AN ABSTRACT OF THE THESIS OF

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Title: Characteriscts of FSO Channel in WIFO

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With explosive growth of Internet access from smart phones and tablets, increasing bandwidth for WIFI system is badly needed. Depending on two years research, we produced a novel communication system called WIFO system, which integrates both RF (Radio Frequency) and FSO (Free Space Optical) techniques. WIFO system can significantly increase the wireless capacities due to retaining the mobility offered by WIFI systems. According to our research, the potential bandwidth of WIFO could be at least 50Mbits/sec, which is much more advanced compared to existing WIFI system.

In this thesis, we are not going to focus much on the mechanisms of WIFO system, but on the characteristics of FSO channel. Since the WIFO system mainly depends on the FSO (LED) channel, it is necessary to characterize it. In hence, this dissertation will analyze FSO (LED) channel via measuring the bit error rate in different situations and implementing Reed Solomen code to reduce transmitting errores.

Characterisсts of FSO Channel in WIFO

by

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Songtao Wang, Author

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I would also like to thank my parents who financially support me for the past 27 years. They gave me the chance of receiving well education and high quality living conditions.

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Chapter 1: Introduction

1.1 The WIFO system and FSO channel

Recently, the wireless communications are facing with some unique challenges, such as the competing between many wireless devices when they are accessing network simultaneously. However, the RF spectrum cannot be unlimited increased due to fundamental limitations imposed by physical laws.

Fortunately, the advances in FSO technology suggests a proper approach to increasing wireless capacity with slightly changes to the existing wireless technologies. More specifically, LED is sufficiently proved that it is possible to transmit data at high frequency. Moreover, the FSO channel would not interfere with RF transmissions such as WiFi system. Naturally, we came up with the idea that increasing wireless capacity via combining the FSO and WiFi system. The overall scene of WIFO system is shown below (Figure 1.1):

As shown in the figure 1.1, the WIFO system is not a stand-alone technology which can guarantee the mobility of clients. In WIFO, we combined the FSO and WiFi that enable wireless device to receive data both from FSO and WiFi, which provides the mobility. Definitely, the WIFO system could be used in the scenarios such as office, lecture rooms, airport terminals and so on.

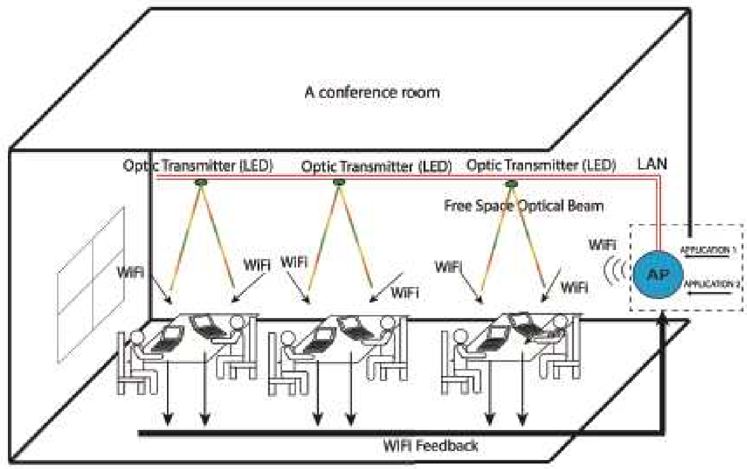

Figure 1.1: Overall realisitic scene of WIFO system

1.2 The mobility protocal

The WIFO system makes use of WiFi and optical transmission simultaneously to ensure the mobility. Basically, the optic transmission has priority if users are located in light cone. The WiFi transmission would take over if users are out of light cone. Figure 1.2 is a simple description of WIFO communication scene.

To illustrate the mobility protocol, here is the general assumptions: There are multi-users under multi-optic transmitter. No optic transmitter overlapping, that is, no user is under more than one optic transmitter. When a user is under an optical transmitter, both WiFi and optic transmission can be used, according to certain flow-control scheme. When a user is not under optic transmitter, only WiFi will be used. Every packet is acknowledged. All transmitters (FSO and WiFi) will not transmit a new packet until the previous packet to be acknowledged or timeout. Once a user enters a cone, the user will receive the beacon and then send an ACK

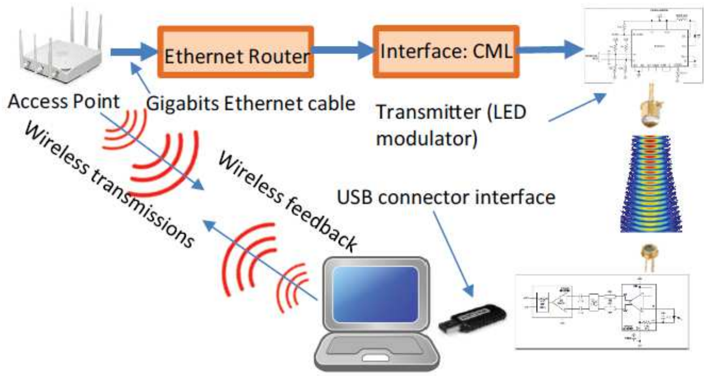

Figure 1.2: Simple description of WIFO system

to notify the server its location. Then, the ACK thread of the server will update the users table to register the new status of this user. The transmitter thread is notified the new status and will send the data to the specific cone accordingly. Once a user leaves a cone, the user will time out after it receives nothing from the FSO channel for a short time. Then, the user will send ACK packets containing a negative cone ID. Once the ACK thread gets this ACK, it will update the user table with current cone ID(which is a negative number) and previous cone ID(which is the cone the user was using), so that the transmitter thread know which cone is to be set idle. At the beginning of any transition, a handshake process is needed to avoid confusion if any ACK is lost. For example, if a user moves out of a cone and send out an negative ACK cone ID, it will be waiting for a confirmation from the server. If this confirmation does not arrive before time out, it will send the same ACK one more time. Figure 1.3 is a basic illustration of the mobility protocol.

