Journal of Engineering Science and Technology
4th EURECA 2015 Special Issue February (2016) 97 - 112

OPTICAL WIRELESS COMMUNICATION SYSTEM

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Abstract

The growing demand of bandwidth in this modern internet age has been testing the existing telecommunication infrastructures around the world. With broadband speeds moving towards the region of Gbps and Tbps, many researches have begun on the development of using optical wireless technology as feasible and future methods to the current wireless technology. Unlike the existing radio frequency wireless applications, optical wireless uses electromagnetic spectrums that are unlicensed and free. With that, this project aim to understand and gain better understanding of optical wireless communication system by building an experimental and simulated model. The quality of service and system performance will be investigated and reviewed. This project employs laser diode as the propagation medium and successfully transferred audio signals as far as 15 meters. On its quality of service, results of the project model reveal that the bit error rate increases, signal-to-noise ratio and quality factor decreases as the link distance between the transmitter and receiver increases. OptiSystem was used to build the simulated model and MATLAB was used to assist signal-to-noise ratio calculations. By comparing the simulated and experimental receiver's power output, the experimental model's efficiency is at 66.3%. Other than the system's performance, challenges and factors affecting the system have been investigated and discussed. Such challenges include beam divergence, misalignment and particle absorption.

Keywords: Optical wireless communication, (OWC), Free space optics (FSO), Quality of service (QoS), Bit-error-rate (BER), Q-Factor.

1. Introduction

The optical wireless communication system mainly comprises of three major parts: the transmitter, receiver and propagation channel. OWC is also known as Visible Light Communication (VLC) or Free Space Optical (FSO) has been propagating signals through at a wavelength between 380nm to 740nm for VLC and 750nm to 1600nm for laser through free and open spaces [1]. Similar with fibre optics, OWC system sends signals from the transmitter to receiver in the form of light. Though fibre optics propagates through glass fibre medium, OWC propagates light through air. OWC should not be confused with RF. Although it shares the same term of being wireless, but OWC is an optical technology that uses properties of light such as IR or laser to propagate [2]. Hence, many industry players are favouring the usage of IR because it brings numerous advantages such as IR is not affected by certain regulations on RF and OWC requires no spectrum licences, thus saving acquiring cost [3]. OWC is promising as a solution for the “last mile” bottleneck in wireless communications. As for radio frequency (RF), it is facing a soon to be congested spectrum, emerging security and terrorism issues, lower data rate and high cost of installation [3].

In the market today, many users are subscribing to RF wireless LAN products as WiFi hotspots commercially or at residential. However, RF wireless LAN uses the unregulated “free” spectrum region of 2.4 GHz and it has limited channel bandwidth [4]. As for fibre optical technology, it does offer good QoS but unable to reach everyone especially in the rural areas and has no mobility advantage because it is a wired technology [5]. OWC system has applications ranging from short range to ultra-long range. Currently, OWC systems are being used by military and space operations. A few vendors have started providing OWC system to industrial and commercial players as well. It is projected that by 2020, RF technologies power consumption will dominate the global network. However, optical link has the best bit rate and the lowest normalised energy consumption compared to the rest of RF wireless communication standards [6]. The main reason behind optical link’s efficiency is due to having optical properties as baseband, resulting in a simpler transmitter and receiver architecture [6]. Whereas for RF systems, its complex transceiver architecture causes substantial dissipation loss of power [6]. In the recent years, there has been an emerging research and applications of integrating both optical and RF wireless network also known as radio over fibre (RoF). RoF systems are capable of reaching data rates up to 500 Mbps but the transmission is still limited by the low carrier frequency [7].

1.1. Advantages of OWC over radio

The term “wireless” is not just limited to radio frequency (RF) applications only, but infrared (IR) also known as OWC are utilizing other regions of the electromagnetic spectrum as well. Due to the tremendous growth in broadband data demands, OWC technology has been accelerated in terms of research and development. Some of the most common OWC systems are IR LEDs and laser diodes (LD) as propagation mediums; photodiodes like PIN and avalanche diodes are amongst the common receivers used. Line of Sight (LOS) link type such as intensity modulation (IM) with direction detection (DD) is the most widely used modulation in OWC systems [8]. OWC systems offer numerous advantages over its RF counterpart, such as [8]:

- Abundance of unregulated bandwidth (200 THz in the 700 - 1500 nm range).

