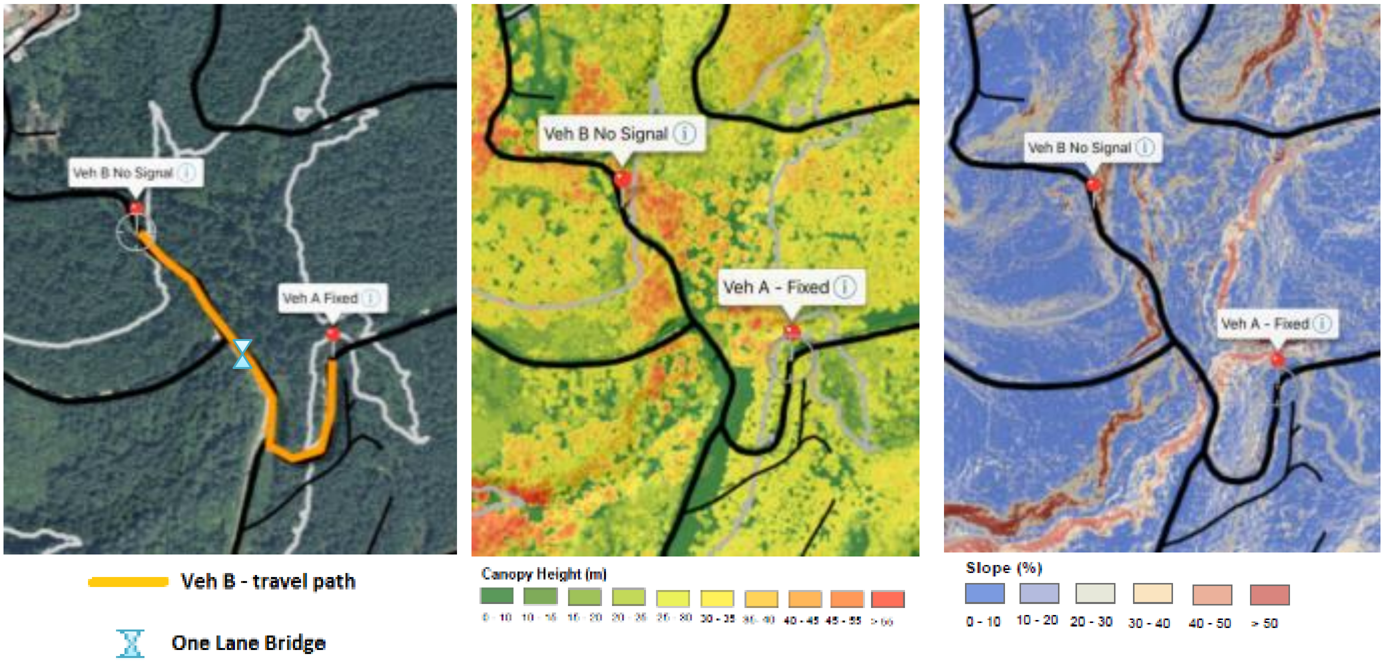


Figure 3. 5.9 GHz DRSC coverage comparison for different test scenarios at transmit power of 23dBm

At test location 1, there was a one lane bridge at the dip as shown in Figure 4. This location demonstrates the coverage at this particular instance when the vehicle is approaching one lane bridge on resource roads. Figure 4 shows the aerial view, canopy height and terrain slope contours. Figure 5 shows the variation of PDR with the distance between transmitter and receiver. The PDR was 90% at LOS and receiving packets continuously. Due to dense vegetation the PDR dropped considerably after the distance of 150 m between transmitter and receiver.



a) Aerial View b) Tree heights c) Terrain slope

Figure 4. Topography and vegetation condition around measurement location 1

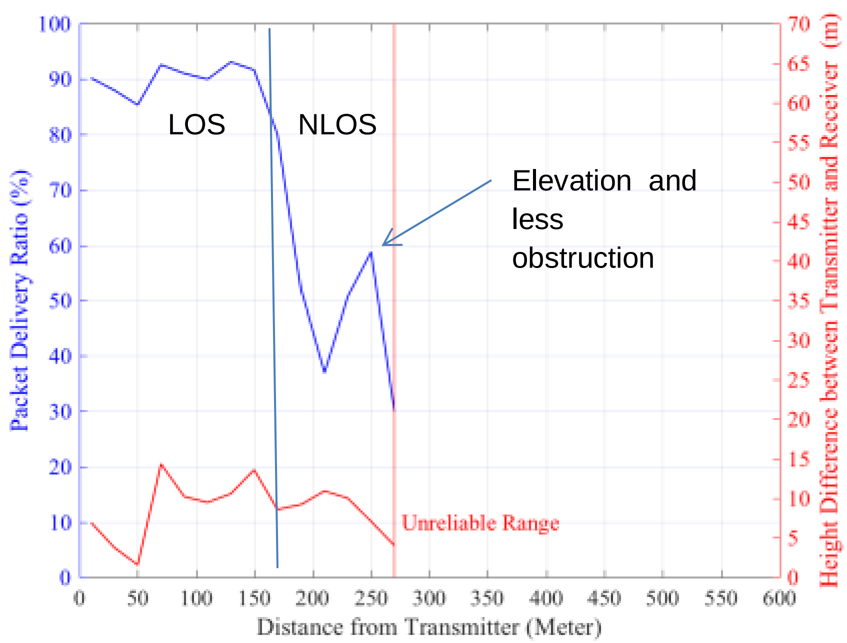
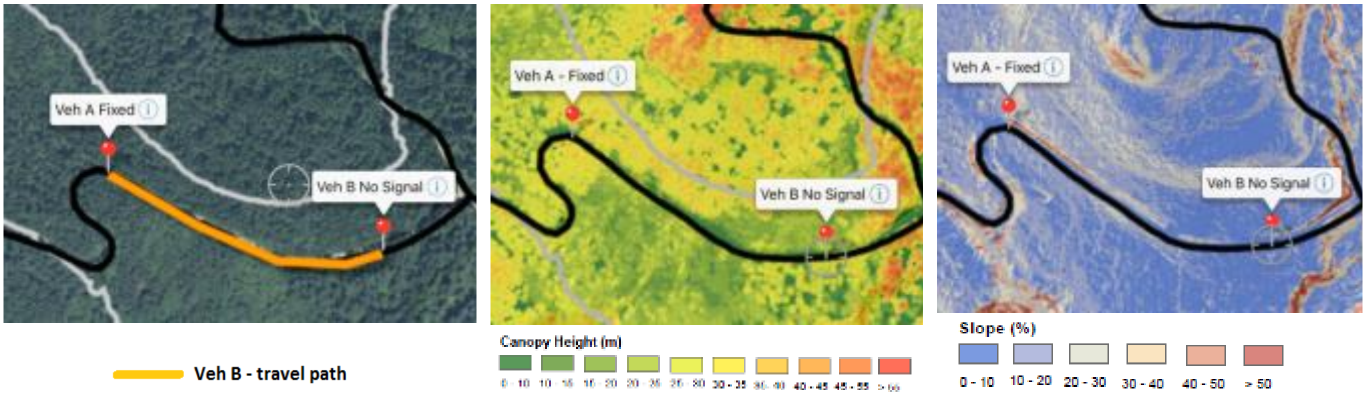