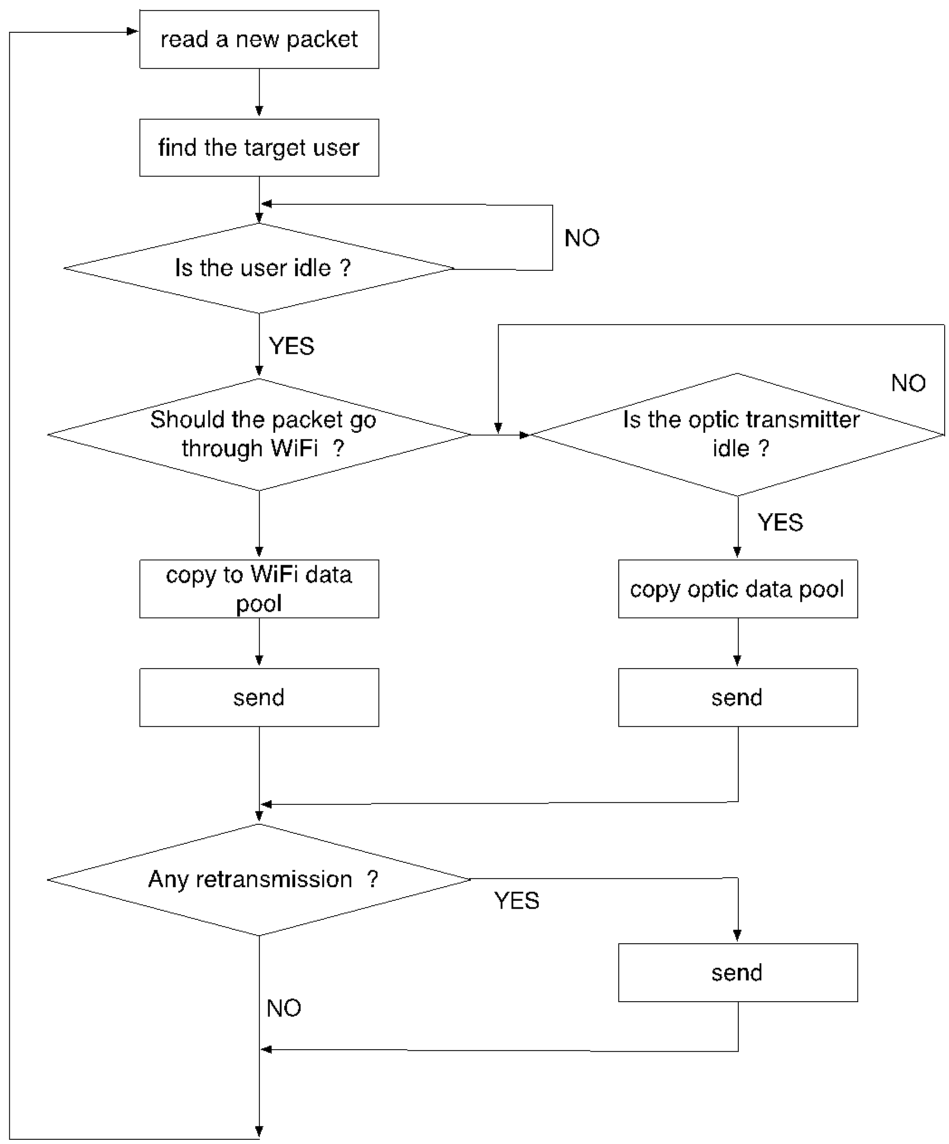

Figure 1.3: Illustration of the mobility protocal

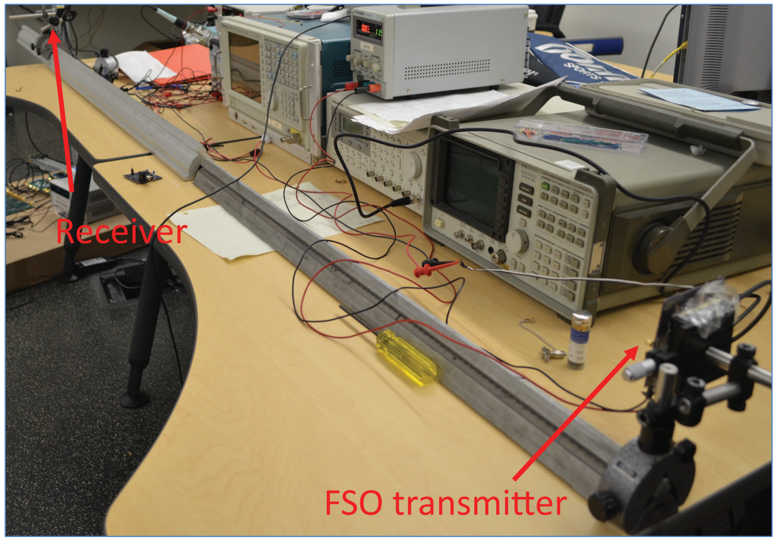

Figure 1.4: Realization of WIFO hardware

1.3 The hardware design

In general, the WIFO system is designed for indoor scenario, and we are trying to make the maximum transmitting distance up to 3 meters, which is the distance from ceiling to desktop. To achieve those objectives, transmitter and receiver circuits are responsible for data transmission. Figure 1.4 is the realization of FSO transmission channel.

Currently, Beaglebone Black is chosen for the transmitter as data processor. However, it is inconvenient to adjust transmitting frequency via Beaglebone. Whats more, we want to use another transmitter to characterize FSO channel which could guarantee the accuracy of the characteristics of FSO channel. Consequently, we took advantage of NI-board (PCIe-6537B) as the other transmitting processor. Moreover, an additional advantage of NI-board is that it can receive and transmit

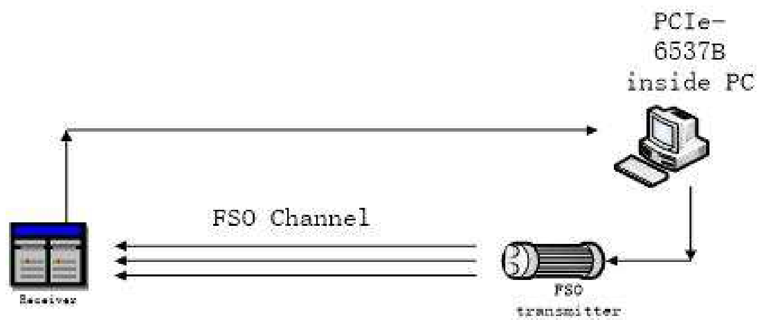

Figure 1.5: Basic schematics

data simultaneously with on-board clock, so we do not need to worry about the problem of synchronization.

For simplicity, the NI-board can output digital signal with rate varies from 0 to 50Mbps, and sending rate could be controlled by LABVIEW software. The basic schematics are shown in figure 1.5:

The distance between transmitter and receiver of FSO channel is 1 to 3 meters which is adjustable. And the transmitting rate varies from 1Mbps to 50Mbps.

Chapter 2: Motivations and Advantages of FSO Transmission

As mentioned before, the WIFO system mainly depends on the FSO channel to increase the wireless capacities. So it is important to have an all-round acknowledge. Furthermore, many research were focused on highly concentrated and powered FSO channel such as laser beam transmission, there is little relevant research on LED FSO channel. Besides, WIFO system solves many problems which WiFi suffers.

2.1 No interference

With growing use of wireless devices combined with the advent of mobility applications business to be diligent in managing interference throughout their deployments. Many wireless devices and commonplace electric devices already in use and newly emerging impede wireless performance. RF interference could be a major inhibitor to wireless performance.

Consider the situation in Kelly Engineering Center, there are a lot of WiFi devices. It is true that the other WiFi devices can cause interference with your device. This interference is known as co-channel and adjacent channel interference. That is, two access points on the same channel would share the channel capacity.

Moreover, the interference with your WiFi is not only coming from other 802.11 devices, but also from many other devices emitting in the unlicensed band. Such as microwave ovens, cordless phone, bluetooth devices, wireless video cameras, outdoor microwave links, wireless game controllers, Zigbee devices and so on. Consider the most widely used WiFi system 802.11g with a theoretically maximum rate of 54Mbps. In reality, this WiFi network operates at only a fraction of the maximum capacity like 5-15Mbps.

However, due to the physical laws, no interference between the FSO and RF channels. When using FSO channel as the downlink channel, the real transmission rate can approach to the maximum rate of FSO channel transmission rate.

2.2 Security

According to above, the interference happens frequently which is not only the performance problem, but also the security risk. The RF security does not stop with WiFi, many other devices could use WiFi spectrum.

WiFi networks are typically locked down with secure access controls, but devices that run on non-WiFi networks, such as Bluetooth devices, are not. A notebook computer with WiFi and Bluetooth connectivity may act as bridge, allowing an intruding device onto the corporate LAN or WLAN. Preventing accidental bridging between insecure networks and the corporate networks requires many professional tools which would increase the cost of building a safety WiFi system.

Moreover, Most enterprises implement some form of WiFi rogue access point detection to find unauthorized (and frequently unsecured) access points on the corporate network. But there are non-WiFi devices (such as Bluetooth access points) that can open up a similar security hole, Like WiFi rogues and so on.

Additionally, Certain non-WiFi devices such as cameras and cordless phones can be used to carry sensitive data out of a restricted area, bypassing corporate security policies. When this is a concern, a zone of restricted wireless operation should be established, and that zone should be enforced through monitoring of the spectrum for unauthorized devices.

However, the FSO channel donates a special and new spectrum that cannot be used by many wireless devices, which guarantee the security of wireless system.

2.3 High data rate

Due to the physical features of LED, we could take advantages of it to transmit data at very high frequency. Based on current FSO technology, can provide a typical bandwidth of 50Mbps per user via local transmissions. According to WiFi 802.11g system, the theoretically maximum rate is 54Mbps,however, the maximum rate can only reach 5-15Mbps due to some limitation such as interference, MAC protocol overhead, the distance between wireless devices and AP. More advanced protocol 802.11n for example, can increase the theoretically, but the real capacity is much more less than the maximum value, e.g., less then 100Mbps, depending on the operation circumstance. Additionally, such limited wireless capacity fail to provide adequate bandwidth for many wireless users.