- No licensing fees needed to use the spectrums.
- No multipath fading when IM and DD is used.
- Very secure connectivity. It requires a matching transceiver carefully aligned to complete the transmission.
- Small, light, compact smaller size components and relatively low cost.
- Well defined cell boundaries and no interchannel interference.
- Use one wavelength to cover a large number of cells, therefore no frequency reuse problem as in RF.
- No need to dig up underground and is easily installed.
- Minimal absorption effects at 800-890 nm and 1500 nm.
- Health-friendly (no RF radiation hazards).
- Lower power consumption compared to RF.
- Lower probability of intercept and antijamming characteristics.
- Highly directional and cone-shaped propagation compared to RF radiate signals in all directions.

RF based technology does offer wireless broadband coverage in outdoors and indoors. However, it has limitations on the number of users per access point. Moreover, RF wireless LANs usually uses the unregulated or 'free' spectrum bands at 2.4 GHz. Other proposed unregulated bands like 17 GHz and 60 GHz technologies are under development [9]. Although RF are great in providing wide coverage but it lacks in terms of data rates due to lower carrier frequencies. As much as RF has diffraction and scattering issues, it can provide full coverage between rooms and walls. On the contrary, OWC system uses wide range of unlicensed spectral band range at 700 - 10,000 nm. It is therefore more cost effective to implement and has data rates exceeding 2.5 Gbps per wavelength up to 5 km range [10]. OWC might be more sensible in applications that require more than 100 Mbps because of its multiple user-sized cells, improved carrier reuse capabilities due to its abrupt cell boundary and reduced interference [10]. To make broadband networks more effective, OWC and RF can be seen as complementary rather than competition in technologies.

1.2. Challenges and gaps of OWC system

OWC system may have major advantages to the communication landscape, however it poses several challenges. According to Debbie Kedar and Shlomi Arnon [11], there are certain challenges and possible solutions to urban optical wireless communication systems. They have identified that OWC faces challenges such as the LOS alignment with the receiver and transmitter module due to external weather conditions such as sway of wind or weak earthquakes. For instance, two tall buildings using OWC system on top of their buildings to establish connections. Sometimes, these buildings are bound by dynamic wind causes to sway along it during the day or even the slight thermal expansion or shrinking of building's frame might cause small misalignment for the transmitter and receiver. Every misalignment of the devices poses a threat to OWC's QoS [12]. As this phenomenon occurs randomly, the performance of the system will be affected at uncertain time. Because OWC employs “point and shoot” approach, and errors of alignment will introduce signal fading. One possible solution is to develop a pointing error mechanism that able to feedback the alignment error and readjust its transmission and receiving behaviour with intelligent protocols, more research has to be done on this area [12].

Besides that, Ahmed Nabih [13] mentioned that weather conditions like rain, snow, fog or even clouds may absorb the light wave propagation and small water particles from the rain can also cause particles scattering. This will cause the OWC system performance to be affected like particle scattering will result in signal attenuation and distortions. Therefore, it is important to maintain a clear line of sight between the transmitter and receiver, especially when LOS link type is used. Sometimes, the LOS can also be interfered by foreign objects such as birds or airplanes, making it a possible threat for temporary downtime of transmission.

Ambient light and artificial light can result in background noise which can degrade receiver’s performance. Moreira et al. [14] performed testing on various ambient light sources and developed a model to describe background noises. One of the largest noise sources is the sun itself. Sunlight is unmodulated and has wide spectral width. It is the major noise source in any photo detection devices. However, artificial light source noise does not produce background current (micro-amperes) as high as the sun (mili-amperes) but it still does contribute to noise background [14]. Bocouvalas [15] and other researchers have done significant amount of work on experimenting optical source noises and proposed advanced signal processing filters to remove many types of such noises and improve overall performance.

The research question for this project: What is the impact of Optical Wireless Communication System to the quality of service (QoS) such as bit error rate, signal-to-noise ratio, Q-factor, receiver’s voltage output; identify challenges and suggestions for improvement?

2. Method

The hardware’s results will be obtained by collecting the receiver’s output and feed it to the multimeters and digital oscilloscopes. By manipulating the propagation distance between the transmitter and receiver, the receiver’s output voltage, current and signal waveforms will be collected. Due to the limited equipment in the engineering lab, Optiwave OptiSystem software will be used to produce a simulated circuit and calculate the model’s BER. As for SNR, MATLAB software will be used to calculate it. The following subchapters will discuss more details.

