Transmission Performance of an Intra-Vehicle Wireless Sensor Network: An Empirical Approach

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***Abstract*— Intra-vehicle wireless communications for sensor-Electronic Control Unit (ECU) links can help reduce wiring harness and improve fuel efficiency - a highly demanded feature for new generation cars. To address the challenges from the inherent poor channel quality and harsh working conditions inside and around a vehicle, this work is aimed to investigate wireless channel properties and transmission performance using a testbed involving a car and wireless communication devices, such as ZigBee, Bluetooth Low Energy (BLE) and Wi-Fi (IEEE 802.11x) modules. Results are generated and analyzed from transmissions across passenger, engine and boot compartments under different environmental and operational scenarios including under interference by other RF signals.**

Keywords—intra-vehicle communications; channel property; transmission performance; testbed

I. INTRODUCTION

Modern vehicles have many sensors, such as temperature, proximity, tire pressure and advanced sensors for autonomous control. Conventionally, sensors are connected using wires to Electronic Control Units (ECUs), which are responsible for collecting sensing data and forward it to corresponding output or applications. The communication protocols of the intra-vehicle sensor network are classified according to the transmission speed and sensing function, from class A requiring low data rates (less than 10 Kbps) to class D with relatively high data rates (up to 1 Mbps). The architecture of the intra-vehicle sensor networks is based on the Control Area Network (CAN) protocol [1] which involves wiring to interconnect among sensor nodes, ECUs, execution actuators and the CAN bus.

As the number of the sensors increases, cabling for connecting different parts in a vehicle will be more problematic. Currently, the wiring harness can have about 4000 parts, 40-50 kg of weight, and 1900 wires for 4 km [2], which imposes significant impacts on fuel efficiency, material cost and diagnostic and maintenance issues. Another issue with the wiring is that for some locations inside the vehicle, it is not possible to connect sensors, such as tire pressure sensors with wires.

To address these issues, wireless communication technologies have been examined for applying in this use case e.g.: deploying wireless sensor networks in vehicles to replace wired connections and provide flexibility to the operation of ECUs. However, this deployment is required to meet strict requirements for safety, level of comfort, energy consumption and pollution [3]. It is also required to meet the demands for increasing the number of on-board sensors as the current intra-vehicle network needs to be re-designed for every production cycle [2]. In addition, the design of such a wireless system in a vehicle will have to address the concerns on the channel behaviour and reliability related performance.

Based on a hardware testbed we set up, this paper presents an investigation on the performance of ZigBee and Bluetooth devices in data transmission across different parts of a vehicle, such as passenger, engine and boot compartments. Our investigation will show the efficiency (throughput), reliability (packet loss rate) of various transmission scenarios, without and with interference. We will also show channel properties in terms of path loss and the cumulative distributed function of the received signal strength for the cases examined.

The organization of the paper is as follows. The related work is discussed in Section II. Section III describes the purposes and settings of four different experiments designed for the investigation on an in-vehicle testbed. The test results and their analysis are presented in Section IV, followed by the conclusion in Section V.

II. RELATED WORK

There has been research work reported that utilized the available wireless technologies, such as ZigBee, specified by the IEEE 802.15.4 standard [4], and characterized wireless channels, such as in Ultra-Wide Band (UWB) [5], millimetre wave [6]. ZigBee and Bluetooth Low Energy (BLE) are main candidate technologies for deploying wireless sensor networks inside vehicles due to their low cost and low power consumption. They both use the unlicensed Radio Frequency (RF) 2.4 GHz global band.

A simple but robust model is presented in [5] to characterize the frequency-dependent transfer function of an in-vehicle UWB channel. A large number of transfer functions spanning the UWB band (3–11 GHz) were recorded inside the passenger compartment of a four-seated car and used to model the intra-vehicle channel encountered and understand the behaviour of the channel in this frequency range.

ZigBee uses the same physical and Medium Access Control (MAC) layers defined in the 802.15.4 standard and has the maximum data rate of 250 kbps, while BLE's data rate is up to 300 kbps. BLE has 40 channels separated by 2 MHz: 3 of them are used for advertisements and 37 channels for data transmission. BLE uses the Frequency Hopping Spread Spectrum (FHSS) technique to hop between these channels [7]. ZigBee has 16 channels on the 2.4 GHz band and uses the Direct Sequence Spread Spectrum (DSSS) technique for the air interface. Both technologies face challenges when they are used for in-vehicle applications due to non-light-of-sight, severe signal scattering and interference problems caused by other sources of radio activities [8].

