Experimental Study of Straight Guiding Structures for Optical Wireless Communications Within a Vehicular Environment

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***Abstract*—Generous increments in powerful electronic systems and functions have produced significant implications for the vehicular industry, especially in connecting the electronics infrastructure as it is complicated and costly. A limited amount of research has been conducted to investigate proper wireless advancements that might reasonable with the emerging network standard within the context of intra-vehicular networks. This paper reports an experimental investigation of Optical Wireless Communication (OWC) links within guiding structures for a vehicular environment. The experiment has characterized the infrared transmission characteristics using different types of materials and the influence of the geometry on significant infrared channel parameters. The upper and lower 3-dB frequencies for line of sight (LOS) transmission in the tubes demonstrate that the tubes do not significantly change the frequency response of the transmission but this rather depends on the other channel factors such as materials and geometry.**

***Index Terms*—Frequency Response; Intra-Vehicle Network; Optical Wireless Communication.**

I. INTRODUCTION

Intra-vehicle wireless networks provide an extensive advantage for supporting many safety and mobility applications in various scenarios, where the vehicle control information is transmitted wirelessly. As the intra-vehicle wiring could be expensive, bulky and heavy, and, may not compliant for the convenience of improvements to the design [1], the signals will be vigorously transferred through the wireless channels at a high rate and reliability. Research into vehicular wireless communication has gained strong motivation under an initiative of the Wireless Access to Vehicular Environments (WAVE) [2] and interest in advanced vehicular applications which require dependable connectivity. Hence, there is an expanding level of demand to design a wireless system. With that in mind, the feasibility of various technologies [such as WLAN, RFID, Bluetooth, ZigBee, etc.] has been studied [3][4][5][6][7]. Thus, the development of reliable vehicular communication systems and standards needs precise propagation channel study in all significant scenarios [2][8][9].

The employment of Optical Wireless Communications (OWC) within vehicular environments was proposed by Green et al [10]-[12]. The vehicle chassis offers potential wave guiding structures that are unfettered by ambient light. A study by Higgins [13] concentrated on the OWC channel in a car cabin, where he defined the power and bandwidth distribution in different fragments of the vehicle. Rihawi et. al. conducts a study on free-space optical communication links using potential guiding structures around a vehicle [14]. Unfortunately, all the aforementioned articles are either based on scientific investigation or simulations, so the estimation findings cannot be used directly on investigating the consistency of the system.

Design of intra-vehicle OWC systems requires an extensive knowledge of the behavior of infrared (IR) propagation in the hollow tubes which act as waveguides. Focusing on the vehicle frame as a transmission medium, the waveguide in this paper can be defined by a sequence of straight tubes with different materials and geometry (rectangular and circular cross sections). This requires detail study of the channel under various experimental settings and using different optical alignments. Such measurements offer the prospect of an in-depth understanding of the behavior of the channel, under diverse surroundings.

The rest of this paper organized as follows: Section II describes the environment studied which acts as the waveguide in the vehicle. Section III presents the experimental results with the discussion. Finally, the conclusion and future work are explained in Section IV.

II. EXPERIMENTAL SET-UP

The experimental environment comprises of 1 meter long straight rectangular and circular cross-section tubes, shown in Figure 1, with each tube's properties are as listed in Table 1.

A B C D E F G H

Figure 1: Tubes sample.

Table I
Tubes Sample and Parameters

Items	Material	Dimension	Measured reflection coefficient
A	Circular cardboard tube	40 mm diameter	0.1
B	Circular plastic tube	35 mm diameter	0.1
C	Circular mild steel tube	35 mm diameter	0.3
D	Square aluminum 6082 tube	40 mm x 40 mm	0.3
E	Square aluminum 6082 tube	20 mm x 20 mm	0.3
F	Circular aluminum tube	20 mm diameter	0.4
G	Circular galvanized aluminum tube	35 mm diameter	0.2
H	Square mild steel tube	40 mm x 40 mm	0.1
I	Free space	(controlled environment)	

Figure 2 shows the block diagram of the measurement system. The sinusoidal signal from the function generator was transformed to the optical field with an optical transmitter. The lightwave propagated in the various tube materials and shapes. The optical power of the received signal was then measured by a radiometer.