Figure 5. PDR vs. Transmitter Distance for measurement location 1

Figure 6 presents the vegetation, terrain condition around measurement location 2. This location demonstrates the vehicles approaching at 170 m horizontal curve radius in the resources roads. The range for packets received was 270 m. Figure 7 shows the variation in PDR with increased distance between transmitter and receiver.



a) Aerial View b) Tree heights c) Terrain slope

Figure 6. Topography and vegetation condition around measurement location 2

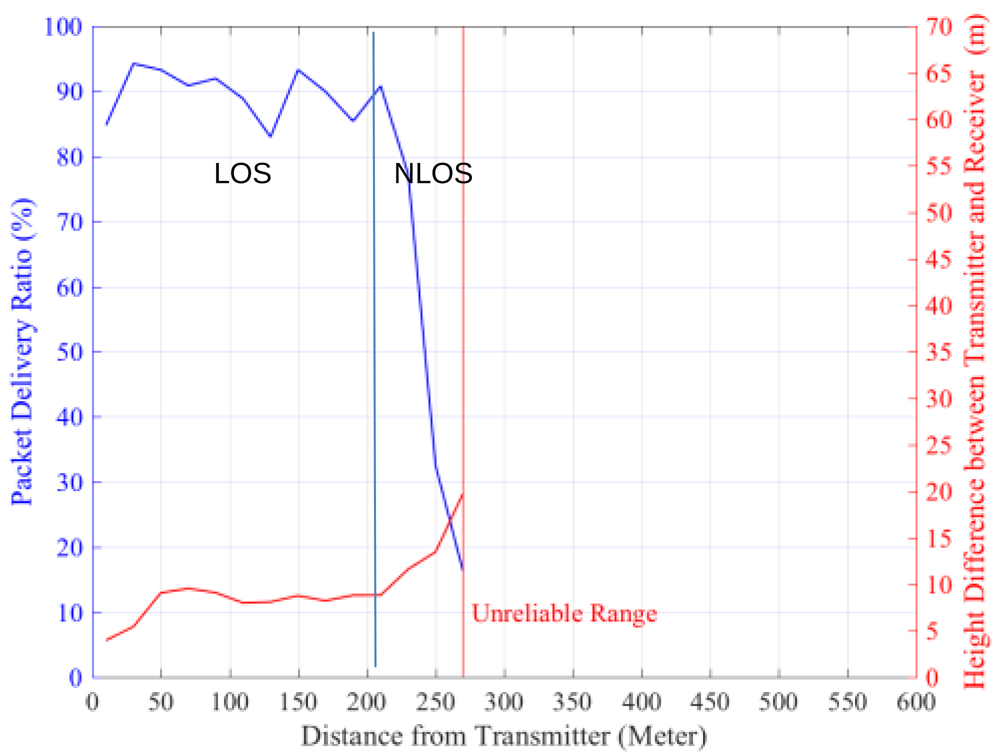
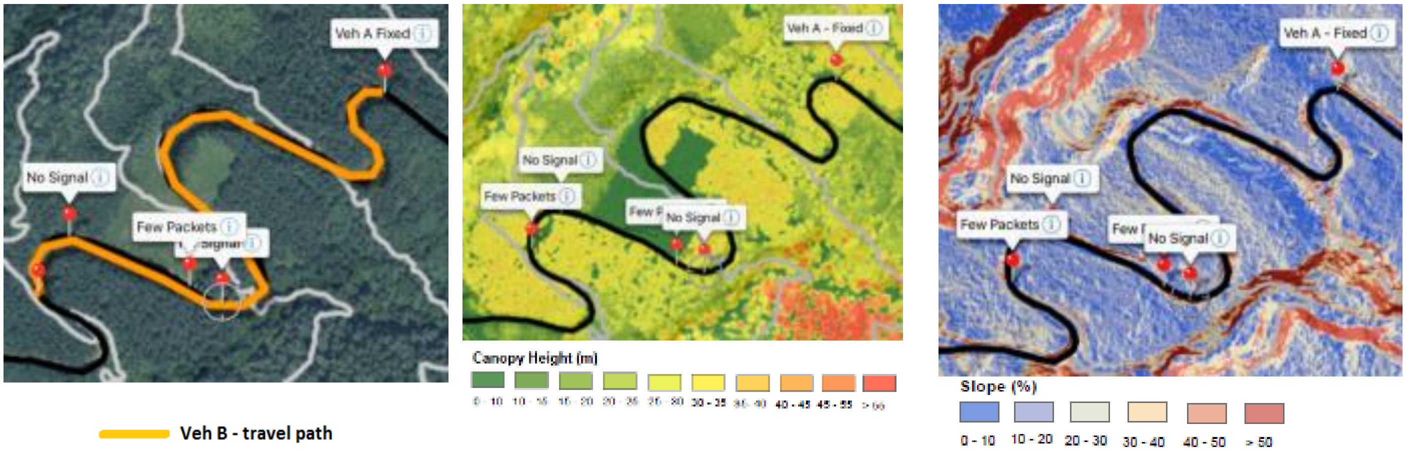