Costa et al. [9] present the channel characterization of a non-line-of-sight in-vehicle wireless communications at 2.4 GHz frequency band, including a signal reflection beam from ground. Helped by 3D EM simulation, the impact of environmental profiles on path loss performance is specified by using static and dynamic on-board measurements.

Similar work also took place on transportation buses where the E-field strength distribution within an urban bus was studied [10]. In this study, multipath propagation and shadowing were considered to enable E-field exposure analysis and determine the function of transceiver's location within the bus.

A research on intra-vehicle channels both 3-11 GHz and the 55-65 GHz frequency bands provided power-delay profiles which exhibit their differences in root mean square value, delay spread, number of resolvable clusters, and variance of the maximal excess delay [11]. The measured and calculated results also indicated a strong level of noise inside the vehicle examined.

Most related work has been focused more on intra-vehicle channel modelling through simulation or tests, while the work reported here was intended to explicitly reveal the transmission performance in terms of efficiency and reliability of existing wireless technologies. This work was carried out in a real-world environment with varied data transmission scenarios, i.e.: with and without interference, to show the potential of the technologies currently available and identify the areas for improvement in future design. In addition, the performance concerned has been examined in three difference compartments across a vehicle, rather than a single compartment reported in other work.

III. Experimental setup

Three testing scenarios (in Engine, Boot and Passenger compartments) were used in our experiments based on a small Vauxhall Corsa 2008 car, as shown in Fig. 1. For obtaining the measurements of the Received Signal Strength Indicator (RSSI), the transmitter was placed in the engine compartment and connected to a laptop to transmit data at a rate of 1Hz (1 packet/s) for one minute each run. The receiving node was placed on the car dashboard. Another laptop having a packet sniffer (Dongle CC2531 for ZigBee or CC2504 for BLE) plugged in was placed close to the receiver node to capture the packet sent from the transmitter. The sniffer was used to monitor and log the RSSI of each received packet.

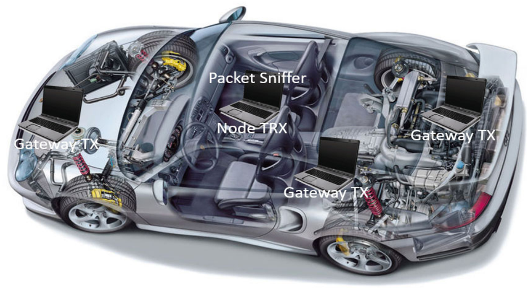


Figure 1. Testbed with testing device positions for three scenarios.

A. *ZigBee Measurements without Interference*

In this experiment, ZigBee transmission was tested for the three scenarios specified above. The receiver was fixed on the dashboard for all scenarios. The ZigBee module used in this research is Digi XBee-PRO S1 802.15.4 with an extended wire antenna. Some of the specifications of this module are shown in Table I.

TABLE I. ZIGBEE PRO S1 SPECIFICATIONS

RF Data Rate	Up to 250 kbps
Receiver Sensitivity	-100 dBm
Frequency Band	2.4 GHz
Interference Immunity	DSSS (Direct Sequence Spread Spectrum)
Transmit Power	0 dBm

Each XBee module was placed on an XBee adapter to provide an easy PC interface for configuring the module using XCTU software. One module was configured as the ZigBee transmitter and the other as the receiver. Both were configured to use Channel 10 and with a transmit power of 0 dBm.

For the throughput and packet loss measurements, the HyperTerminal was used to send out a text file through the XBee module. The file data was transmitted in 4848 packets of size 128 Bytes each. At the same time, the logging software located on the dashboard was capturing the packets from the air.

B. *ZigBee Measurements with Interference*

The impact of the interference from Wi-Fi on ZigBee was observed, given the fact that some Wi-Fi channels have the same frequency as those of ZigBee channels, e.g., Wi-Fi Channel 11 overlaps with five ZigBee channels, 20-24. An ad-hoc connection between two laptops was setup using Wi-Fi and the channel was set to 11 while the ZigBee channel for both the transmitter and packet sniffer was set to 23, to be compatible with the Wi-Fi channel in terms of operating at the same frequency. ZigBee's transmission using HyperTerminal started after setting up the File Transfer Protocol (FTP) between the two laptops.

