An Experimental Evaluation of WiFi-Based Vehicle-to-Vehicle (V2V) Communication in a Tunnel

Harri Viittala[1], Simone Soderi[2], Jani Saloranta[1], Matti Hämäläinen[1], Jari Iinatti[1]

[1]Centre for Wireless Communication
University of Oulu
Oulu, Finland
{harri.viittala, jani.saloranta, matti.hamalainen, jari.iinatti}@ee.oulu.fi

[2]GE Transportation Systems
Florence, Italy
simone.soderi@ge.com

***Abstract*—New automated solutions are needed, e.g., in mining industry to improve efficiency and productivity of every process. In addition, costs have to be reduced, and health and safety of employees need to be enhanced. This paper studies vehicle-to-vehicle (V2V) communication to be utilized in, e.g., mining vehicles in a tunnel to increase safety and productivity of a transportation of mining goods. The objective of the paper is to experimentally evaluate maximum achievable range of WiFi radio in a real tunnel environment including line-of-sight (LOS) and non-LOS (NLOS) links. The measurement campaign was carried out in an artificial tunnel using commercial off-the-shelf WiFi radios and antennas. The experimental system was able to reach 150 m range when applying a single data stream, and 100 m for two simultaneous data streams without loss in throughput.**

Keywords— Communication; Tunnel; Vehicle; WiFi.

I. INTRODUCTION

Mining industry is facing new challenges when competition in global market is getting more and more intense. Efficiency and productivity of mining processes should be improved, not forgetting that costs are needed to be reduced meanwhile. This all has to be done simultaneously with enhancing healthy and safety of employees. The mining industry will also encounter the shortage of skilled workers in the future. Mining companies move into more remote, unsafe or unpleasant areas when expanding their activities and it becomes difficult to find skillful people to operate mining equipment. This means that mining processes have to be automated and skilled employees are needed as mine operators to supervise and control the processes. In autonomous mining, main benefits are accuracy and repeatability of operations. Autonomous trucks could be positioned correctly for loading and dumping. They will operate at the same efficiency through a working day. The truck cycle time will be consistent through a work shift. The autonomous system controls speed, location and truck routes. An onboard computer, e.g., maximizes fuel efficiency, reduces exhaustions, controls distance to a truck ahead and monitors health of a truck. The autonomous system improves efficiency and utilization of resources, and thus decreases costs of mining process. In addition, it improves safety in a mine site by removing human errors due to fatigue and loss in focusing. In a tunnel where there is not guaranteed connection to a system operator, autonomous communication between trucks to achieve these objectives is required. [1-4]

The 802.11 orthogonal frequency division multiplexing (OFDM) physical (PHY) layer defined in [5] has shown its strength as a PHY layer for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The 802.11a amendment was used as a basis for the 802.11p amendment which is applied as a PHY layer of wireless access in vehicular environment (WAVE) applications [6]. WAVE is using the 5.9 GHz frequency band dedicated for road safety including V2V and V2I communications [6].

Utilization of the unlicensed frequency band at 2.4 GHz gives a freedom to apply WiFi worldwide without taking care of radio regulations. In general, there are other radio systems operating in the unlicensed frequency band but mining sites are typically remote and isolated areas where no other radio systems share the same frequency band. The current IEEE 802.11-2012 standard includes also a mesh operation mode [5]. With meshing functionality, the wireless V2V system can be implemented without a need for fixed infrastructure. This will decrease the installation costs, and provide flexible and scalable system.

A vehicular channel in a tunnel is a challenging environment. It sets its own requirements and limitations for system design. When relative speed of objectives increases, an impact of the Doppler spread becomes more and more dominant factor in the system performance [7]. A tunnel can be considered as an oversized waveguide in terms of electromagnetic (EM) wave propagation. Electromagnetic (conductivity, permittivity and permeability) and mechanical properties (shape, cross-section and curvature) of the tunnel have a significant influence on what EM modes exist and what is the maximum wavelength that propagates [8].