Figure 7. PDR vs. Transmitter Distance for measurement location 2

Figure 8 shows the vegetation and terrain condition for measurement location 3. The roads were curvy and winding road with some patch of clear cuts. Due to the larger elevation difference, the range was considerably longer than other measurement locations. However, there were sections where patchy packets were received. Figure 9 shows the variation of PDR with increased transmitter distance. The sporadic variation in packet delivery was due to variation in vegetation and elevation.



a) Aerial View b) Tree heights c) Terrain slope

Figure 8. Topography and vegetation condition around measurement location 3

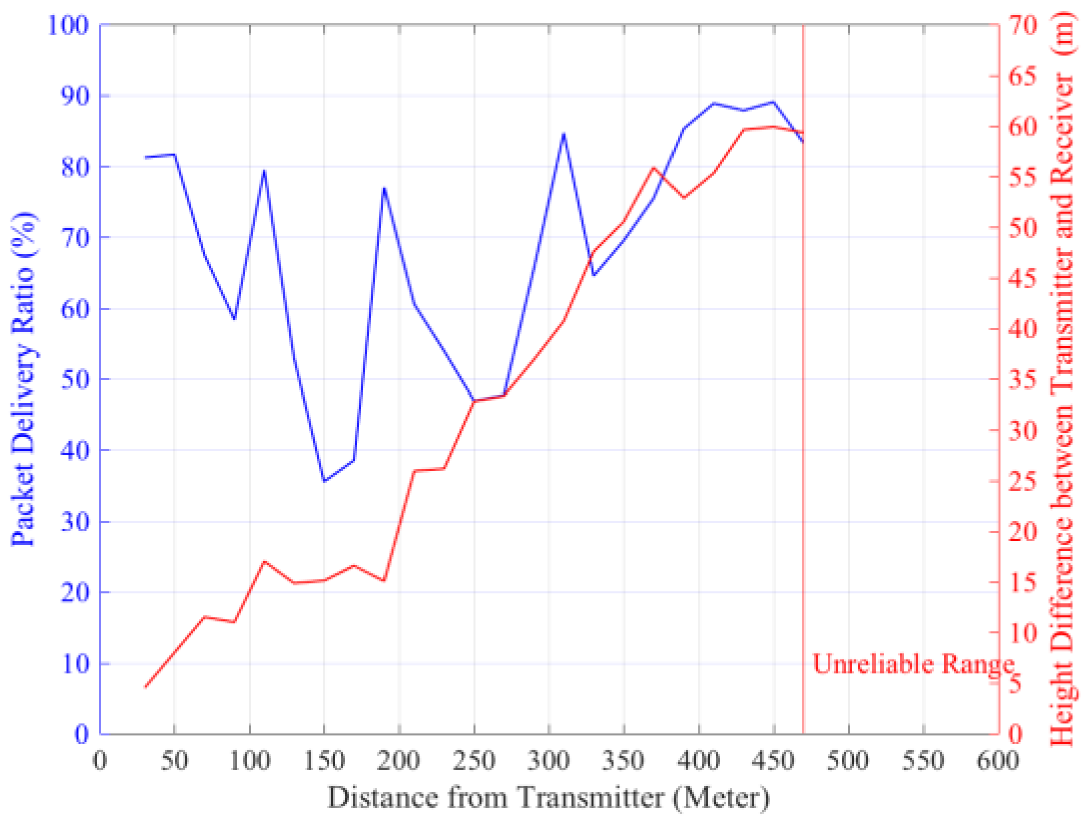
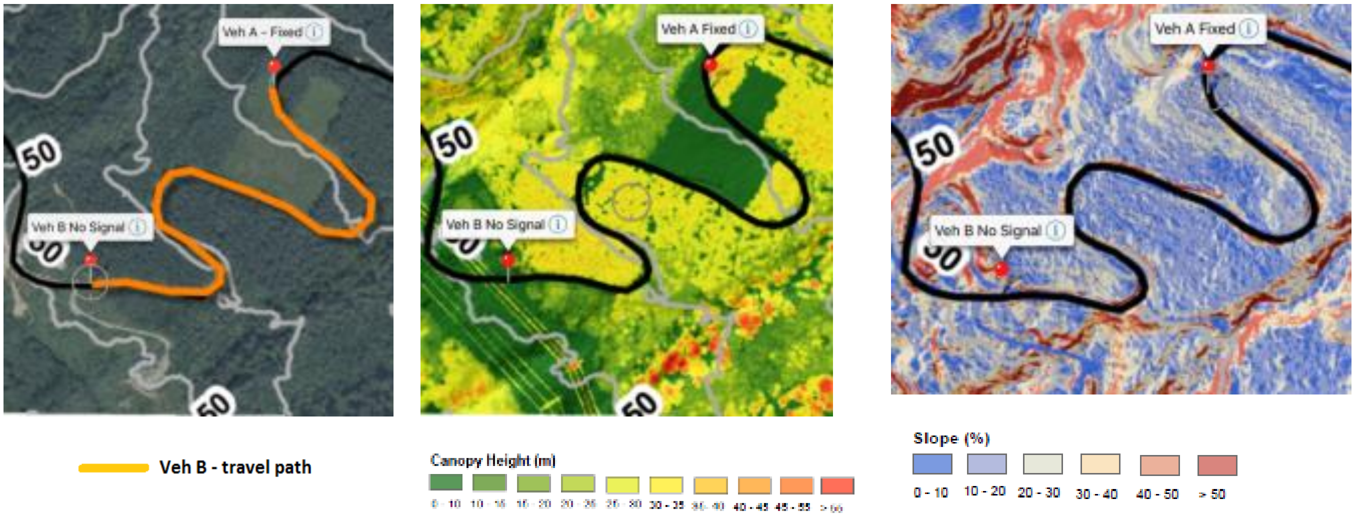


Figure 9. PDR vs. Transmitter Distance for measurement location 3

Figure 10 presents another winding road with the clearing stand near the transmitter vehicle (vehicle A fixed). PDR was continuous with high delivery rate for clearing area; toward the end of the foothill vegetation attenuate the signal and the range for location 4 was 339 m (Figure 11). The average stem density and stem volume was bit greater for location 4 than location 3.