ISBN: 978-1-61208-720-7

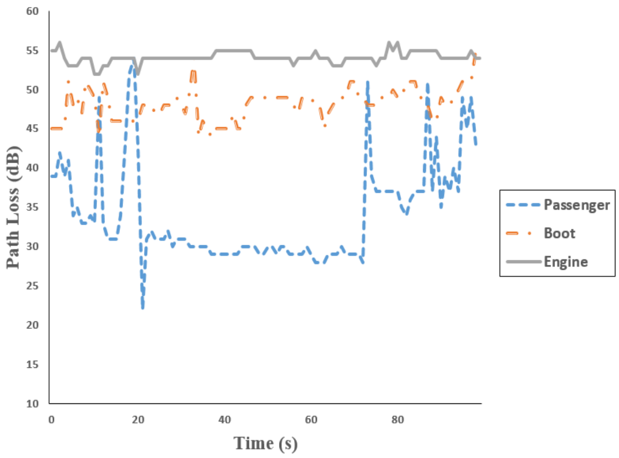


Figure **2**. Path loss for ZigBee.

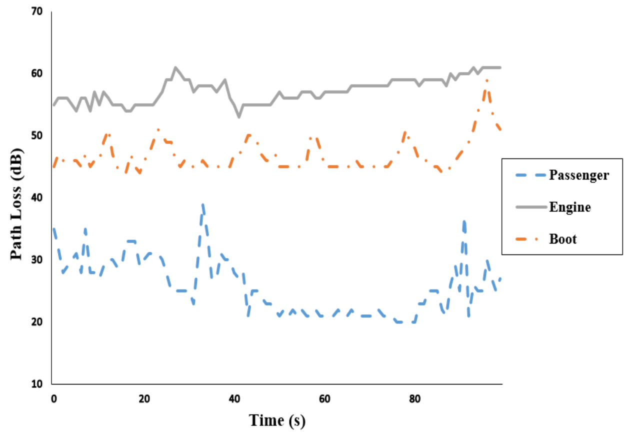


Figure **3**. Path loss for BLE.

C. BLE Measurements without Interference

BLE has been considered for use in wireless sensor networks inside the vehicle due to its attractive performance in terms of low power, low complexity and low cost [12]. In this experiment, the evaluation of BLE was done by using two BLE nodes, an Android phone that supports BLE, and a BLE packet sniffer attached to a laptop. The phone was used as a sensor node and the CC2540 dongle with a receiver sensitivity of -87 dBm was used as the packet sniffer or receiver. The performances, such as the path loss and packet loss rate were obtained by analyzing the packets captured and applying certain metrics discussed later.

An Android phone was placed inside one of the car compartments, followed by adjusting the transmit power to 0 dBm and the sending rate to 1Hz. The packet sniffer was then used to collect the RSSI value of each packet on 1 second interval up to 100 second in total. For throughput and packet loss measurements, packets were sent at a rate of 7 Hz for a period of one minute. The car was parked in an area without Bluetooth or Wi-Fi signal in order to eliminate any possible interference.

D. BLE Measurements with Interference

To examine the effect of coexistence of BLE and Wi-Fi, wireless FTP connection was setup between two laptops. As the BLE frequency is hopping around the three non-overlapping Wi-Fi channels, the Wi-Fi channel was randomly selected from these three channels. The Adaptive Frequency Hopping (AFH) technique specified in BLE was disabled as the transmission was for a single direction only.

E. Metrics

We apply the following metrics in this paper for performance evaluation; first, we define some variables:

Packet loss rate (%): $$p = \frac{N - (NR - NF)}{N} \qquad (1)$$

Throughput (bps): $$S = \frac{(NR - NF) \times 8B}{T} \qquad (2)$$

Path loss (dB): $$L_P = EIRP - P_r \qquad (3)$$

where N is the number of transmitted packets, NR the total number of received packets, NF the number of packets that failed Cyclic Redundancy Check, T the total transmission time in second, B the packet size in byte, $EIRP$ the Equivalent Isotropic Radiated Power (transmit power + transmitter antenna gain) in dBm, P_r the received power at the output of the receiver antenna in dBm.

IV. Results and Analysis

The measurements collected from different experiments will be displayed and discussed in this section.