2.1. System model

The transmitter circuit (Fig. 1) is intended to be designed such a way that it can transmit wirelessly to the receiver. The input signal is an audio signal that will fed by the audio generator. The laser is responsible to transmit the light at a distance. The photo transistor at the receiver’s end supposed to be directed Line of Sight (LOS) link to the transmitter’s laser beam.

The receiver circuit (Fig. 2) is proposed to use phototransistor to receive laser signals from the transmitter. As the received signals produce voltages, it is further amplified with the signal amplifiers. Then it will be converted back to audio signals and to be heard by the speaker. The speaker has an in built gain or volume dial to further boost the signal amplification.

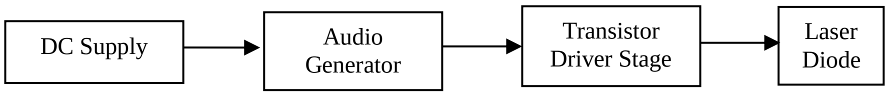

Fig. 1. The audio is transmitted by a laser diode.

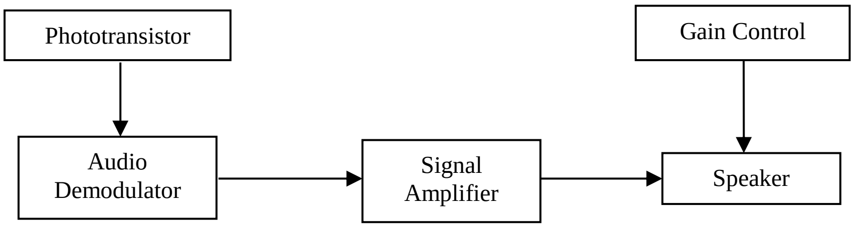

Fig. 2. The audio is being received by the photo transistor.

Table 1 shows the fixed parameters for both the experimental and software OWC model to reduce fluctuations of the results.

After identifying the project hardware specifications Fig. 3 introduces the experimental model of the OWC system and Fig. 4 introduces the simulation model of the OWC system using OptiSystem software.

Table 1. OWC system parameters for this project.

Transmitter Front End (Laser + Modulator)		**Receiver Front End (Photodetector + Amplifiers)**	
Operating Wavelength	650 nm	***Type of Photodetector (PD)***	PIN Photodetector (Solar Cell)
Class	Class 3A	***PD Responsivity***	0.233A/W
Average Optical Output Power	5 mW	***PD active area***	0.5 cm^2
Bit Rate	320 kbps	***Amplifier Frequency Response***	100 Hz - 10 khz
Input Signal	Audio Song (Pseudo-Random NRZ bits)	***Amplifier Power Output***	200 mW
Transmitter Aperture Diameter	0.2 cm	***Receiver Aperture Diameter***	0.8 cm

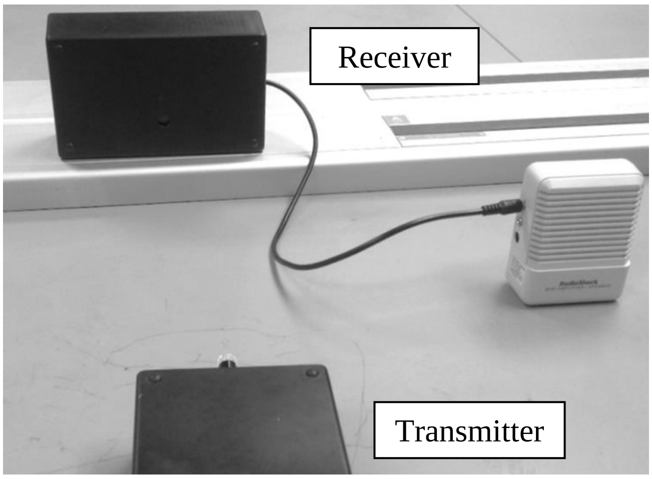

Fig. 3. Experimental model of OWC system.