Chapter 3: Related works

Optical transmission has been used since long time ago in human history. In ancient Greek and China history, people use torches as signal to warn invading activity of enemies. In 1880, Alexander Graham Bell invented the photophone, which could transmit sound via light beam. During the world war one, since telephone wire was often cut, German created a optical Morse transmitters to communicate important information. Recently, around 1960s, laser beam has been invented, which opens a new world of optical transmission. For now, many kinds of optical transmission device are common to us, such as optical fibers.

However, laser beam transmission requires huge amount of energy and meets many uncontrollable disturbs, such as fog, beam dispersion, atmosphere absorption, snow, rain, interference from background light and so on.

For indoor optical transmission, a famous project is on going called LIFI [1], a high speed and fully networked system that similar to WiFi. LIFI system, basically, uses visible light as communication media, is trying to be a replacement in contexts of data broadcasting. But its disadvantage is obvious, LIFI has to find a relatively complex modulation way to enlarge its bandwidth due to the limited bandwidth of visible light. Applying complicated optic modulation such as QAM needs some expensive components, and it would be hard to control the size of the whole transmission system.

While the WIFO network is designed to be complementary to the limited RF system. Making use of FSO and RF transmission simultaneously has been extensively studied. For example, [2] did research on throughput and delay for hybrid FSO/RF networks. [9] reports the use of FSO to transmit modulated RF analog signal and analyzed many key performance. Obviously enough, FSO gain significantly importance due to its large bandwidth, license free spectrum, high data rate, low mass requirements and so on. [5] presents a comprehensive survey on many kinds of challenges faced by outdoor FSO communications, and they provided many details of various performance mitigation techniques.[6] did some analysis one the error performance of FSO communication over multiple hops.However, no matter how fast development of outdoor FSO transmission did, the atmosphere turbulence is still a major problem of outdoor FSO communication [7]. [3] described several communication techniques to mitigate turbulence-induced intensity fluctuations. Since WIFO focus on the indoor FSO communication, which has the features of short distance, low energy consumption, no atmosphere turbulence and so on, people paid more attention on how to enlarge its bandwidth, simplify its modulation, lower its cost, etc. As mentioned before, LIFI [1] is a notable technology using visible light to transmit data in short range. [4] discussed a low power consumption 10MHz FSO system that is designed for mounting on mobile platforms. WIFO system is the first combined FSO/RF system with inexpensive components that could provide large bandwidth and mobility. Also, WIFO system could be integrated into some small size chips which can be easily mount into tablets.

Chapter 4: Experiment result and analysis

While in this chapter, the process of characterizing FSO channel will be introduced. It includes the experiment setting, software designing, LEDs power measurement and the bit error rate testing under different circumstances. As mentioned, it is necessary to have the FSO channels parameters as many as possible, which is important for proposing an accurate FSO channel model.

4.1 Power measurement of the transmitter

4.1.1 Experiment setting

The testing experiment is on the condition of 17°C indoor temperature with ambient light on. To get rid of the interference of ambient light, we turned on the power meter before LEDs working and reset the zero point so that the sensor can only detect power introduced by LED. Due to the characters of LED(VSMY2850RG), the peak wavelength is 850nm and angle of half intensity is 10 degrees. Since the distance between power meter and LED is 1 meter, so the radius of light cone is 0.17 meter. For the experiment, we have a 3 meter long railway to set the LED transmitter and receiver(the sensor of power meter), which can guarantee transmitter and receiver are fixed on the same straight line, as shown in figure 1.4. Besides, we assembled a 0.6 meter long railway on the 3 meter long railway which

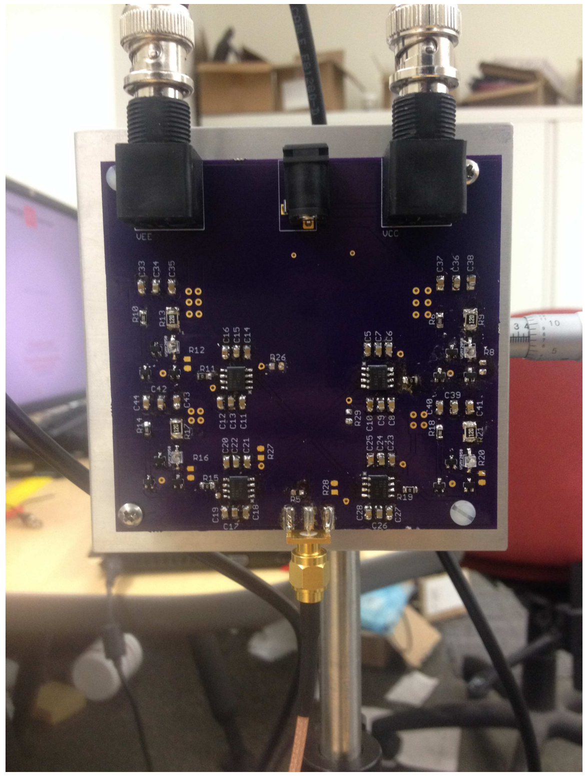

Figure 4.1: Realization of transmitter

perpendicular to each other. So the receiver can move freely on the diameter of the light cone. For the transmitter, two LEDs are assembled on a PCB board one inch apart, as shown in the figure 4.1.

An important thing needed to be mentioned is that all the hardware settings were built by Spencer and Anidita. As results, all the experimental results are based on those hardware settings.

When testing power of one LED, opaque rubberized fabric was used to cover one of the LED, then move the receiver(sensor of power meter) from one endpoint of the diameter to the other endpoint. For each 1cm displacement, we stopped and recorded the value of power as shown in the figure 4.2. For the power testing of 2 LEDs working simultaneously, the measuring method is the same except opaque tapes coverage.

4.1.2 Result analysis

As shown in the figure 4.1, the power was measured at each 1cm displacement. The goal of this experimental part is to characterize the receiving power on the receiver at different divergent angles. The figure 4.2 shows that the power intensity of each single LED decreases as the distance from the center of the light cone increases, or the divergent angle increases. Moreover, the received power intensity is Gaussian-like shape.

Before introduce the second part of the experiment, a basic assumption was made: the FSO channel is an additive channel, which means the power intensity should be added up due to measure the power intensity of two LEDs emitting simultaneously. Figure 4.3 shows that the power at receiver is also a function of the distance from the center of the light cone, or a function of divergent angle. Significantly, this result is approximately the same as the sum of individual powers get from two LEDs that measured independently as shown in the figure4.3. In hence, it is a good reason to announce that the FSO channel is an additive channel.

Recently, a simple OOK modulation method is used to transmit data in WIFO system. Specifically, the receiver detect signal as 1 when LED is on, and detect signal as 0 when LED is off. By OOK modulation, the bandwidth is limited due to physical laws of the light. However, since we have the result that the FSO channel