a) Aerial View b) Tree heights c) Terrain slope

Figure 10. Topography and vegetation condition around measurement location 4

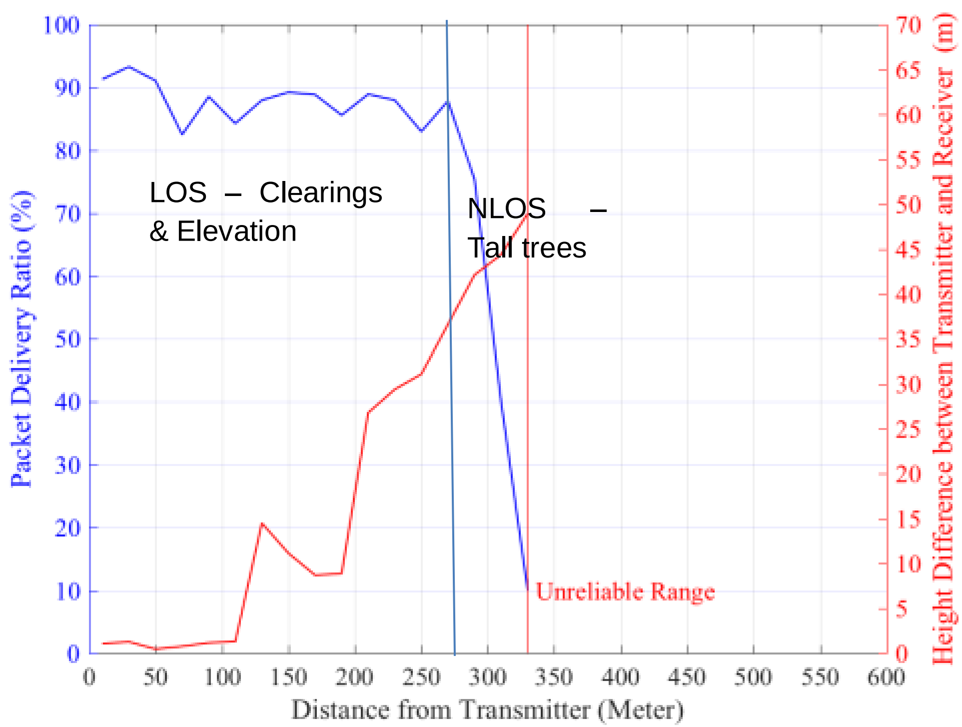
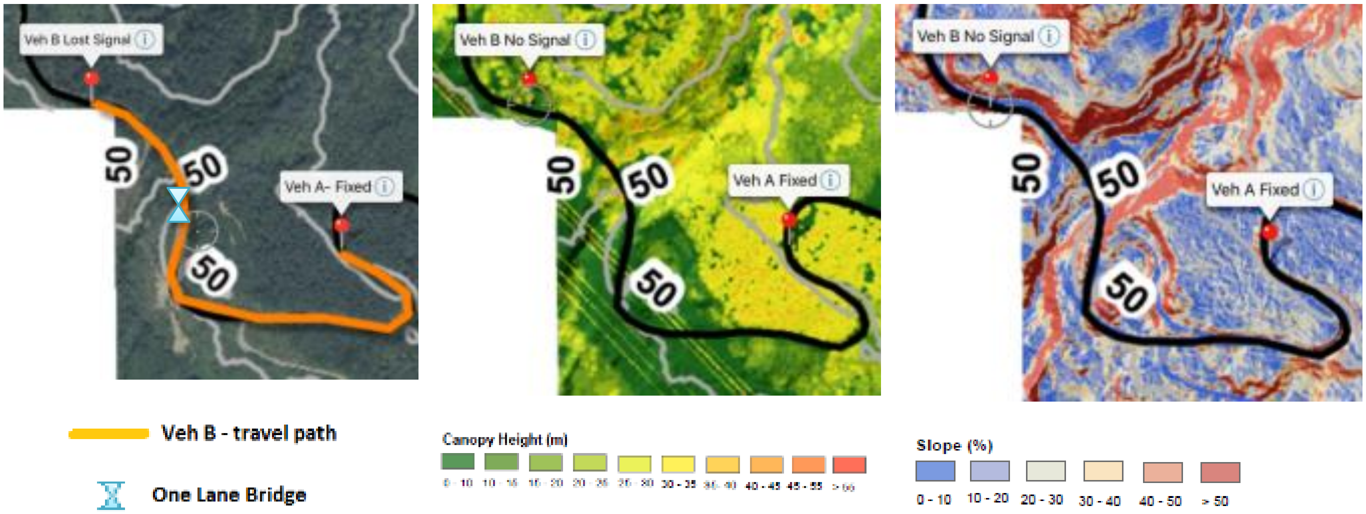


Figure 11. PDR vs. Transmitter Distance for measurement location 4

The scenario of a sharp horizontal curve with one-lane bridge at approximately 300 m was considered as one of the measurement locations. Figure 12 shows the topography and vegetation condition around this location 5. Thick vegetation of stem density 600 stems per ha and stem volume of 500 m^3/ha near transmitter vehicle attenuated signal and the elevation difference and dip around one lane bridge helped in a bit receiving packets. Figure 13 shows the variation of PDR with the distance between two antennas.