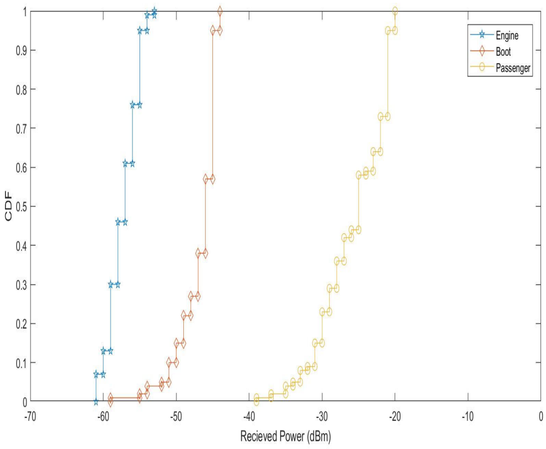
A. ZigBee and BLE Transmission without Interference

The path loss results for both ZigBee and BLE are shown in Fig. 2 and Fig. 3, respectively, which exhibits a very similar channel behavior although measured by different transmission protocols. The Passenger channel varies in a range of 20-30 dB in some instances due to driver movement. The Engine channel has the highest loss among them due to significant signal degradation, caused by multipath fading in such a small enclosure with mixed material, despite the small distance between the engine and the dashboard.

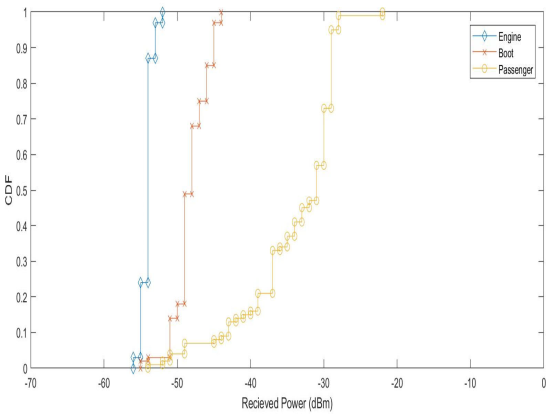
Table II shows the mean and the standard deviation of all the RSSI measurements obtained. The mean of the received signal for the Engine scenario is above the sensitivity threshold of 0.1% of Bit Error Rate (BER) define by both ZigBee and BLE specifications. Both Engine and Boot scenarios seem to have a relatively small variation despite the existence of passengers inside the car.

The Cumulative Distribution Function (CDF) of the measured RSSI is shown in Fig. 4. The specification of BLE [7] mandates a sensitivity better than −70 dBm, but the CDF shows that the probability of the RSSI below that level is almost zero, i.e. even the Engine scenario is also above this standard threshold given the transmit power of 0 dBm.

 ISBN: 978-1-61208-720-7



(a) Bluetooth Low Energy



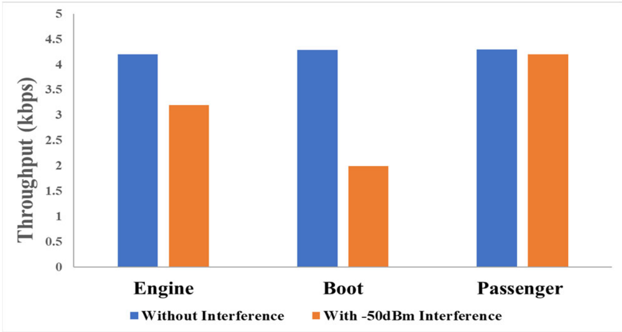
(b) Zigbee

Figure 4. Cumulative distribution function of the recieved power: (a) Bluetooth Low Energy, (b) Zigbee.

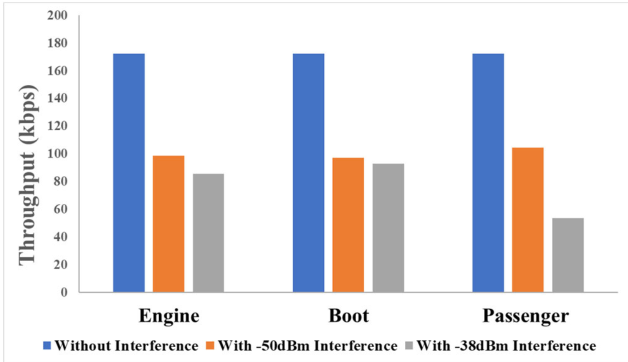
The throughput performance is shown in Fig. 5, with the maximum throughput being achieved when no interference exists. Fig. 6 also shows that packet loss is not significant for both ZigBee and BLE without interference, although the BLE link has more dropped packets compared to ZigBee.