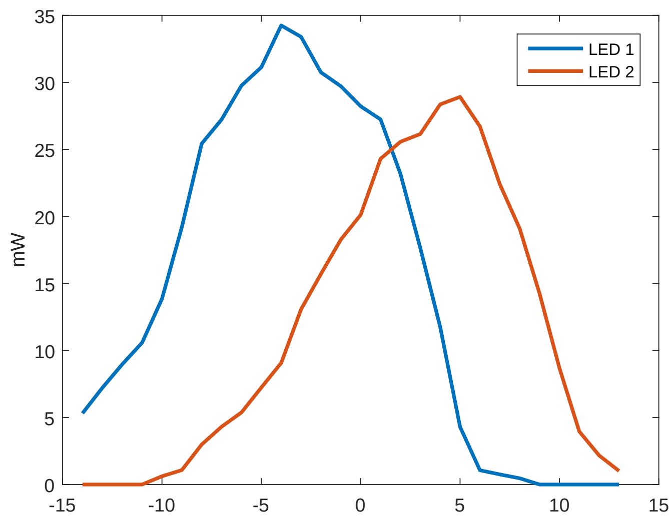

Figure 4.2: Power measurement of two LEDs emitting independently

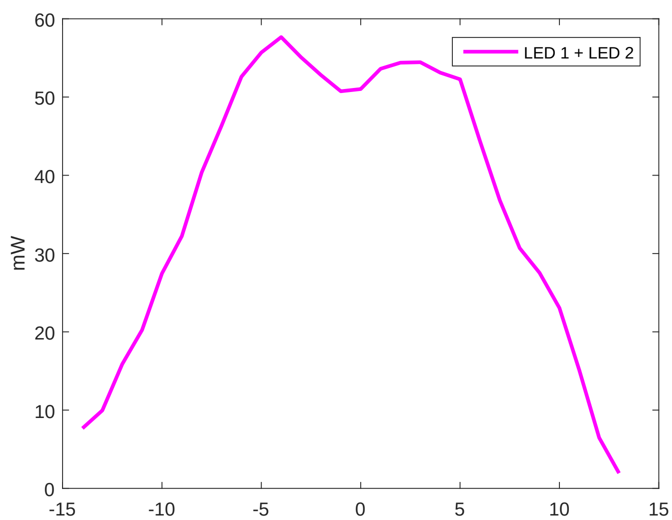

Figure 4.3: Power measurement of two LEDs emitting simultaneously

is additive, more efficient modulation methods could be taken advantage of, such as PAM, OFDM and so on. Furthermore, the additive property is the fundamental theory for more complicated scenarios solution. For example, as shown in the figure4.4(a), if a user is only covered by a single transmitter, then the transmission should be simple and convenient. However, as shown in the figure4.4(b), since a user is covered by two transmitters light cone simultaneously, interference would be occurred if one transmitter is responsible for the user, and another transmitter is responsible for other users. Actually, this scenario can be made use of to increase the transmission efficiency rather than decrease it. Since the additive property is known, and the user is covered by two light cone at the same time, it is possible to create a coding method to send data via two transmitter simultaneously. Actually, [9] came up with an algorithm to solve this problem.

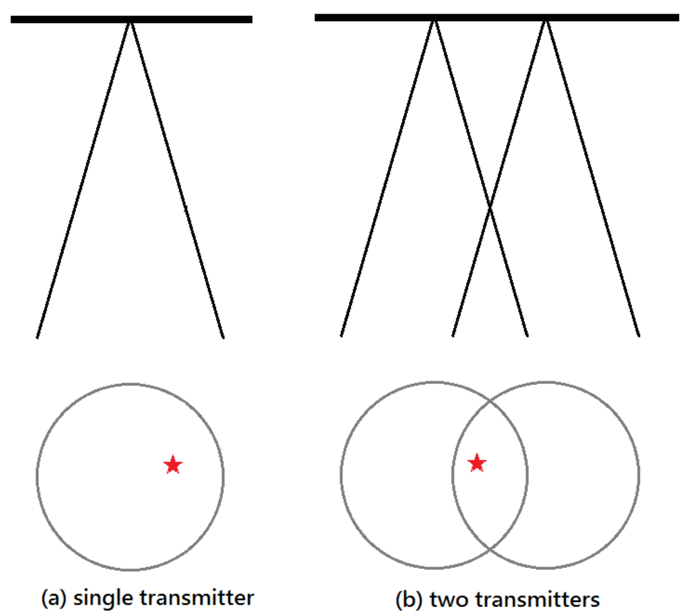

Figure 4.4: Singe and multiple transmitters' scenario

4.2 Bit error rate measurement

4.2.1 Introduction of NI-board (PCIe-6537B) and LABVIEW

According to the WIFO project, we want to make use of FSO channel to transmit data. Currently, Beaglebone Black is chosen as the transmitter. However, due to some hardware problems, Beaglebone Black is not a very convenient choice for BER experiment. We took advantage of NI-board (PCIe-6537B) as a new transmitter. Moreover, an additional advantage of NI-board is that it can receive and transmit data simultaneously with the on-board clock, thus we do not need to concern the problem of synchronization.

For simplicity, the NI-board can output digital signal with rate varies from 0 to 50Mbps, which can be controlled by LABVIEW software. The basic schematics are shown in the figure1.5. While the distance between transmitter and receiver of FSO channel is set as from 1meter to 2.8meters. And the transmitting rate varies from 1Mbps to 50Mbps.

Basically, LABVIEW is platform and development environment for a visual programming language created by National Instrument. Specifically, for the bit error rate experiments, LABVIEWs benefits include easily programming, large libraries, compatible with other text programming language and so on. More significantly, since both LABVIEW and NI-board (PCIe-6537B) are produced by National Instruments, they could corporate easily.

4.2.2 Software design

The data that chosen for transmission is a 10Mbits size pure random package, that is, every single bit in the data is normally distributed. Furthermore, before random data was sent out, a 32-bit long header would be added to the package. As NI-board (PCIe-6537B) and PC are share same memory and CPU, the data streaming rate can easily keep up with the LEDs blinking rate. While the FSO channel has low bit error rate [8], often as low as e-12 level for laser beam transmission. For WIFO system, although LED is used for transmitting data, which has much less emitting energy compared to laser beam, the short transmission range, indoor environment and few interference should keep the bit error rate at very low level. In hence, in the transmitters programming scenario, the data package was designed to send repeatedly. More specifically, the pure random data would be send 100 times for every experimental scenario. The reason for sending data 100 times is due to the limitation of memory size. More powerful devices are required for more accurate result. In hence, the minimum bit error rate is 1e-9, and any bit error rate lower than 1e-9 cannot be detected due to current hardware setting. The transmitter programming is shown in the figure4.5.

While on the receiver, in order to observe the original and accurate bit error rate, oversampling is not applied. In physical scenario, the optic signal would be acquired by photo detector and sent to the signal amplifier board. After that, the signal with peak to peak value of 600mV would be sent to the comparator board. Finally, NI-board (PCIe-6537B) receives signal out from the comparator. Any signal with voltage level higher than 1.25V would be treated as 1 and lower than

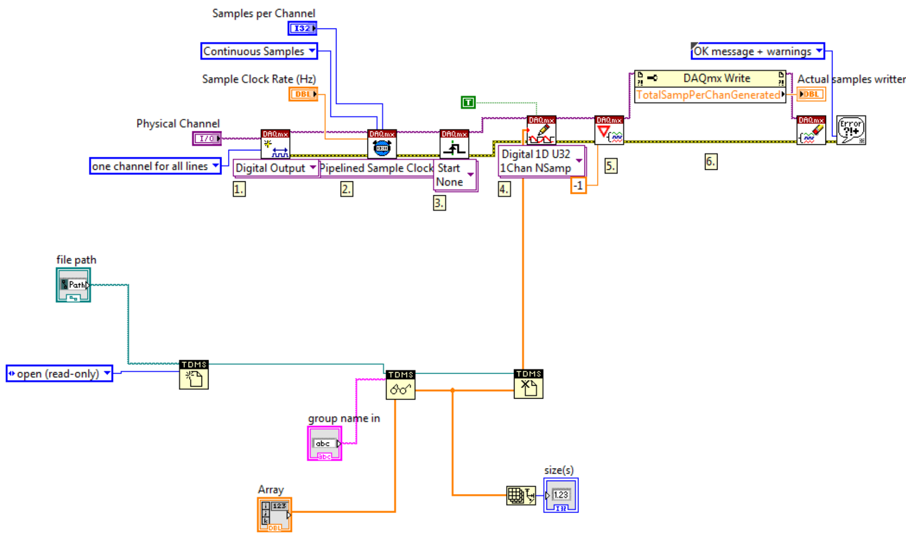

Figure 4.5: The transmitting program

0.5V would be treated as 0. Both transmitting and receiving process are started at the same time, and transmitting process end up with data sending ends, while receiving process end up with 0.5 second after transmitting ends. The receiver programming is shown in the figure4.6.