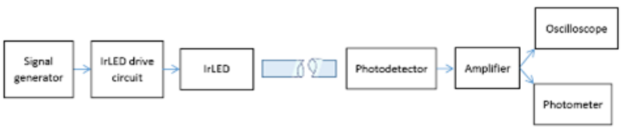

Figure 2 Measurement setup

III. RESULTS AND DISCUSSION

The study concerns straight tubes, and three criteria was considered to quantify the characteristic of the transmission: the frequency response, the optical power, and the optical path loss.

A. *Frequency Response*

Channel frequency responses were based on the frequency profiles obtained at 0.5 meter and 1 meter separations. The transmitter and the receiver were aligned to acquire the highest received signal and remained at the same positions throughout the process. The normalized response for each of the tubes at transmission distances of 0.5 meters and 1 meter are plotted in Fig 3 through to Fig 11. The normalized responses in the graph were calculated based on the standard dB formula of $20\log_{10}(P_r/P_t)$ and were normalized to their respective peak values.

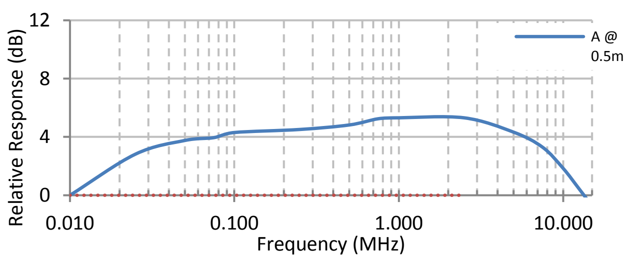

Figure 3: Relative response of circular cardboard tube (Item A)

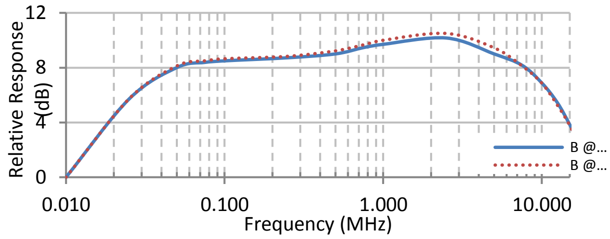

Figure 4: Relative response of circular plastic tube (Item B)

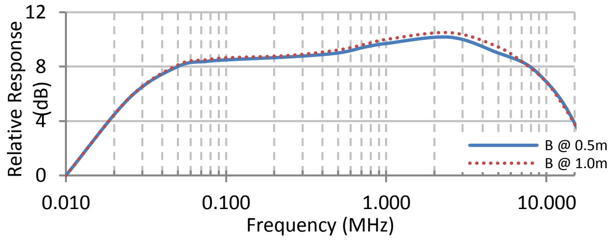

Figure 5: Relative response of circular mild steel tube (Item C)

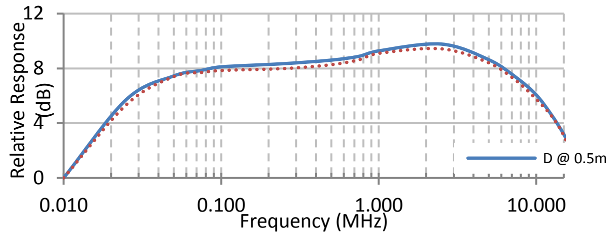

Figure 6: Relative response of square aluminum tube (Item D)

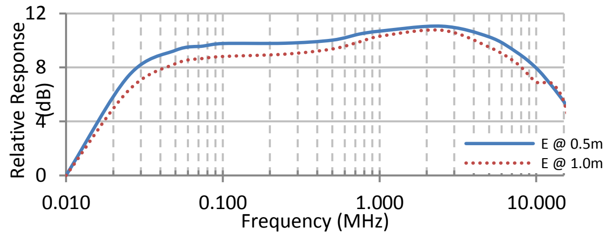

Figure 7: Relative response of square aluminum tube (Item E)

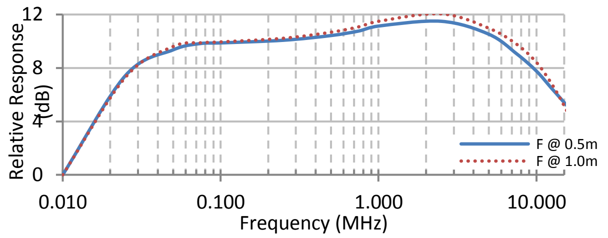

Figure 8: Relative response of circular aluminum tube (Item F)