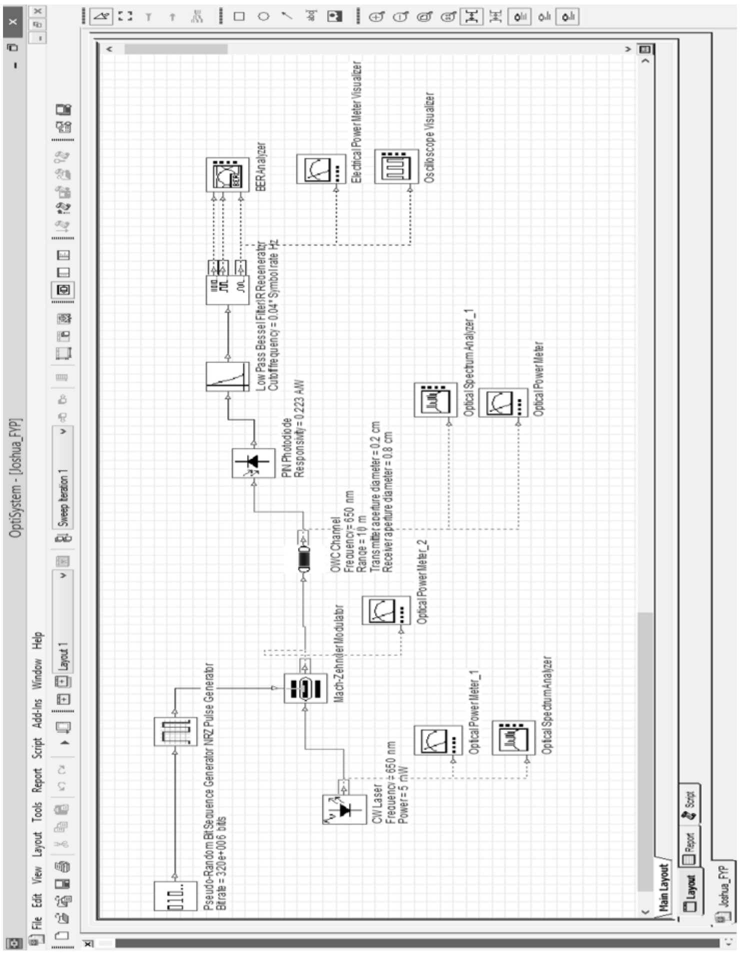

Fig. 4. OWC system in OptiSystem.

2.2. System efficiency between simulated and experimental model

Comparison will be made between the simulated data by using OptiSystem and experiment data. The manipulated variable will be the propagation link distance given a 320 kbps audio signal. The responding variable will be the output power produced at the PIN photodetector. Once the comparison is made, the efficiency of both the transmitter and receiver circuit can be calculated in terms of output, refer to Eq. (1). Repeat the whole process again by manipulating the propagation distance between the transmitter and receiver from 0.5 meter to 15 meters.

$$\text{systemefficiency}, \eta = \frac{P_{o\text{experimental}}}{P_{o\text{simulated}}} \times 100\% \quad (1)$$

2.3. Signal-to-noise ratio (SNR)

Signal-to-noise ratio is a measure of how a certain signal is being corrupted by noise. Defined as the ratio of signal power to the noise power along the signal, a ratio of more than 1 indicates more signal than noise. In communication system, higher SNR is favourable. Eq. 2 shows that the SNR in decibels (dB) [16]. For this project, SNR will be calculated with MATLAB by using Eq. 2 [16] because there is a limitation of tools to measure background noise power.

$$SNR_{dB} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \quad (2)$$

2.4. Quality factor (Q-Factor)

In optical communication, the common existence of signals are power and noise. That is why SNR is an important parameter for any communication systems. Q-factor is a dimensionless measurement where it simply indicates quality factor of the system whether it is underdamped or overdamped [17]. Given SNR, Q-factor is able to be calculated as shown in Eq. 3 [18]. T is the bit period and Bopt is the bandwidth of the optical filter used. In Optisystem, the Q-factor are calculated based on this equation.

$$Q = \frac{SNR\sqrt{2TB_{opt}}}{1+\sqrt{1+2SNR}} \quad (3)$$

2.5 Bit error rate (BER)

Bit error rate is usually a standard data given by any transmission devices. BER is the number of bit errors received by the total bits of the transmission media. These bit errors are usually due to noises or other interferences. The BER formula for this OWC system is shown in Eq. 4 [18]. This project will be built and simulate in OptiSystem software in order to get the BER and the Q-Factor using the BER analyser tool as shown in Figs. 5 and 6.