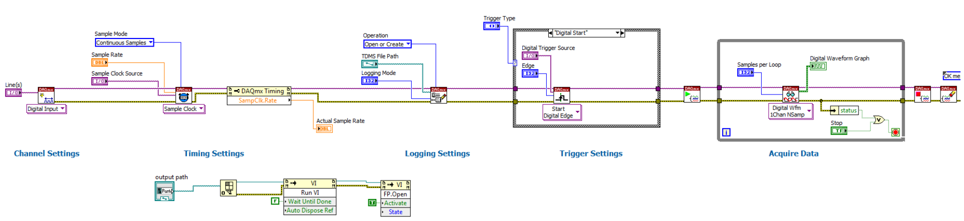

Figure 4.6: The receiving program

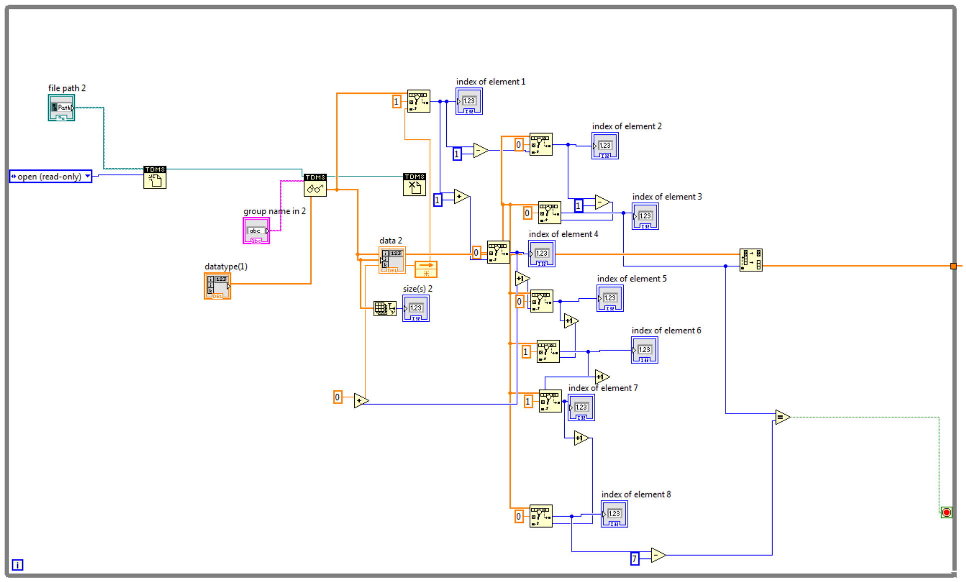

Figure 4.7: The part of proceeing program

As long as transmitter and receiver share the same on-board clock, there is no synchronization issue. Hence, the bit-by-bit checking method was applied. The original data stored in the memory and waited on comparing process. After NI-board (PCIe-6537B) sent receiving data to the PCs memory, the check program would start checking the header from the beginning of the receiving sequence. After 32 bits long header was found, register would deliver ten 10Mbits-long sequences in a row to the comparison register. After that, the comparison process was get started, and the total number of error would be recorded. In this way, the error rate was calculated by dividing those error numbers by 100M. The error calculation programming is shown in the figure4.7 and figure 4.8.

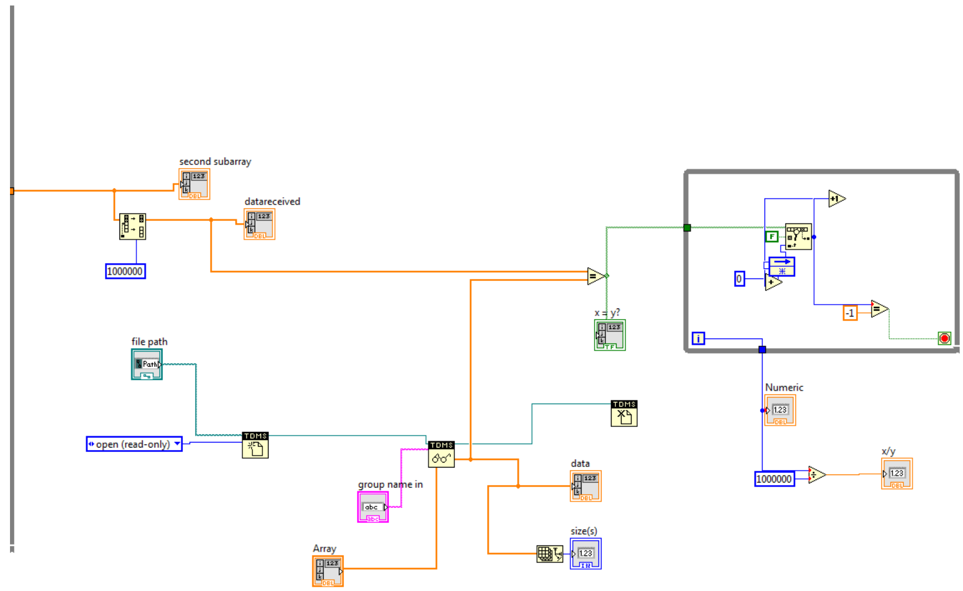

Figure 4.8: Another part of receiving program

4.2.3 Bit error rate vs. Transmitting rate

While in this experiment, receiver and transmitter are fixed on the 3 meters long straight railway. The distance chosen for the test varies from 1 meter to 3 meters. For each 0.2 meter, The bit error rate is tested at sending rate varies from 1Mbps to 50Mbps. Moreover, there is no rotation angle of receiver in this experiment scenario. The measurements results are shown in the figure4.9, figure4.10, and figure4.11.

As we can observe from the figures, some important properties can be acquired. First, as long as the bit error rate and transmitting rate are negative related, where the bit error rate increase as transmission rate increase, we have good reason to believe that the frequency response of FSO channel is a decreasing function.