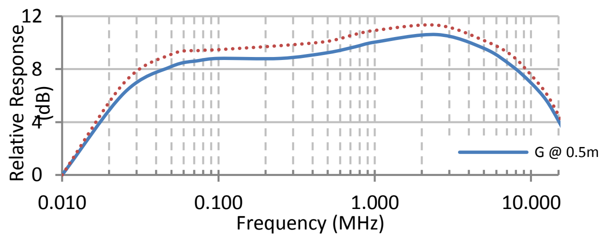

Figure 9: Relative response of circular galvanized aluminum tube (Item G)

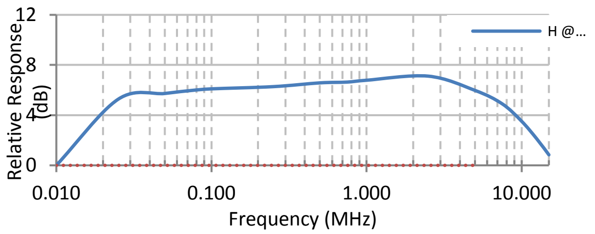

Figure 10: Relative response of square mild steel tube (Item H)

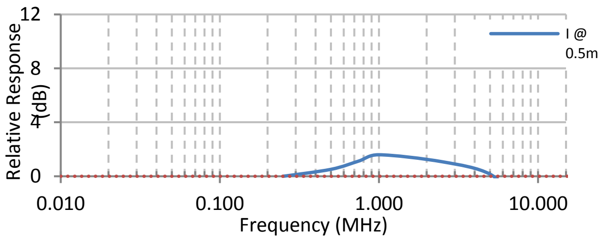

Figure 11: Free space (denoted by I)

For all the plots, the 3-dB cut-off frequency for each of the tubes is about 13 MHz from the constant relative response, except for transmission in free space. The normalized response for all the tubes has the same pattern. The only difference is the relative response gain. It shows that the materials with a high reflection coefficient receive a much higher power compared to the ones with a lower reflection coefficient. The worst power received is the transmission over free space where the signal power has been dispersed and does not benefit from reflections in transmission as in the guided setup.

Clearly, the shape of the frequency response is almost identical, and the only difference is in the amplitude of the received signal. The response at 0.5 meters and 1 meter are almost the same. Unfortunately, for the free space transmission, the received signal is weak at 0.5 meters, and surely there is no detectable signal was received at a range of 1 meter.

B. Transmitted Optical Power

Measurements for radiometric optical power, in Watts, and photometric power output, in Watts per square cm, were executed to estimate the transmitted optical power, Pt, for the particular IRLED. The results are plotted in Figure 12 and Figure 13 respectively. As expected, the light output power increases as the IRLED forward currents increases.

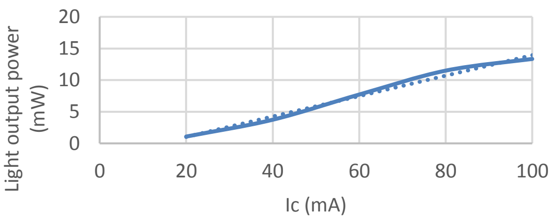

Figure 12: Radiometric output power for different IRLED forward currents.

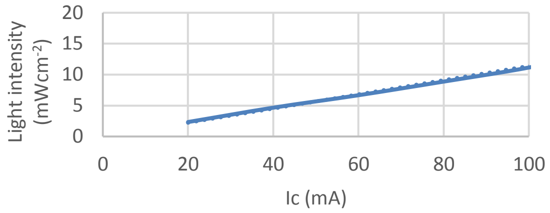

Figure 13: Photometric output power for different IRLED forward currents.

C. Received Optical Power

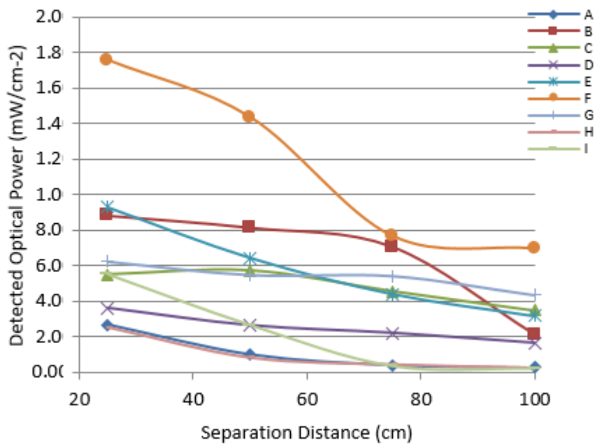

Figure 14: Received optical power plotted against separation distance.