a) Aerial View b) Tree heights c) Terrain slope

Figure 12. Topography and vegetation condition around measurement location 5

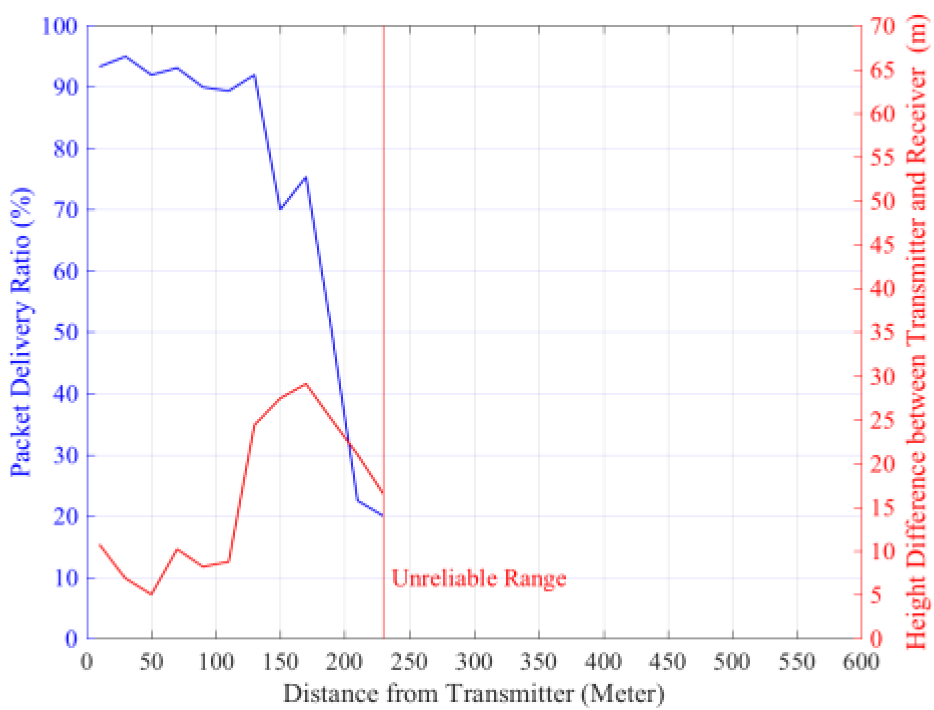
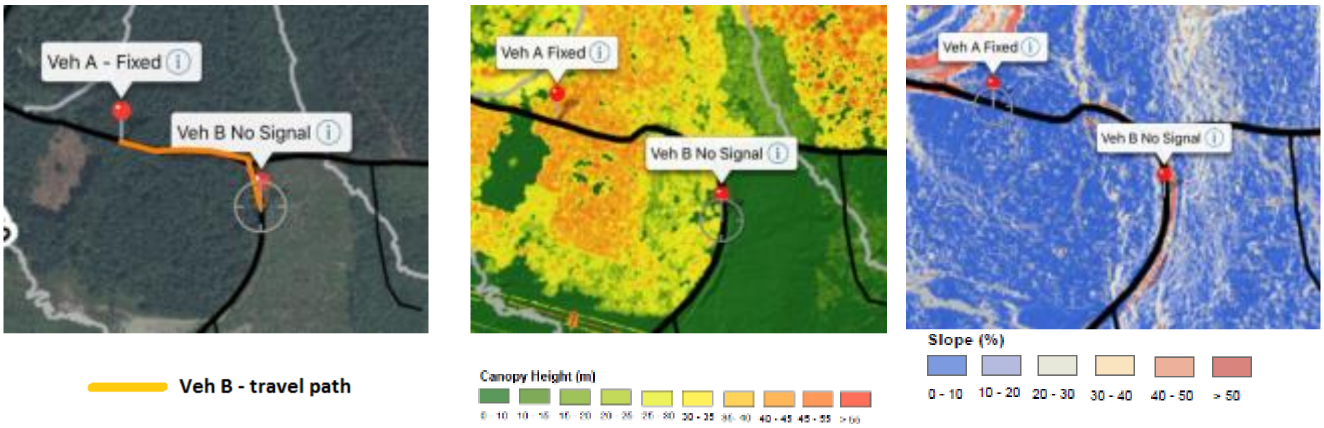


Figure 13. PDR vs. Transmitter Distance for measurement location 5

The intersection awareness with limited sight distance was considered at the measurement location 6. Figure 14 shows the topography and vegetation condition around this area. This area had a thick vegetation with average stem density of 340 stems/ha and stem volume of 510 m^3/ha and with nearly no elevation difference. PDR dropped drastically at 200 m distance between antennas and sporadic packets were received till 240 m (Figure 15). This communication range is too short for communication at an intersection on resource road. This area should be considered as a location of interest and when any improvement in radio performance is proposed, it should be tested at this location.