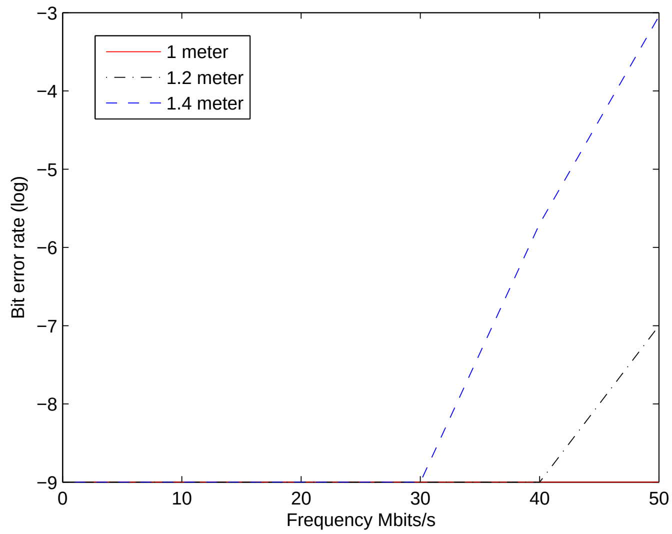

Figure 4.9: BER vs. Transmitting rate

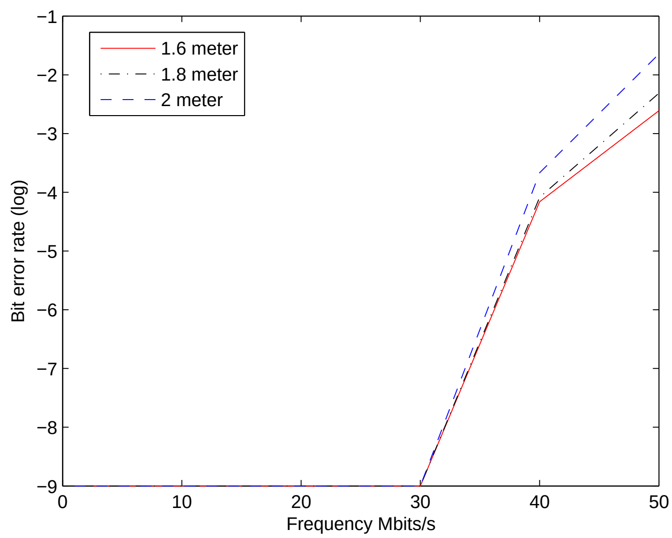

Figure 4.10: BER vs. Transmitting rate

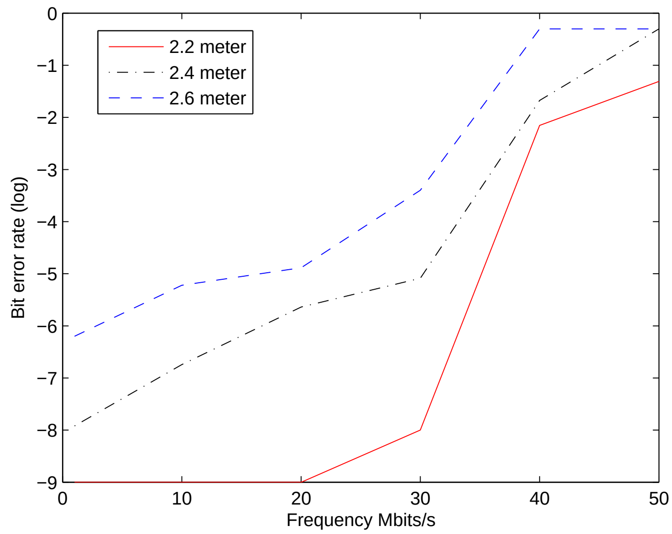

Figure 4.11: BER vs. Transmitting rate

Secondly, the bit error rate and transmission distance are negative related as well, where the bit error rate increases as long as the transmission distance increase. This is easy to understand due to the free space attenuation of optic transmission [9]. Namely, as the transmission distance increases, the receiving power decreases, so the signal to noise ratio also decreases, which pulls up the bit error rate.

Finally, due to the forward error correction techniques, the error rate could be reduced significantly if it is lower than 10^{-4}. In hence, as observed in those figures, if transmission distance shorter than 2.6 meters, any sending rate lower than 30Mbps could find a proper coding method to have an acceptable bit error rate.

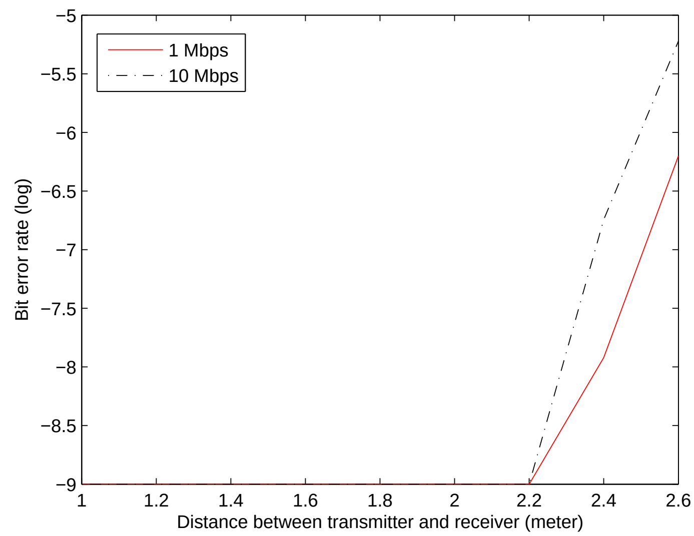

Figure 4.12: BER vs. distance

4.2.4 Bit error rate vs. Transmission distance

While in this experiment, the hardware setting is similar to the BER vs. Transmitting rate measurements. As transmitting rate is fixed, the receiver moves away from transmitter every 0.2 meters. And the transmitting rate is also varies from 1Mbps to 50Mbps, where bit error rate was measured every 10Mbps. The experiment results are shown in the figure4.12, figure4.13, and figure4.14.

Due to the observation to the results, some properties were obtained. At first, the bit error rate increases obviously due to the increasing of transmitting rate, which proves the claim that the frequency response of FSO channel is a decreasing function. And the decreasing tendency increases as the transmitting rate increases. So the decreasing frequency response is not linear.

On the second, as the transmitting rate was fixed, the bit error rate increases as the

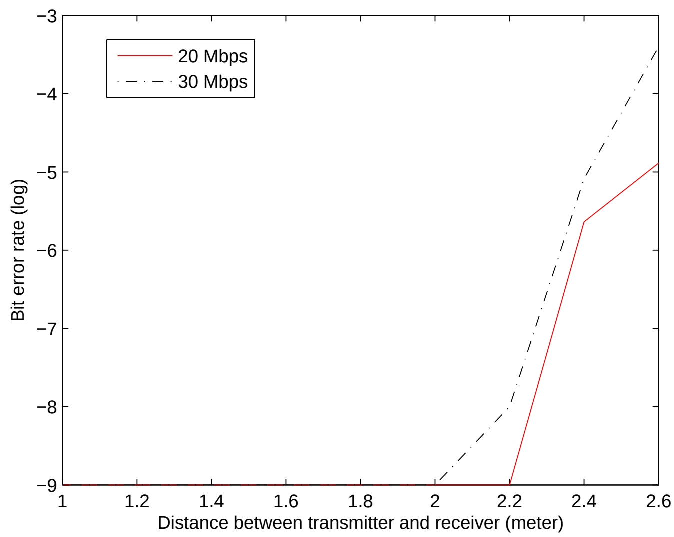

Figure 4.13: BER vs. distance

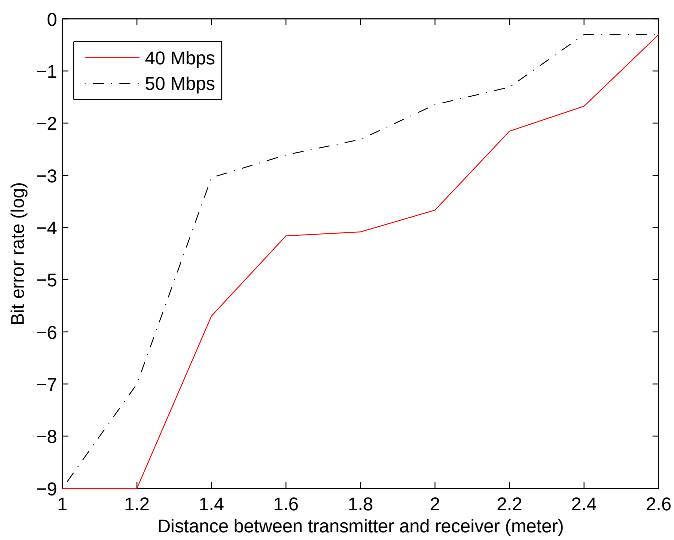

Figure 4.14: BER vs. distance

transmission distance increases, which is also the other testimony of the optic free space attenuation. It is also obvious that the attenuation is not linear. Actually, the free space optical attenuation equation is given by:

$$I(r,z) = I_0 \left(\frac{w_0}{w(z)}\right)^2 \cdot exp\left(\frac{-2r^2}{w^2(z)}\right)$$

Finally, due to the fact that forward error correction code could be applied to significantly decrease bit error rate if the original bit error rate is lower than 10^{-4}, transmitting rate could reach as high as 50Mbps when the transmission distance shorter than 1.2 meters. While if transmitting rate is lower than 30Mbps, the maximum transmission distance could be as long as approximately 2.2 meters.