TABLE II. MEAN AND STANDARD DEVIATION OF RSSI

	ZigBee		BLE	
Scenario	Mean (dBm)	Deviation (dBm)	Mean (dBm)	Deviation (dBm)
Passenger	-34.13	6.44	-25.70	4.49
Boot	-48.17	2.20	-46.83	2.66
Engine	-54.11	0.74	-57.27	1.97



(a) Bluetooth Low Energy



(b) ZigBee

Figure **5**. Throughput for all scenarios: (a) Bluetooth Low Engergy, (b) Zigbee.

B. Impact of Interference

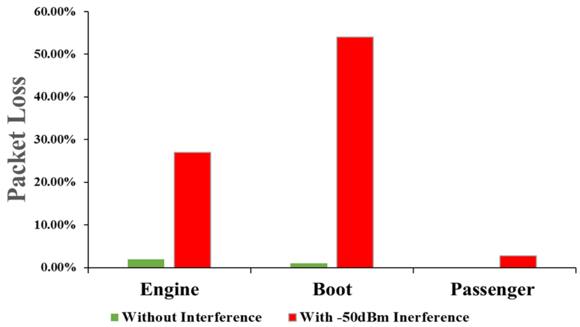
ZigBee has 16 channels separated by 5 MHz at the 2.4 GHz frequency band, hence any of the non-overlapping Wi-Fi channel with 20 MHz of bandwidth at the same band can overlap with 5 ZigBee channels except Channel 1 in Wi-Fi which only overlaps with 4 ZigBee channels.

In this experiment, Wi-Fi Channel 11 was used to transfer a large file for 2 minutes, and the corresponding ZigBee Channel 23 was used in this case. The ZigBee link suffers from packet losses due to continuous Wi-Fi transmission (Fig. 6). The number of packets dropped increased considerably on a scale of more than 30 %, compared to the zero-interference case. This factor can vary depending on the signal-to-interference ratio (SIR), defined as:

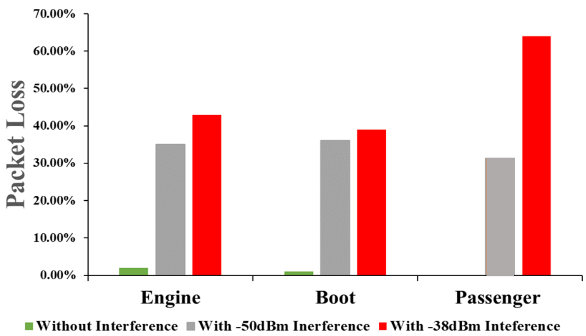
$$SIR\ (dB) = P_r - P_i \qquad (4)$$

where P_r is the received signal power of ZigBee/BLE and P_i is the interfering power by Wi-Fi (all in dBm) detected at the receiver.

BLE has 37 data channels with separation of 2 MHz [8]. Only 9 out of 37 BLE channels are free from Wi-Fi interference, which means most of the time the centre frequency during the hopping is overlapping with one of the Wi-Fi channels. This effect can be observed using one of the Wi-Fi analyzer Apps. In this experiment, Adaptive



(a) Bluetooth Low Energy



(b) ZigBee

Figure 6. Packet loss for all scenarios: (a) Bluethooth Low Energy, (b) Zigbee.

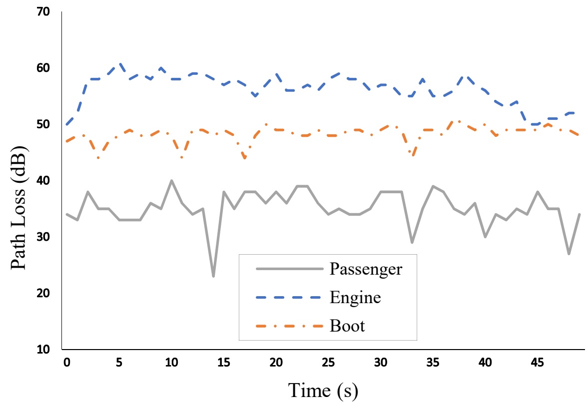


Figure 7. Path loss for Wi-Fi.

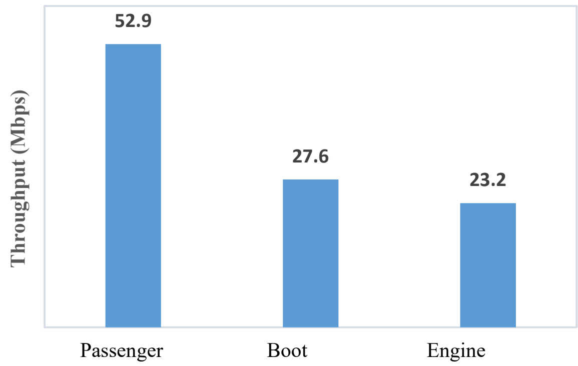


Figure 8. Throughput for Wi-Fi.