a) Aerial View b) Tree heights c) Terrain slope

Figure 14. Topography and vegetation condition around measurement location 6

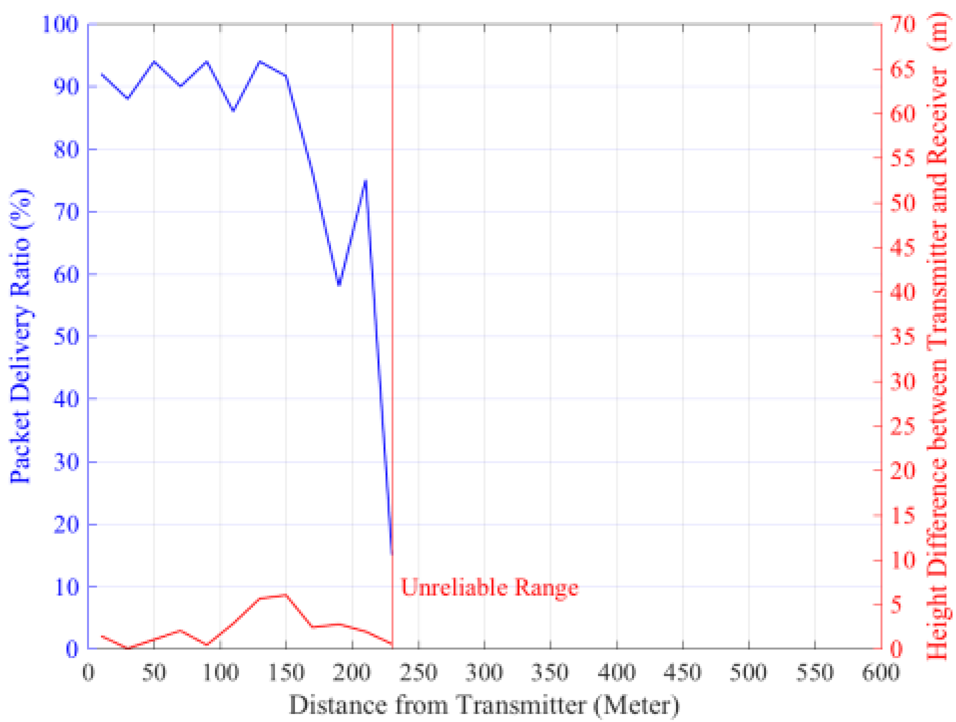
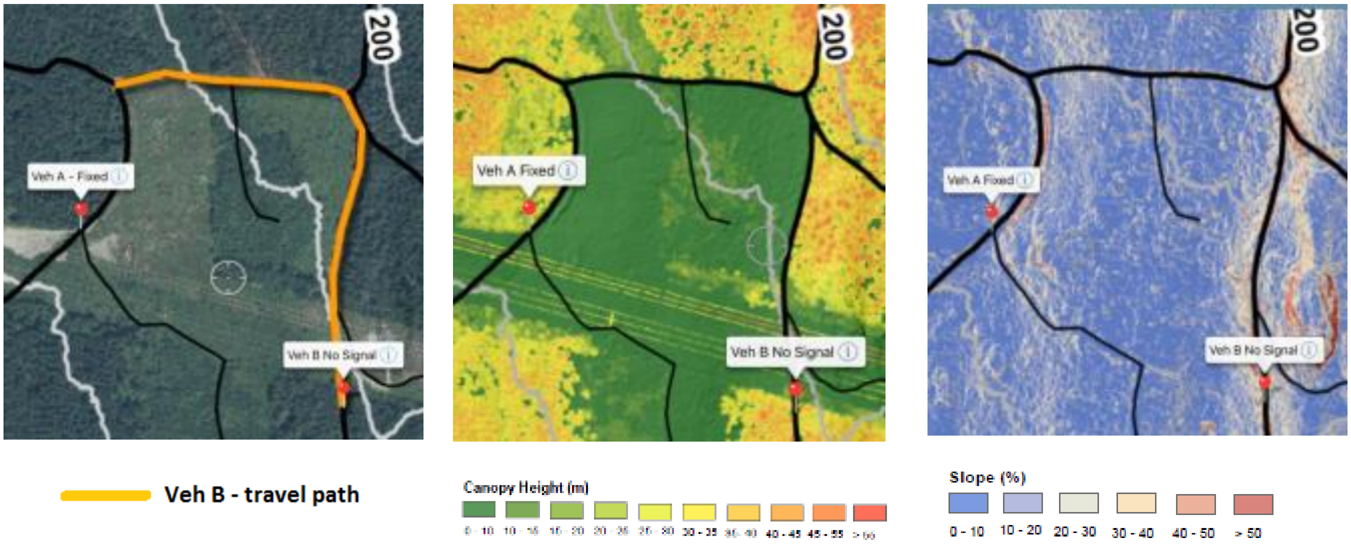


Figure 15. PDR vs. Transmitter Distance for measurement location 6

Figure 16 presents the intersection approaching scenario with less vegetation. Figure 17 shows the variation of the PDR with the distance between two antennas at location 7. The young plantation with stem density of 800 stems per ha and stem volume of 75 m^3 per ha has an adverse effect of signal propagation. The PDR dropped by 50% while Vehicle B was travelling through this plantation.



a) Aerial View b) Tree heights c) Terrain slope

Figure 16. Topography and vegetation condition around measurement location 7

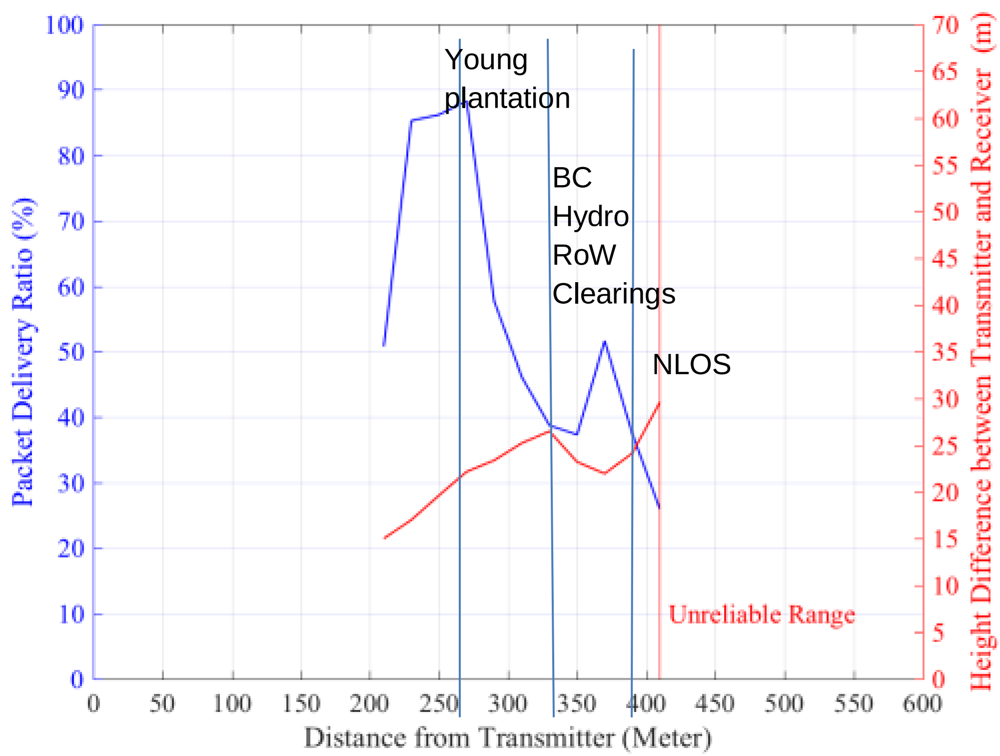
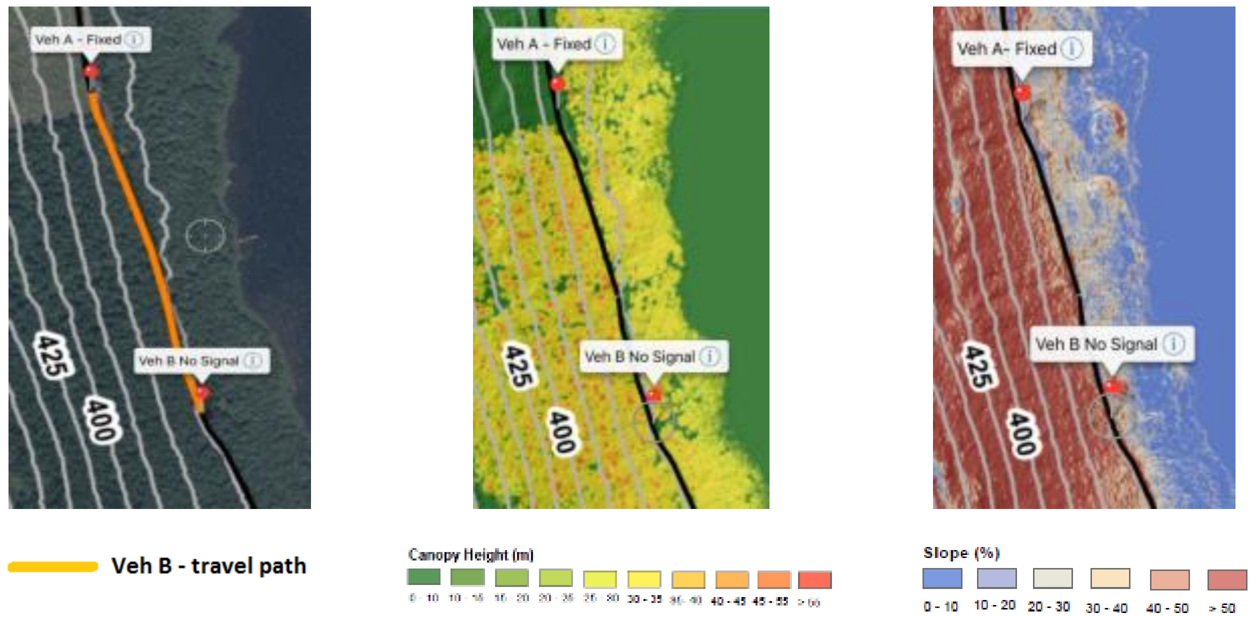