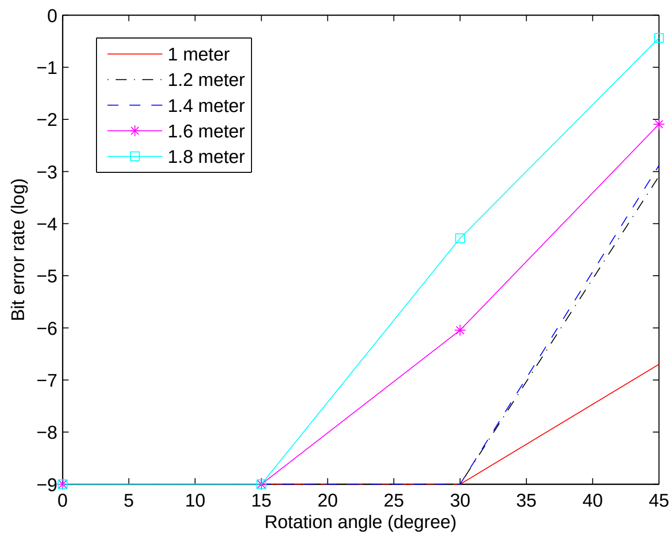

Figure 4.15: BER vs. Rotation angle

4.2.5 Bit error rate vs. Rotation angle

In this experiment, the distance between transmitter and receiver varies from 1 meter to 2.8 meters. And the rotation angle of receiver varies from 0 to 45 degrees. Basically, the bit error rate at different rotation angle is measured at every 0.2 meter distance. What is more, all the data was acquired at the transmission rate of 30Mbps, since WIFO system has a relatively reasonable performance at the bit rate of 30 Mbps. And the measurement data is shown in the figure4.15 and figure4.16.

By observation, it is clear that the bit error rate and receivers rotation angle are negatively related. The reason is because the photo detector that assembled on the receiver has less and less area to receive optical power as rotation angle goes larger and larger. With the receiving power decreases, the SNR would decrease

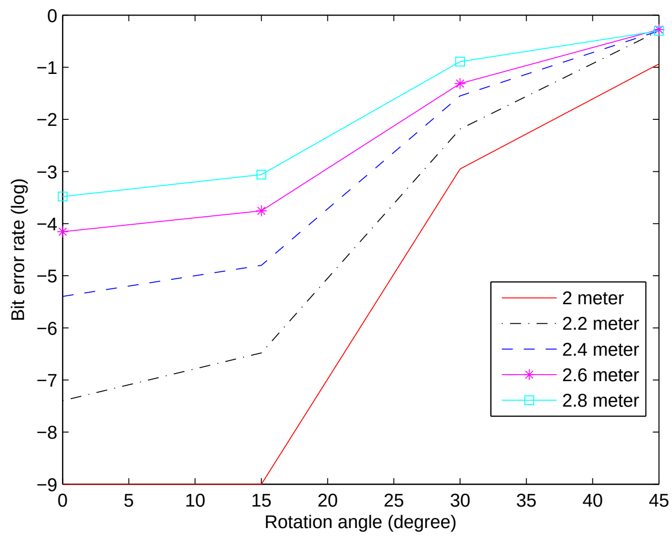

Figure 4.16: BER vs. Rotation angle

as well, so the bit error rate increases. Furthermore, when the receivers rotation angle within 15 degrees, the bit error rate is relatively constant, but it goes up rapidly as rotation angle larger than 20 degrees. Thus performance is acceptable due to real scenario. For instance, user may move around in a room, and the angle from photo detector towards LED may vary. The transmission performance could still be acceptable when rotation angle within 20 degrees. As usual, by using 20 degrees of rotation angle and the bit error rate of 10^{-4} as a standard, transmission distance as high as 2.6 meters and at rotation angle of 20 degrees could offer a acceptable bit error rate which could be improved by applying proper forward error correction code. Clearly enough, the performance can be better with lower transmission frequency.

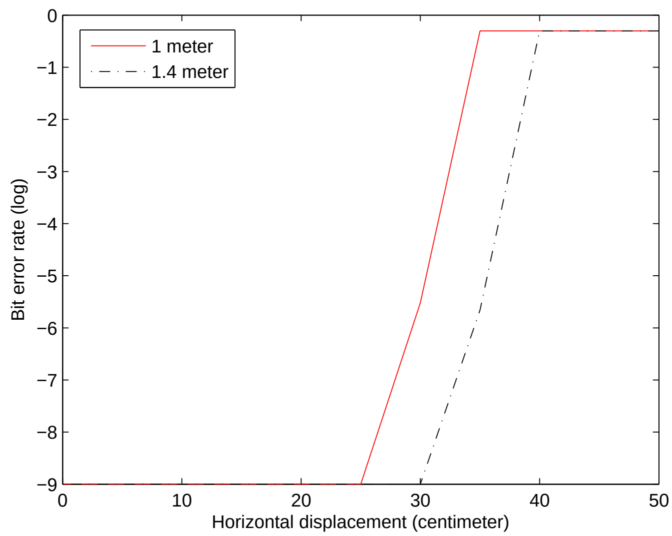

Figure 4.17: BER vs. Horizontal displacement

4.2.6 Bit error rate vs. Horizontal displacement

In this experiment, a new 0.6 meter long railway was horizontally assembled in the original railway, so that the receiver could move horizontally. Specifically, the transmission rate was set at 30Mbps which is fixed. And on the main railway, the bit error rate is tested every 0.4 meter, while the receiver move horizontally every 5 centimeters. The results are shown in the figure4.17 and figure4.18.

As shown in the figure 4.2 and figure 4.3, the power intensity of the transmitter is a Gaussian-like shape function. Namely, due to the light power distribution, the bit error rate should keep relatively constant within a certain range of horizontal displacement, and has a quick drop as the horizontal displacement exceed some certain value. Not only the light intensity itself has a fast decreasing tendency, but also the angle of half light intensity is 10 degree. Consequently, any distance that

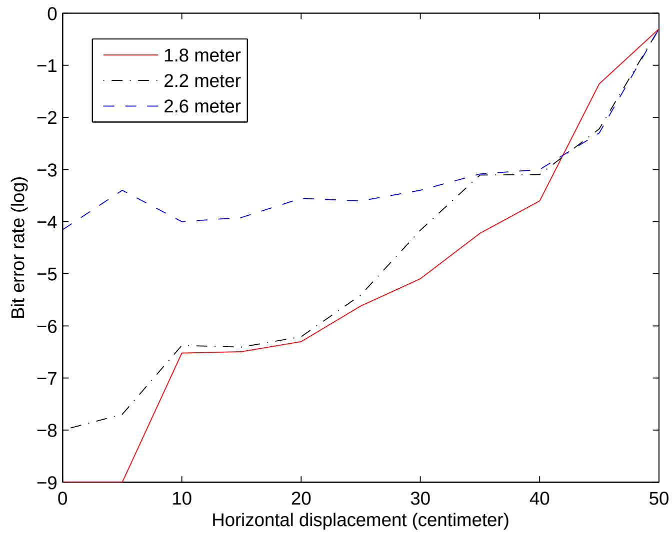

Figure 4.18: BER vs. Horizontal displacement

exceed the light cones coverage would also has a sudden power loss.

As the result of observation, the bit error rate measured at every vertical distance has an increasing tendency, which exactly matches the result of power intensity measurement. In general, this result is very important, because it shows the fact that WIFO system is capable of being applied to real scenarios and will have promising performance as well. Specifically, assuming the distance between ceiling and desktop is approximately 3 meters, then the radius of light cone would be 0.8 meters. Furthermore, users can move freely within the light cone and still have stable and fast internet access. Additionally, the result shows that within the vertical range from 1 meter to 2.6 meters, the bit error rate is approximately low than 10^{-4}, which indicates that proper forward error correction code can be applied to reduce its bit error rate.