A radio channel in a mine tunnel is studied, e.g., in [9] and [10]. With 1000 MHz center frequency, the path loss was found to be 40 dB/decade in a straight cave [9]. It was also observed that the radio channel in a mine is not reciprocal. When the center frequency is shifted up to 2.4 GHz, the path

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loss is near to free space loss, e.g., 23 dB/decade [10]. Measurement results achieved from the subway tunnel at 2.64 GHz showed that path loss can be less than free-space path loss in line-of-sight (LOS) region even in a curved tunnel [11]. In [12], 4x4 multiple-input multiple-output (MIMO) channel correlation in railway tunnel is studied using different antenna configurations at 2.4 GHz and 5.8 GHz. The propagation channel is either empty or blocked by other train. Difference in correlation factors between frequencies is indistinguishable. Instead, a wrong antenna configuration can corrupt communication with totally correlated MIMO channels.

The objective of this paper is to evaluate WiFi-based V2V communication to be applied in a mining tunnel by using inexpensive commercial off-the-self WiFi radios operating in a license-exempt frequency band. The paper is organized as follows. Section II introduces the measurement setup, and Section III continues with the discussion on measurements. In Section IV, the results from the measurement campaign are presented and analyzed. Finally, the paper is concluded in Section V.

II. MEASUREMENT SETUP

The measurement setup is presented in Figure 1. Antennas are installed in an aluminum plate which is on the top of a three-leg stand. The aluminum plates emulate the roof of vehicles. An IEEE 802.11 standard compliant WiFi module consists of two antenna outputs and an Ethernet port. WiFi modules are connected via Ethernet to PC with Linux OS. There are Iperf network testing applications [13] running in both PCs. The receiver side runs an Iperf server, and a client is running at the transmitter side. A PC equipped with Wireshark packet analyzer software [14] and an AirPCAP wireless packet capture tool [15] is applied to monitor an over-the-air traffic.

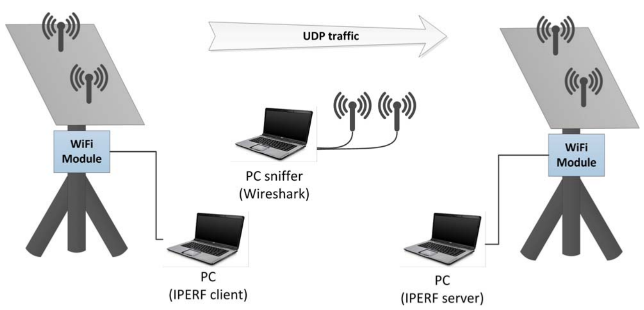

Figure 1. Measurement setup

Iperf client generates 1470 bytes user datagram protocol (UDP) data packets with specified rate, i.e., 10 Mbps and 54 Mbps in this study. The Iperf server computes throughput, jitter and packet loss at an application layer. It counts lost datagrams based on an ID numbers of datagrams. The size of the UDP packet varies between 8 – 65 535 bytes and it is usually consisted of several internet protocol (IP) packets. Losing one IP packet will lose the whole UDP packet. The UDP packet size was set to 1470 bytes as a default value in Iperf to avoid fragmentation when the maximum transmission unit (MTU) is 1500 bytes. Therefore, we can call a datagram as a packet, and the number of lost datagrams is equal to lost packets.

It is possible to transmit two separate data flows by setting two Iperf instances. Iperf applies –S argument to specify the type-of-service (TOS) for outgoing packets [13]. In our study, we gave the highest priority for the lower UDP bandwidth, which emulates the vital information, e.g., intelligent speed control and emergency notification to be transmitted from a vehicle to a vehicle. The higher UDP bandwidth has lower priority and it was considered to be non-vital data such as logistics information.