Figure 17. PDR vs. Transmitter Distance for measurement location 7

Figure 18 shows the measurement location around 500 m of line of slight with mature trees of stem density 360 stems/ha and avg stem volume 585 m^3/ha along the road side. Due to snow on some of the roads, a straight 1 km stretch of road was not accessible for testing. On this stretch of road, the packet were delivered continuously at more than 90% PDR for 400 m and the received packet rate drop when the vehicle was not in line of sight i.e after 400 m (Figure 19).



a) Aerial View b) Tree heights c) Terrain slope

Figure 18. Topography and vegetation condition around measurement location 8

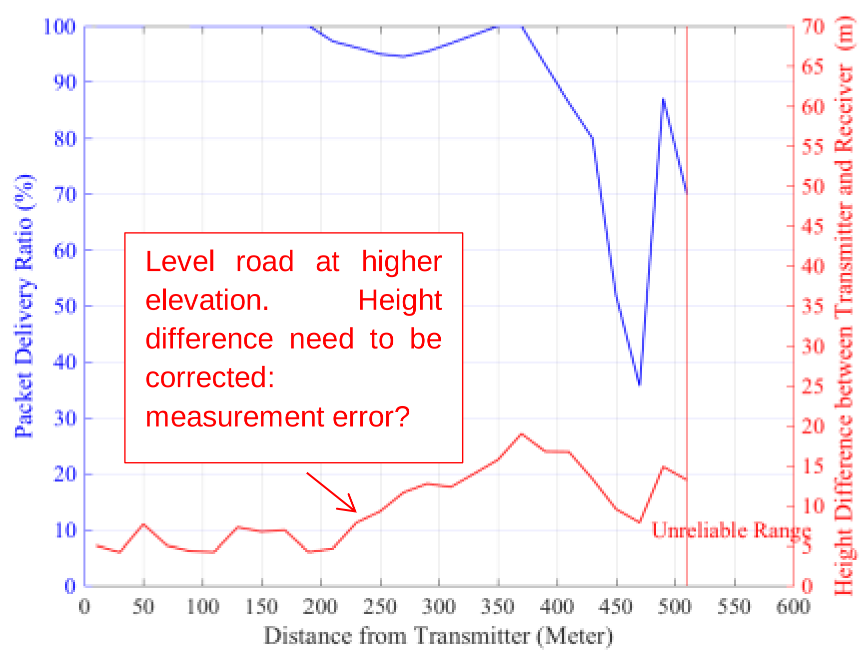


Figure 19. PDR vs. Transmitter Distance for measurement location 8

6. DISCUSSIONS

The average communication range for 5.9 GHz DSRC at +23 dBm transit power is less than 500 m as these systems are designed for urban environments; however the range of these frequencies at the low-transmit power would be inadequate for resource road applications due to possible signal attenuation in dense foliage and rugged terrain environment. Sabouni's (2011) evaluation study reported the range of 200 m in a rural environment for NLOS condition. The greater communication range at NLOS is required for resource road operations due to narrower road, limited passing locations, lesser interference with other frequency bands. The safety message information received by the vehicle about the oncoming traffic should be from approaching vehicles which are more than one kilometre apart. Michelson and Michaelsen (2017) has recommended the use of dual-band DSRC radio (that operate in both the designated 5.9 GHz band for compatibility with urban ITS and UHF bands between 500 and 700 MHz) or high power 5.9 GHz channel for resource road operations.

Channel 184 (frequencies 5.915-5.925 GHz), a high-power, longer-distance communications dedicated exclusively for public safety applications uses involving safety of life and property, including road intersection collision mitigation, could be used for resource road operations. DSRC operating in 700 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 better and transmit data over long distance. The actual performance of the DSRC system on Canadian resources roads needs to be confirmed with testing. In addition, the traffic flow and density, and driving conditions on the resource roads are quite different than the urban roads and highway; therefore, some of the safety applications need to be tailored for the resources road use with the appropriate DSRC technology.

Table 5 presents the theoretical free space coverage and estimated coverage with environmental attenuation for channel 172 of 5.9 GHz DSRC and 700MHz at different transmit power. Friis equation was used to calculated theoretical free space distance, and the equation and assumptions made are presented in Appendix B. Environment attenuation was assumed as 80% of theoretical distance. The losses and sensitivity may differ for different transmit power and frequencies; however, for simplicity the losses and receiver sensitivity were assumed as same for all scenarios. The coverage for 5.9 GHz DSRC at transmit power of 40 dBm (10W) and 44.8 dBm, and coverage for 700 MHz at transmit power 23 dBm (0.2 W) and 33 dBm (2W) seem appropriate for resource road connected vehicle safety application such as collision avoidance.