$$BER = erfc\left(Q/\sqrt{2}\right)/2 \quad (4)$$

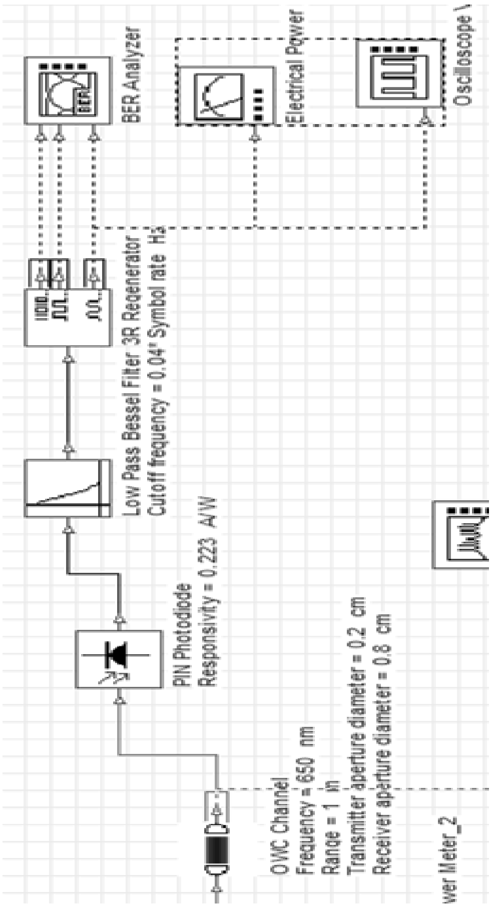

Fig. 5. BER analyser tool is connected to the simulation model output.

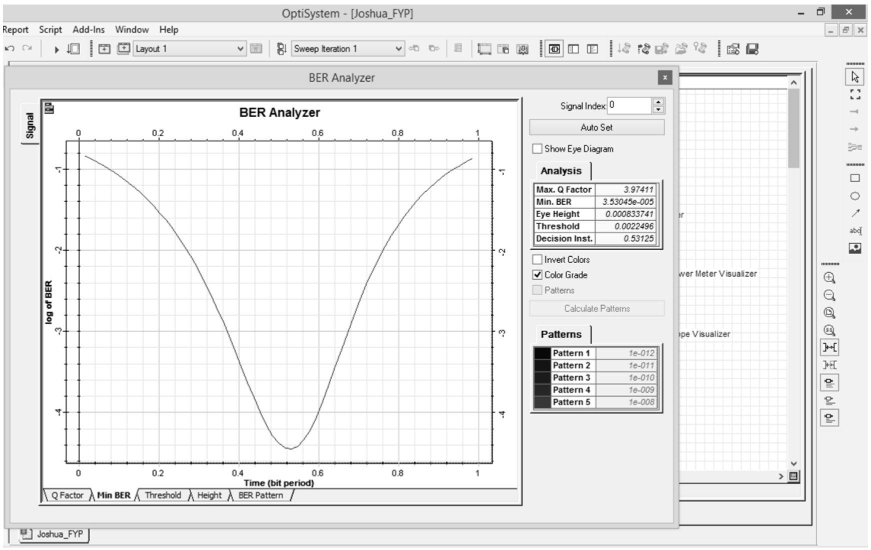

Fig. 6. BER graph in the analyser tool.

3. Results and Discussion

The project prototype has successfully built and various experiments have been done to obtain the data for analysing. After performing experiments with the project prototype, the model is being built and simulated in OptiSystem software to further validate, verify and compare the actual experimental results. More details will be discussed in the subchapters.

3.1. Receiver's power output vs. link distance

An audio signal that has a bit rate of 320 kbps was made as input of the transmitter. The laser then transmit light to the receiver at a distance ranging from 0.2 m to 15 m. A multimeter was tapped onto the output of the receiver's circuit for data collection. Once the experiment is done, a simulated model was performed using OptiSystem 12. The power output of the simulated design is also being recorded.

From Fig. 7, results have shown that the receiver's power output is experiencing a decrease as the propagation link distance increase; just as expected in the initial proposal. At 0.2 m, the experimental receiver managed to give an output of 3.35 mW, the highest recorded; while the simulation model gives 4.91 mW. Bear in mind that the transmitter is sending a signal power 5 mW. At close proximity, the sound amplifier gives a very clear and loud audio sound. This is a classic trend in any audio wireless signal system where it shows that power signals become weak as propagation distance increases. At 9 m and beyond, the power loss became very obvious when the sound amplifier produced a very faint and soft audio sound. Unless the transmitter source increases its signal power, the receiver will suffer from poor signal power reception. In the case of laser, it is challenging to increase transmitting power because of the eye safety regulations that are in place. A higher power laser may cause harm and damage to human eyes.