The received power as a function of the separation distance is shown in Figure 14, and drops rapidly reduces as the distance increases. The detected optical power measured in each tube was different depending on the size, geometry and the reflection coefficient of the tubes at a given range. Smaller tube dimensions gave a high-detected optical power compared to larger tubes. Moreover, as one would expect tubes with high reflection coefficients give better performance.

Figure 15 illustrates the received optical signals for 20 mm, 35mm and 40 mm diameter tubes at 0.5 meter and 1 meter ranges. The plot shows that the optical power received was higher using a smaller tube diameter and in shorter tube range. As the tube diameter and the distance increases, the optical power detected weakened accordingly. For a 20-mm tube, the circular aluminum tube offers higher optical power received compared to square aluminum tube. The results for 35 mm tube were inconsistent for the 0.5 meter and 1 meter ranges. At 0.5 meters, the best to the lowest optical power received was in circular plastic, circular mild steel and circular galvanized aluminum tubes respectively but at a range of 1 meter, the order was reversed. This shows that the circular galvanized aluminum tube is suitable for longer tube ranges. In the 40-mm tube, the detected optical powers for circular cardboard and square mild steel tubes are nearly the same at 0.5 meter and 1 meter ranges.

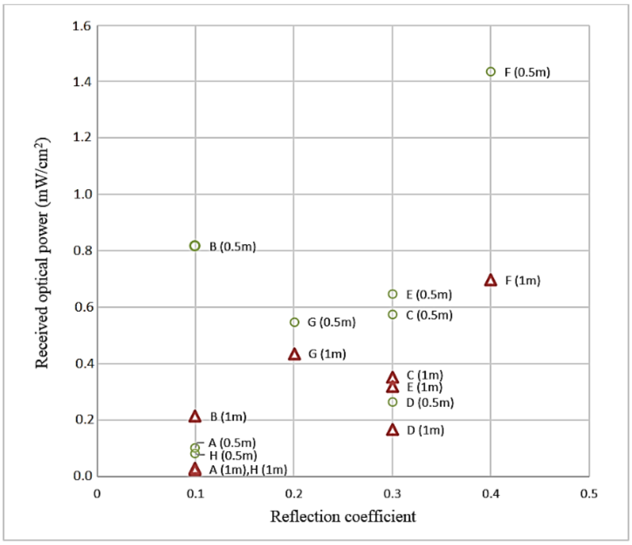

Figure 15: Received optical power plotted against reflection coefficient at 0.5 metre and 1 meter range.

D. Optical Path Loss

The measured LOS optical path losses are illustrated in Figure 16. The path loss is very different in different tubes at the same link distances. Optical path loss increased linearly for all of the tubes, and the tubes with small a diameter have the lowest path loss. The path loss for the free space situation deteriorates rapidly after a distance of 0.5 meter, as well as for the cardboard and steel tubes. In other tubes, the optical beams still could be measured at the receiving end, even though the received signal was weaker over the distance. The optical path loss increases rapidly in free space, plastic tubes and mild steel tubes as the optical waves are diffusely reflected by light colored objects (plastic tube) and absorbed by dark objects (free space, under controlled conditions, and mild steel tubes).

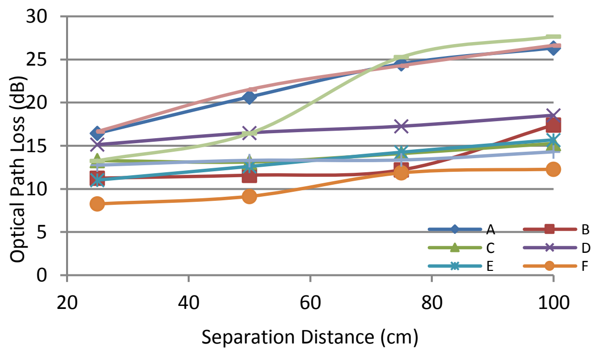

Figure 16: LOS optical path loss at different separation distances

IV. CONCLUSION

This paper reports on an experimental investigation of OWC channel characteristics within a vehicular environment, focusing on LOS transmission. The objectives of this experiment were to characterize the IR transmission properties of different materials and geometries for various IR channel parameters. The upper and lower 3-dB frequencies for LOS transmission in the tubes are nearly the same. It can be concluded that the tubes do not significantly change the frequency response for the bandwidth of the optoelectronics employed, which was 13 MHz. The only effect that the tubes have so far is because of the differences of the reflection coefficient and geometry of the tubes relative to beam spreading, and acceptance angle of the receiver. The limitation of the transmission comes from other factors, such as the optoelectronic devices at the transmit end, and at the receiver itself.