The radio dynamically selects the best modulation-coding scheme and the number of spatial streams according to the channel conditions. The measurement system utilizes the antennas whose physical shape is similar to a modern shark fin antenna applied in new vehicles. The antenna is designed for four frequency ranges from which the range 2400 – 2700 MHz was proper for our case. Within that frequency range the antenna provides 9.5 dBi antenna gain. The horizontal radiation pattern with a ground plane is illustrated in Figure 2.

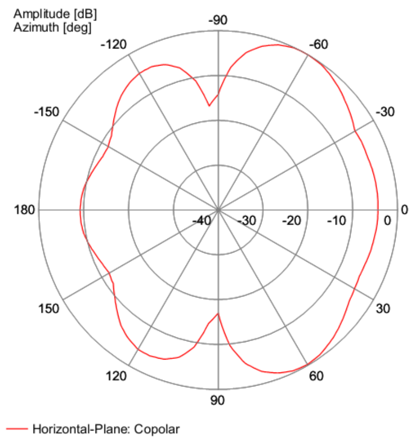

Figure 2. Radiation patterns of antennas at 2450 MHz with ground plane

III. MEASUREMENTS

The tunnel where the measurements were carried out in July, 2012 is located at Vuokatti, Finland. The artificial tunnel was built in 1997. The length of the tunnel is 1.2 km and has the vertical of 18 m. The cross-section of the concrete tunnel is a perfect hemisphere as presented in Figure 3. The tunnel was complete within the measurement ranges and there were no discontinuities in the structure. During the measurements, a transmitter (TX) and a receiver (RX) were always placed in the middle of the tunnel, having 4 m distance from a stand to a wall. The height of the antenna plate was measured underneath the plate, being 2 meters. These distances were measured by using Fluke 416D laser distance meter. In the same plate, the antennas were separated by 0.74 m. TX position was fixed in all the measurement cases. TX was placed to 51.3 m from the beginning of the tunnel to avoid structural irregularities due to the tunnel entrance. The position of RX was changed with 50 m steps. The measurement points are illustrated in Figure 4.

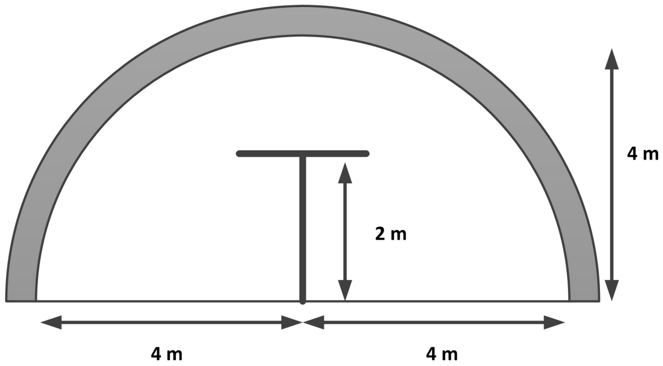

Figure 3. Cross-section of the tunnel

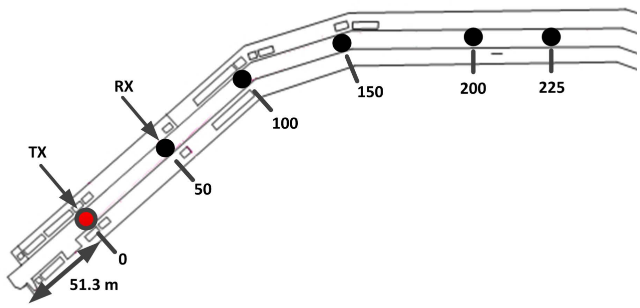

Figure 4. Positions of RX

A. Parameters

During the measurements, the radios were adjusted to use the 802.11g+n radio protocol with 2453 MHz channel center frequency and 20 dBm transmitted equivalent isotropic radiated power (EIRP). The transport protocol was UDP with the packet size of 1470 bytes and the bandwidth of 10 Mbps and 54 Mbps. The parameters are summarized in Table 1. During a 3-minutes measurement run, approximately 153 000 UDP packets (10 Mbps) for vital and 820 000 UDP packets (54 Mbps) for non-vital were transmitted.