By comparing the simulated and experimental output, the overall system efficiency is at 66.3%. Generally, hardware components are bound by power losses such as heat dissipation, power supply fluctuations, minor current and voltage leakage, conversion rate of input signal to output signal. However, the major factor of such drop in efficiency is the atmospheric effect. Dust particles found in atmosphere can cause particle absorption and scattering. Thus, the drop in receiver's ability to achieve maximum 5 mW power given by the transmitter.

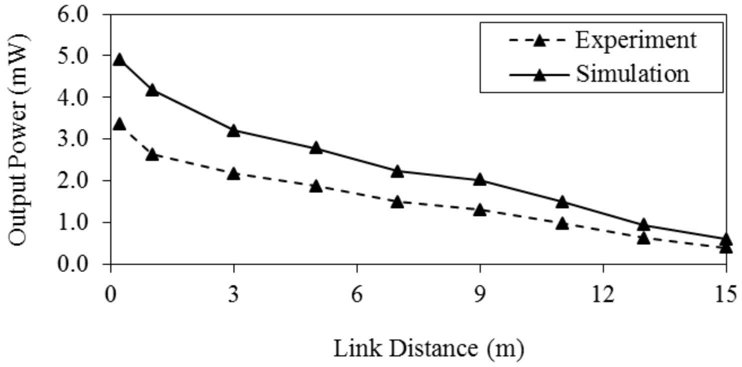

Fig. 7. Receiver's output power vs. link distance.

3.2. SNR vs. Link distance

To aide calculations, MATLAB algorithms has been used to find out the SNR at link distance of 0.2 m to 15 m. Figure 8 shows the results of SNR vs. link distance curve.

The SNR results demonstrated in Fig. 8 that SNR decreases as the link distance increases. As explained in the research methodology, it is known that SNR is the ratio of signal power over noise power. Logically as the link distance increases, the receiver's output power would decrease too. As a result, the signal power diminish quickly and the noise power steadily increases. Hence, the SNR has decreased in respect of link distance just as expected. Poor SNR is a major concern in communication systems; therefore it is a priority to find ways improving the performance. Other than keeping the transmitter and receiver distance at closer range, the introduction of signal processing filters at both ends are good methods to curb noise signals.

3.3. Q-Factor vs. Link distance

Quality Factor (Q-factor) is a very useful parameter to indicate the performance of any communication systems. As mentioned in the research methodology, Q-factor at different link distance is being recorded by using the OptiSystem model. The BER Analyser tool measured both BER and Q-Factor. Figure 9 shows the results of this OWC system Q-factor at distance of 0.2 m to 15 m.

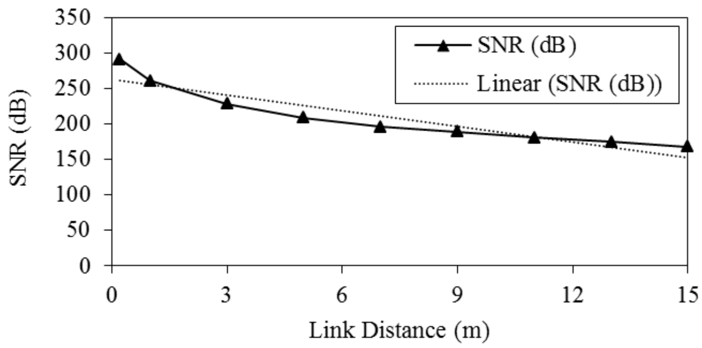

Fig. 8. SNR vs. Link Distance.

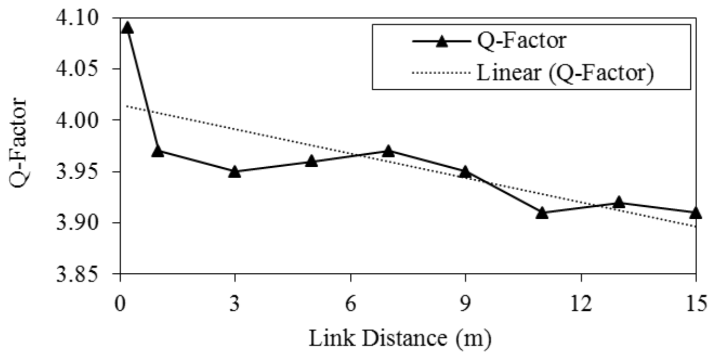

Fig. 9. Q-Factor vs. Link Distance.