The size, geometry and reflective properties of the tubes mainly determine the received signal power level at any point. The experimental works proved that transmission through the small tube with higher reflection coefficient was great. As the tube diameter increased the detected optical power get worse. Further, the received optical power also deteriorates in the lower reflection coefficient tube.

The experimental work also demonstrated that great path loss is affected by large distance links, indicating that, at greater ranges, the link is very much power-limited. The detected optical power is related to the optical path loss. At longer ranges, a high-powered source is necessary, especially with large tube diameter with low reflection coefficient where the path loss becomes very significant.

REFERENCES

[1] G. Leen and D. Heffernan, "Vehicles without wires," Computing & Control Engineering Journal, vol. 12, no. 5, pp. 205–211, 2001.
[2] D. N. Cottingham, "Vehicular wireless communication," University of Cambridge, Computer Laboratory, Technical Report, no. UCAM-CL-TR-741, 2009.
[3] H. M. Tsai, W. Viriyasitavat, O. K. Tonguz, C. Saraydar, T. Talty, and A. MacDonald, "Feasibility of in-car wireless sensor networks: A statistical evaluation," in Proceedings of the 4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 2007, pp. 101–111.
[4] O. K. Tonguz, H.-M. Tsai, T. Talty, A. Macdonald, and C. Saraydar, "RFID technology for intra-car communications: A new paradigm," in Proceedings of 64th IEEE Vehicular Technology Conference, 2006, pp. 1–6.
[5] H. M. Tsai, O. K. Tonguz, C. Saraydar, T. Talty, M. Ames, and A. Macdonald, "Zigbee-based intra-car wireless sensor networks: a case study," Wireless Communications, IEEE, vol. 14, no. 6, pp. 67–77, 2007.
[6] M. Heddebaut, V. Deniau, and K. Adouane, "In-vehicle WLAN radio-frequency communication characterization," IEEE Transactions on Intelligent Transportation Systems, vol. 5, no. 2, pp. 114–121, 2004.
[7] A. Chandrasekaran, "Intra-Vehicle Channel Characterization in the 5 GHz Band," 2011.
[8] C. F. Mecklenbrauker, A. F. Molisch, J. Karedal, F. Tufvesson, A. Paier, L. Bernado, T. Zemen, O. Klemp, and N. Czink, "Vehicular channel characterization and its implications for wireless system design and performance," in Proceedings of the IEEE, 2011, vol. 99, no. 7, pp. 1189–1212.
[9] A. Agarwal and T. D. C. Little, "Role of directional wireless communication in vehicular networks," in Intelligent Vehicles Symposium (IV), 2010 IEEE, 2010, pp. 688–693.
[10] M.D. Higgins, R. Green, and M. Leeson, "Optical Wireless for Intra-Vehicle Communications: A Channel Viability Analysis," IEEE Transactions on Vehicular Technology, no. 99, pp. 123–129, 2012.
[11] Higgins, M. D., Rihawi, Z., Mutalip, Z. A., Green, R. J., & Leeson, M. S. (2013). Optical Wireless Communications in Vehicular Systems. Communication in Transportation Systems, 209.
[12] R. J. Green et al., "Networks in automotive systems: the potential for Optical Wireless integration", 14th IEEE International Conference on Transparent Optical Networks (ICTON 2012), Coventry, UK, 2012, paper Tu.D3.1.
[13] Higgins, M. D., Green, R. J., & Leeson, M. S. (2009). A genetic algorithm method for optical wireless channel control. Journal of Lightwave Technology, 27(6), 760-772.
[14] Z. S. Rihawi, Z. A. Mutalip, R. J. Green, M. D. Higgins, and M. S. Leeson, "Free-Space Optical Communications in Vehicular Networks Using Rectangular Guiding Models," IEEE Photonics Technology Letters, vol. 28, no. 13, pp. 1430–1433, 2016.