IV. RESULTS

Throughput and jitter were recorded in four distances d = 50, 100, 150 and 225 m. When measuring two data streams simultaneously, the Iperf instances were launched manually. In that case, first and last three seconds of a measurement were discarded due to delay of manual start-up of two separate Iperf instances. The channel changed from line-of-sight (LOS) to non LOS (NLOS) when RX was moved from 100 m to 150 m.

TABLE 1. MEASUREMENT PARAMETERS

Parameter		**Value**
Radio protocol		802.11g+n
Frequency channel		9 (2452 MHz)
Transmitted EIRP		20 dBm
Transport protocol		UDP
UDP packet size		1470 B
UDP bandwidth	Vital	10 Mbps
	Non-vital	54 Mbps
Antenna height		2 m
Distances		50, 100, 150, 225 m
Scenarios		LOS, NLOS
Transmission time		180 s

Figure 5 presents the results for the vital data when distance was 150 m. Iperf averaged the results over 1 s time interval to present one data point. The measured mean throughput was 9.99 Mbps with 0.048 Mbps standard deviation (σ) and the mean jitter was 0.22 ms (σ = 0.10 ms). When vital and non-vital data are transmitted simultaneously, the mean throughput of vital data is 8.63 Mbps as illustrated in Figure 6. Correspondingly, the mean jitter is increased by a factor of 5. Even though the vital data is given the highest priority by the ToS flag at a transport layer, the contention-based medium access method of WiFi (EDCA) bases the channel access on access categories (AC) each having the maximum number of backoff slots [5]. ACs with high priority has the minimum number of slots, and mean waiting time for channel access is the shortest. But sometimes the lower priority AC gains an access to channel and this explains why the throughput of vital data is decreased when the non-vital data is transmitted simultaneously. The results for non-vital data with 150 m NLOS are presented in Figure 7. The throughput has the mean of 7.04 Mbps (σ = 1.37 Mbps), and the mean jitter is 2.81 ms (σ = 2.37 ms).

Figure 8 and Figure 9 show the summaries of the measurements including all the distances. Each data point is an average of 180 s measurement run. When applying only one data stream, the distance of 150 m is overcome without loss in throughput. In 225 m, the loss is 23.5 % in throughput. The mean jitter is below 0.3 ms till 200 m. When the both data streams are transmitted simultaneously, distance of 100 m is gained without losses in throughput, i.e., the throughput of vital and non-vital data are 10 Mbps and 54 Mbps, respectively. Beyond that point, the mean throughput of non-vital data decreases ending up to 2.71 Mbps (d = 225 m). For the vital data, the mean throughput is 52.4 % of the offered load. The maximum mean jitter for the vital data is 1.12 ms, and for non-vital 3.42 ms.

The Wireshark results were recorded to monitor the over-the-air traffic. Interesting results on the usage of MIMO by radios was discovered. It was noticed that radios applied MIMO for 0.09 % of captured packets when distance was 50 m. i.e., SISO communication was used for the most of time. Beyond 50 m, MIMO was not utilized at all.