The Q-Factor of this OWC system reflects the same trend as the BER and SNR. As explained in the previous chapter, Q-factor is a way of measure the quality performance of any communication system. Just as expected in the initial proposal, the Q-factor decreases as link distance. However at 0.2 m to 15 m, the Q-factor decreases at a very small rate. Just like the BER results (refer 3.4); the laser optical properties do not have immediate impact towards the system performance at such ranges of link distance. According to the simulated model, the system's non-functional point is at 600 meters. That is when the Q-Factor approaches 0.

3.4. BER vs. Link distance

With the implementation of this OWC system in OptiSystem, the BER of this OWC system is able to be collected. Simply by connecting a BER Analyser Tool to the model's output, readings such as the eye diagram, BER and Q-Factor are able to be displayed.

From Fig. 10, higher BER indicates that the data signal has higher probability of error in its propagation. This is not favourable in all communication systems. However in this project, the BER is still within the range of 10-5 at 0.2 m to 15 meters. It was initially expected to increase exponentially but it shows that it increased steadily instead. This is due to the property of laser diode at a narrow 1 nm optical bandwidth, which is less prone to particle scattering and fading signals compared to IR LEDs. Figure 10 illustrates the trend of the BER vs. Link Distance from 0.2 m to 15 m. It shows a linear increase in the BER as link distance increases.

Since the range of 0.2 m to 15 m did not display a significant decrease in performance, a larger link distance range (250 m - 600 m) has been investigated. In order to investigate the maximum distance when the BER is 1 for this system, the simulated model in OptiSystem was used. When BER is 1, it signifies that the probability of error in this system is unavoidable. According to Fig. 11 output results, it is found that the maximum distance for this system to achieve BER=1 is 600 meters. From the results, it is inevitable that BER increases as link distance increases.

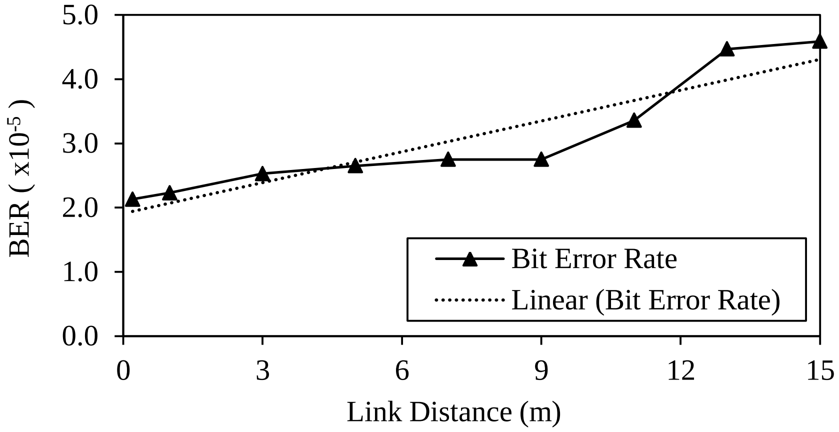

Fig. 10. BER vs. Link Distance (0.2 m-15 m).

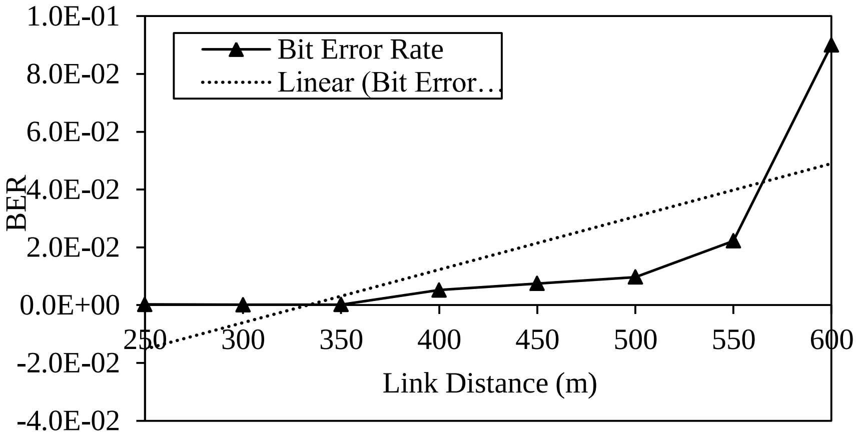

Fig. 11. BER vs. Link Distance (250 m-600 m).