Table 5. Estimated coverage for 5.8 GHz and 700 MHz at different transmit power

Parameters	Unit	5.9 GHz				700 MHz	
DSRC Channel		172, 175, 181, 182	172, 174, 176, 178, 180, 184	172 (added), 184	172 (added), 178, 180		
Transmit Power	dBm	23	33	40	44.8	23	33
	W	0.2	2	10	30	0.2	2
Theoretical free space coverage	km	1.6	5.1	11.5	19.9	13.6	43
Estimated coverage with environmental attenuation	km	0.3	1.0	2.3	4	2.7	8.5

7. CONCLUSION

The average communication range at 10% PDR is about 346 m (i.e. 20% of theoretical free space value). The environmental factors such as vegetation and topography have a strong influence on the coverage and could potentially attenuate the signal by more than 80%. The range varied from 239 to 514 m for different test locations at 10% PDR using dual antenna, +23dBm transmit power and a moving vehicle. In some occasion, patchy packets were received at a further distance. The 5.9 GHz DRSC range observed in this study at +23 dBm will not be adequate for traffic safety application on resource road. Further testing in same locations with higher allowable transmit power for 5.9 GHz and lower transmit power for 700 MHz would be required. Few other areas along with the measurement location 6 where the vehicle intersection awareness was tested and the range was very limited should be considered as the baseline for testing the improved DSRC radio for resource roads.

8. NEXT STEPS

The next step is to seek the feedback from ISED (Industry Canada) on the possibility of use of high transmit power of 5.9 GHz DSRC system at Channel 184 that is designated exclusively for high-power, longer distance public safety applications and low transmit power 700 MHz DSRC for the frequency band in licenced spectrum.

Following steps are recommended for testing:

- Explore suitable spectrum band that would mostly work nationwide at remote locations
- Test any improvement made in transmit power or frequency at the same measurement locations as initial trial to confirm the improvement achieved
- Consider testing the unit installed on log truck to record any improvement with antenna height gain
- Test the improvement in other two forest and weather conditions

9. REFERENCES

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10. APPENDIX A STAND DENSITY ESTIMATES FOR DSRC TESTING LOCATIONS (POWER 2017)

Malcom Knapp Research Forest assisted FPInnovations in estimating the tree density in terms of stem per hectare and stem volume m^3 per hectare around the measurement locations. Table 6 presents estimation of tree density in terms of stems per hectare and Table 7 presents estimation of tree density in terms of stem volume m^3 per hectare. Table 8 provides the stratum description for each measurement locations.

Table 6. Tree Density: Stems per hectare (>= 10 cm DBH)

Test#	Location	Stratum 1 Stems/ha	S1%	Stratum 2 Stems/ha	S2%	Stratum 3 Stems/ha	S3%	Stratum 4 Stems/ha	S4%	Weighted Avg Stems/ha
1	G Road	400	70%	250	20%	0	10%			330
2	G Road	250	85%	800	10%	0	5%			293
3	G Road	250	60%	0	20%	400	10%	800	10%	270
4	G Road	250	50%	0	25%	400	10%	800	15%	285
5	G Road	250	45%	0	25%	500	20%	800	10%	293
6	A Road	400	85%	0	15%					340
7	A Road	800	40%	0	35%	400	25%			420
8	K30 Road	400	90%	0	10%					360

Table 7. Tree Density: Stems volume (m^3) per hectare (>= 10 cm DBH)

Test#	Location	Stratum 1 m^3/ha	S1%	Stratum 2 m^3/ha	S2%	Stratum 3 m^3/ha	S3%	Stratum 4 m^3/ha	S4%	Weighted Avg m^3/ha
1	G Road	900	70%	300	20%	0	10%			690
2	G Road	300	85%	250	10%	0	5%			290
3	G Road	300	60%	0	20%	900	10%	150	10%	285
4	G Road	300	50%	0	25%	900	10%	150	15%	263
5	G Road	300	45%	0	25%	600	20%	150	10%	270
6	A Road	600	85%	0	15%					510
7	A Road	75	40%	0	35%	600	25%			180
8	K30 Road	650	90%	0	10%					585

Table 8. Description for stratum for each test location

Test#	Strata Description
1	1. Mature 145 year old mixed 2. 1972 Douglas-fir planted, thinned 3. Roads / clearings
2	1. 1972 Douglas-fir plantation, thinned 2. 1984 mixed plantation, unthinned 3. Roads/clearings
3	1. 1972 Douglas-fir plantation, thinned 2. Roads / reforested 2014 3. Mature 145 year old mixed 4. 1990 mixed plantation, unthinned
4	1. 1972 Douglas-fir plantation, thinned 2. Roads / reforested 2014 3. Mature 145 year old mixed 4. 1990 mixed plantation, unthinned
5	1. 1972 Douglas-fir plantation, thinned 2. Roads / BC Hydro RoW 3. Mature 145 year old mixed 4. 1990 mixed plantation, unthinned
6	1. 1957 mixed plantation 2. Roads/ reforested 2015 / BC Hydro RoW
7	1. 2005 mixed plantations 2. Roads/ reforested 2015 / BC Hydro RoW 3. 1957 mixed plantation / 1931 mixed natural
8	1. 1931 mixed natural 2. Roads/ reforested 2015

11. APPENDIX B FREE SPACE RANGE ESTIMATION USING FRIIS EQUATION

The theoretical free-space communication range was estimated using equation 1

$$P_r = P_t + G_t + G_r + 20log_{10}\left(\frac{\lambda}{4\pi R}\right) \quad \text{--} \quad (1)$$

Where P_r is Power at receiving antenna (dBm)

P_t is Power at transmitter antenna (dBm)

G_t is Transmitter antenna gain (dBi)

G_r is Receiver antenna gain (dBi)

λ is wavelength (m)

R is distance between antennas (m)

Assumption: Receiver Rx Sensitivity -83 dBm

Wavelength – 0.0512 m (Channel 172) and 0.428 (700 MHz)

Antenna gain and cable loss -3dBi (for both Rx and Tx)

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