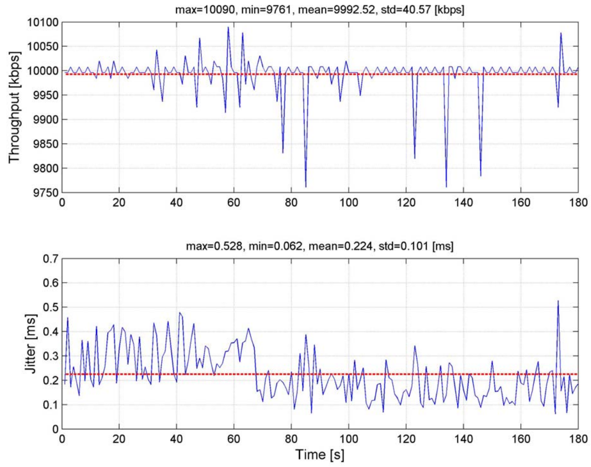

Figure 5. Iperf outputs for vital data (one stream), d = 150 m, NLOS

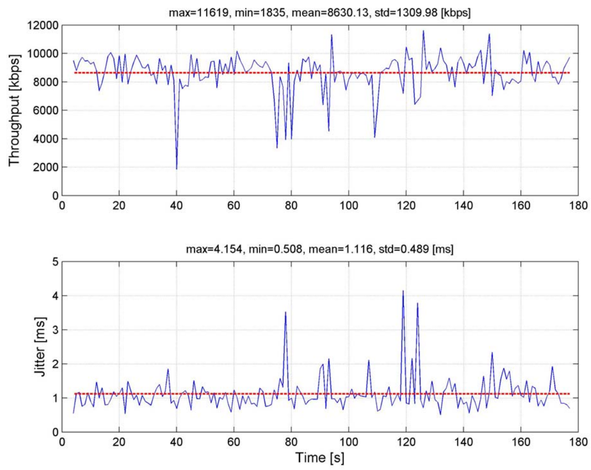

Figure 6. Iperf outputs for vital data (two streams), d = 150 m, NLOS

V. CONCLUSION

The paper presented the results achieved from the measurement campaign to evaluate usability of the commercial off-the-shelf WiFi radios for V2V communication in tunnel environment. Throughput and jitter were recorded by using Iperf network testing tool. It was shown that 150 m can be covered when applying single data stream, and 100 m for two simultaneous data streams without loss in throughput. When channel changed from LOS to NLOS (d = 150 m), no remarkable difference in throughput performance was registered for single data stream. For two data streams, the performance of lower priority data stream with higher UDP bandwidth of 54 Mbps decreases dramatically.