3.5. Beam divergence, misalignment and particle absorption

In LEDs and lasers, the optical source is subjected to beam divergence due to its optics property. Likewise, this experimental model has faced the same issue but with minimal impact to its output results due to the low laser power output at 5 mW. Figure 12 shows the beam divergence at 0.2 m and 15 meters. It can be seen that the laser beam aperture diameter has increased from 1 centimetre to 2.5 centimetres as link distance increases at 0.5 meter to 15 meters. One of the method to overcome this challenge is to increase the receiver's photodetector active area to receive larger aperture lasers. Throughout the experiment, there were difficulties to align the laser propagation especially when the link distance increases. No signal or weak signal is received whenever misalignment of laser occurs.

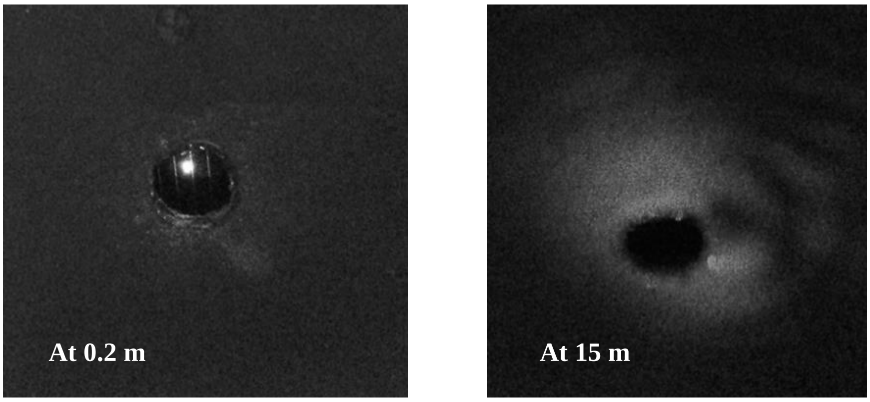

Fig. 12. Laser beam divergence occur at 0.2 m and 15 m at the receiver.

For experimental and investigation purposes, water spray has been introduced during the propagation of signal between the transmitter and receiver. As the water is being sprayed perpendicularly to the propagated laser path, the receiver's sound amplifier produced distorted signals and fading signals such as hissing and thunder sounds. Such distortion is caused by particle absorption. Where photons' energy did not successfully channel to the receiver but absorbed by the particles in the atmosphere such as dust and water droplets. Figure 13 shows the water spray is being introduced to the system for experimentation.

Fig. 13. Water is being sprayed at the laser beam propagation path.

4. Conclusion

This OWC system has clearly demonstrated the expected outcome that was initially raised in the project proposal. From the results collected, it can be seen that the efficiency of experimental vs. simulation model is at 66.3%. As the link distance increases, the BER increased, SNR and Q-Factor decreased. These outcomes are in line with hypothesis. According to the OptiSystem simulated model, this OWC system has a break down limit at 600 meters; where the BER is at 1 and Q-Factor at 0. There are also some challenges faced during the experiment. Laser beam divergence is a common issue and usually a larger receiver active area is one of the immediate ways to overcome it. Particle absorption phenomena has also been demonstrated in this experiment, as well as noise signals from the ambience light can be heard as link distance increases. It is proposed that the implementation of signal processing noise filters can help to improve signal quality. In order to overcome random errors throughout the experiment, a few attempts of data recording has also been done. The average mean of the results are used in this report. Table 2 shows a summary table of all the results collected in this project.

Table 2. Summary of OWC results.

Link Distance (m)	Output Power from Experiment (mW)	Output Power from Simulation (mW)	Bit Error Rate (x 10^{-5})	SNR (dB)	Q-Factor
0.2	3.35	4.91	2.13	291.2	4.09
1.0	2.63	4.18	2.23	260.9	3.97
3.0	2.17	3.20	2.53	227.9	3.95

5.0	1.88	2.78	2.65	208.8	3.96
7.0	1.49	2.22	2.75	195.6	3.97
9.0	1.30	2.03	2.75	188.6	3.95
11.0	0.98	1.50	3.36	180.7	3.91
13.0	0.63	0.94	4.47	174.3	3.92
15.0	0.39	0.60	4.59	168.16	3.91

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