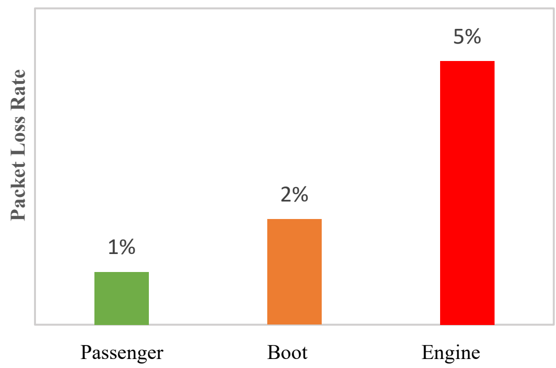


Figure 9. Packet loss rate for Wi-Fi.

Frequency Hopping is disabled, i.e., no avoidance of potential interfering channels. As expected in this case, the Boot scenario has a packet dropping rate of 54 %. There is a discrepancy between the packet dropping rates among the three scenarios because *SIR* is high enough for the passenger compartment compared to the other two scenarios. Frequency hopping is operated randomly hence it is difficult to make the same interference period for all the scenarios tested.

C. *Wi-Fi Transmission*

We have also examined the Wi-Fi transmission performance over this testbed. Fig. 7 shows the path loss for each scenario. As expected, the Engine channel suffers a loss around 56-60 dB, more than the other channels. This feature is also reflected in the throughput and the packet loss results, as shown in Fig. 8 and Fig. 9, respectively. Both results are consistent across all scenarios.

There is a significant reduction in throughput for the Engine and Boot scenarios because of the effect of multipath fading on the coherence bandwidth of the channels involved. The Passenger channel can achieve a throughput of up to 52.9 Mbps given the transmitter data rate of 54 Mbps. However, the overall packet loss rate in the Wi-Fi transmission is higher than those in the Zigbee and BLE cases without interference.

The CDF plot in Fig. 10 verifies that the received signal is above the receiver sensitivity (approx. -73 dBm for 54 Mbps) and a reduction in the transmitting power for the Engine scenario could fail this sensitivity threshold.

The results of these experiments have shown that communications between the transmitter and the receiver in a vehicle can be made reliable provided that some key parameters are adjusted with caution based on the receiver sensitivity specified. The transmit power in the engine compartment needs to be increased to compensate losses, while transmit power reduction can be considered in the passenger compartment to avoid dissipating excessive energy

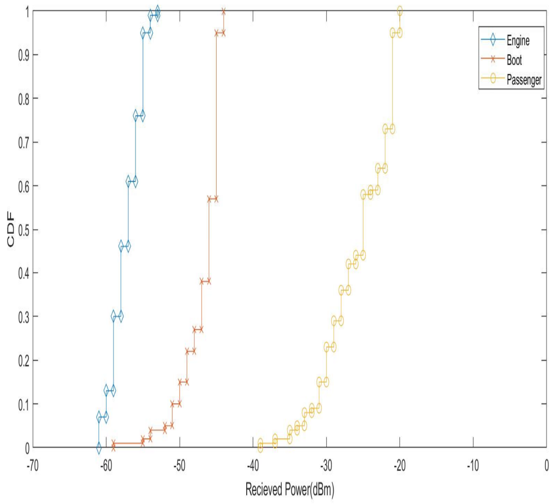


Figure 10. Cumulative distribution function of the recieved power for Wi-Fi.

and causing interference to neighbouring users. In particular, the interference examined in this work exhibits a significant impact on the intra-vehicle transmission performance.

V. CONCLUSION

In this paper, we have investigated wireless channel properties inside a vehicle and the transmission performance of ZigBee, BLE and Wi-Fi as the popular components of intra-vehicle wireless sensor networks. Results have indicated that both ZigBee and BLE can meet the physical layer requirements in terms of the link reliability when they are deployed in any of the compartments in a car. However, the performance can be degraded significantly with co-existence of Wi-Fi transmission, which will lead to serious considerations of the 2.4GHz band in this type of deployment.

To address the problems identified, more robust and adaptive communications protocols and optimization algorithms, such as cooperative communications with virtual MIMO (Multiple Input and Multiple Output) and power control technologies, can be applied to enhance transmission reliability and mitigate the interference encountered.

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