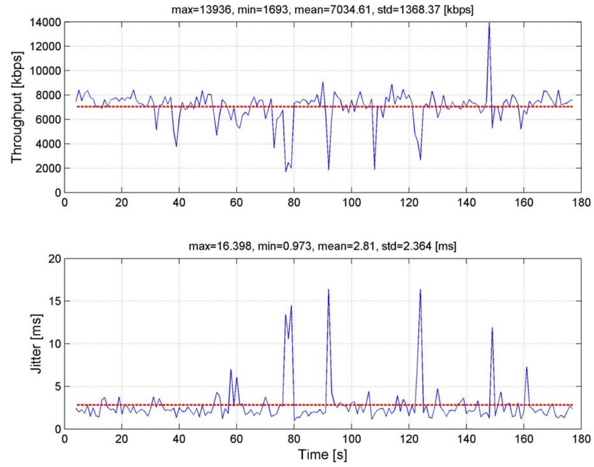

Figure 7. Iperf outputs for non-vital data (two streams), d = 150 m, NLOS

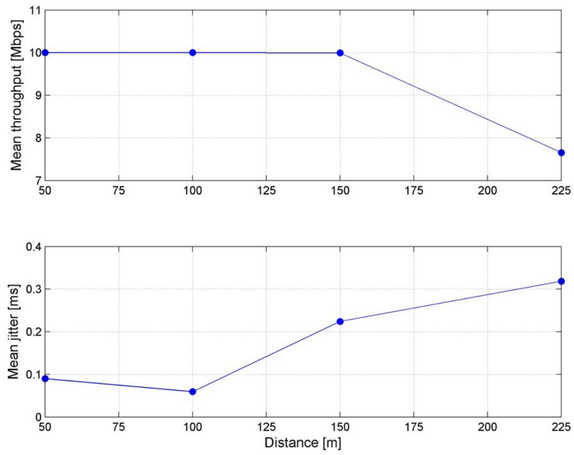

Figure 8. Averaged Iperf results for vital data

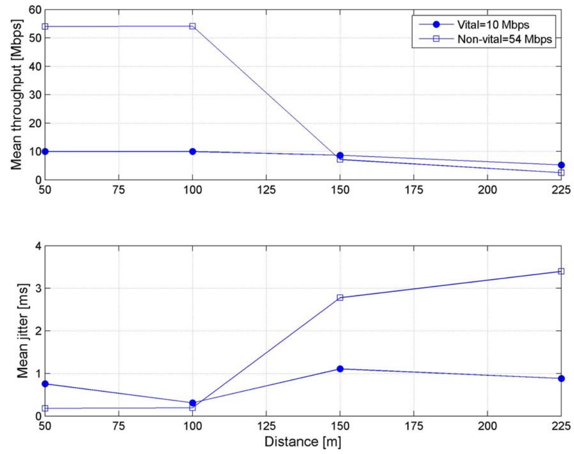

Figure 9. Averaged Iperf results for both data simultaneously

The results also pointed out that when radios selected modulation-coding scheme to be used for transmission based on the quality of a channel, MIMO communication was not applied at all in our experiment. With high quality hardware having better receiver sensitivity and lower receiver noise level, the situation could be better in terms of MIMO usage. In a mining site, speed of vehicles is much less than civil vehicles in a highway. Therefore, the achieved results indicate that the gained range of WiFi in a tunnel is sufficient to ensure communication distance so that vehicles can be stopped without a crash in a case of emergency.

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REFERENCES

[1] B.S. Fisher and S. Schnittger, “Autonomous and Remote Operation Technologies in the Mining Industry: Benefits and Costs,” BAE Research Report, Feb., 2012.

[2] Caterpillar Inc., “Building the Technologies for the Mine Sites of the Future,” Viewpoint: Perspectives on Modern Mining, Issue 4, 2008.

[3] C. Brown, “Autonomous Vehicle Technology in Mining,” Engineering and Mining Journal, May 2011.

[4] M. Dye, “Wireless in the Mining Industry,” [Online]. Available: http://www.wireless-mag.com/Features/13873/wireless_in_the_mining_industry.aspx.

[5] IEEE Std 802.11-2012: Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, March, 2012.

[6] IEEE Std 802.11p-2010: Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment 6: Wireless Access in Vehicular Environments, July. 15, 2010.

[7] C.F. Mecklenbräuker, et al., “Vehicular Channel Characterization and Its Implications for Wireless System Design and Performances,” Proc. of the IEEE, pp. 1189 – 1212, July, 2011.

[8] R.E. Collin, “Field Theory of Guided Waves,” McGraw-Hill, 606 p., 1960.

[9] H. Hämäläinen, J. Talvitie, V. Hovinen and P. Leppänen, ”Wideband Radio Channel Measurements in a Mine,” in Proc. IEEE ISSSTA’98, Sept. 2-4, 1998, pp. 522–526.

[10] C. Neguizian, C.L. Despins, S. Affès and M. Djadel, “Radio-Channel Characterization of an Underground Mine at 2.4 GHz, “ IEEE Trans. Wireless Comm., Vol. 4., Sept., 2005, pp. 2441 – 2453.

[11] M-S. Choi et al., ”Path-loss Characteristics in Subway Tunnel at 2.65 GHz,” Microwave and Optical Technology Letters, Vol. 48, Feb. 2, 2006, pp. 383 – 386.

[12] Y. Cocheril, M. Berbineau, P. Combeau and Y. Pousset, “On the Importance of the MIMO Channel Correlation in Underground Railway Tunnels,” Journal of Communications, Vol. 4, May 2009, pp. 224 – 231.

[13] Iperf Forum. [Online]. Available: http://iperf.fr/.

[14] Wireshark. [Online]. Available: http://www.wireshark.org/.

[15] Riverbed Technology Inc., “Riverbed AirPCAP,” Data sheet, 2010.