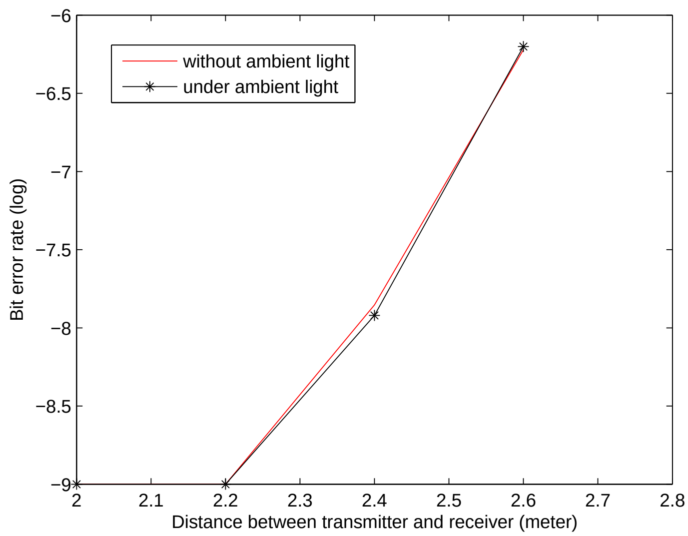

Figure 4.19: BER comparison at 1Mbps

4.2.7 Bit error rate comparison with and without ambient light

In previous experiments, every scenario was under the condition of ambient lights on which were emitting white light constantly. Since the LED that we were using has the wavelength of 850nm, it is possible to be interfered by the white light. Although the photo detector has a lens which is capable of filtering all kinds of light other than that with wavelength of 850nm, it is still necessary to check and compare the bit error rate with and without the influence of ambient light. The measurements are shown in the figure4.19, figure4.20, figure4.21 and figure4.22. All the experiments were at the rate varies from 1Mbps to 30Mbps.

As we can see in those figures, the influence of ambient light is limited. Especially in short transmission range, the results with and without ambient light are almost the same. However, when transmission distance became longer, and as the

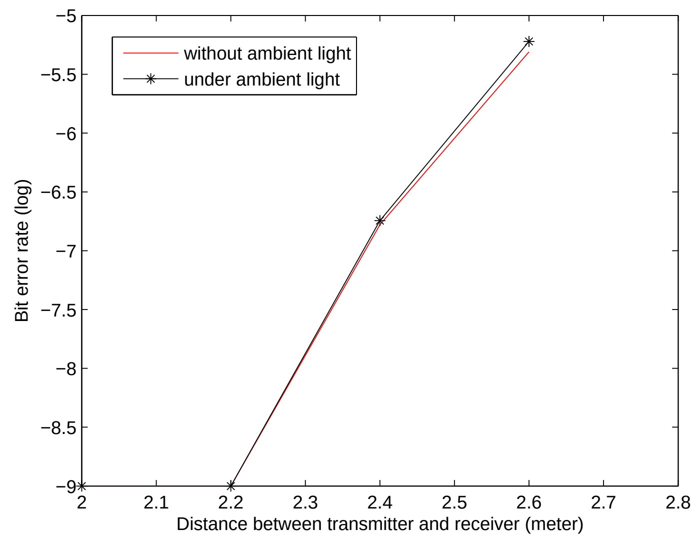

Figure 4.20: BER comparison at 10Mbps

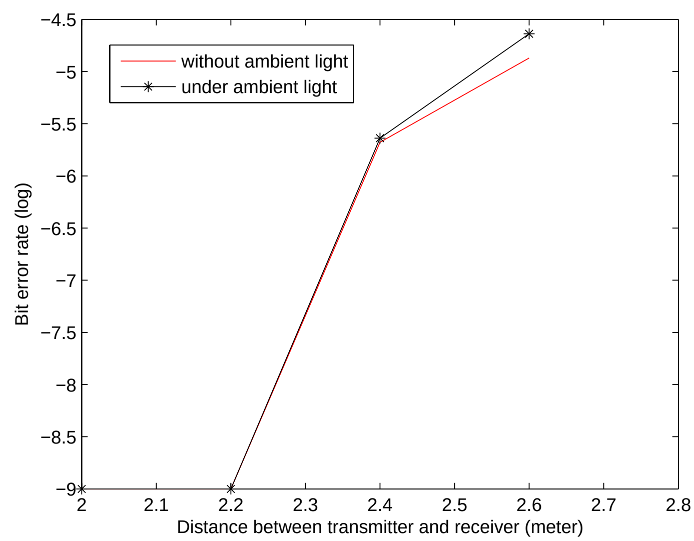

Figure 4.21: BER comparison at 20Mbps

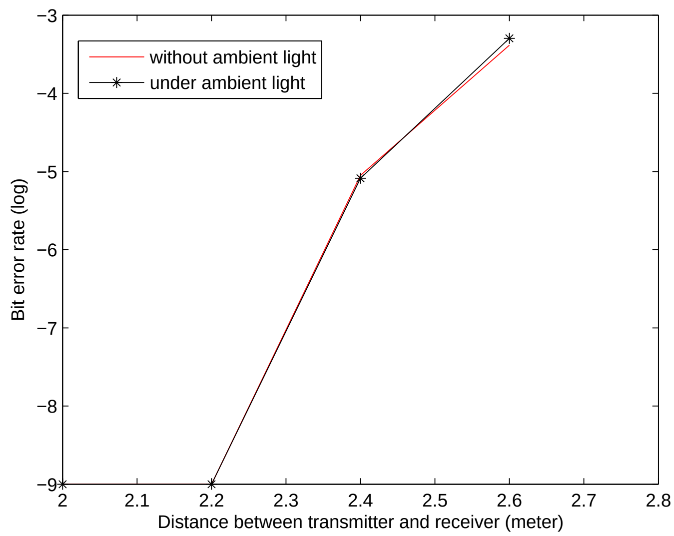

Figure 4.22: BER comparison at 30Mbps

SNR decreases, the difference became more clear. In general, the ambient light is introducing interference. However, the WIFO system could maintain good performance by making use of optical filter. Since in real scenario, the main source of environmental interference is coming from ambient light or sunlight, WIFO system could overcome it by assembling optical filter.

4.2.8 The bit error rate improvment by applying Reed Solomon code

As mentioned, according to the fact that the BER could be significantly reduced if the original BER is lower than 10^{-4}, I applied Reed Solomon code to verify it. This is also important due to the reason that proper coding methods would be used in WIFO system for practical application in the future.

Two experiments were operated in this section. The first one is under the condition that the transmitting rates were fixed at 30Mbps and 40Mbps, and the BER was measured as the distance between transmitter and receiver varies from 1 meter to 2.6 meters, as shown in the figures 4.23 and 4.24. The second experiments is under the condition that the transmitting rate was fixed at 30Mbps, and the transmission distances were fixed at 1.8 meters and 2.6 meters. The BER was measured as the horizontal displacement varies from 0 to 50 centimeters, which is shown in the figures 4.25 and 4.26. In both experiments, two different weight RS codes were applied to transmitted data, which were RS(255,247) and RS(255, 223).

By observation, we could confidently conclude that RS code is a good employ if BER is lower than 10^{-4}. As we can see in every single picture, the RS code can maintain the BER lower than 10-8. In most cases, the BER is lower than 10-9. Consider the fact that the minimum BER is 10^{-9} due to the limitation of hardware setting, the real BER is possible much lower than 10^{-9}. Furthermore, the performance can be improved by adding more check bits of RS code. However, more check bits means consuming more bandwidth to transmit the same size of information in the same amount of time. That is, properly choosing a RS code

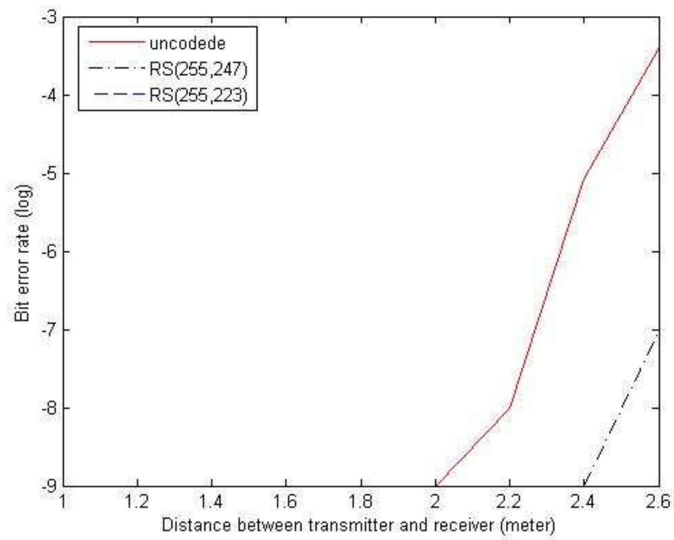

Figure 4.23: BER improvement by applying RS code. Transmitting rate is 30Mbps

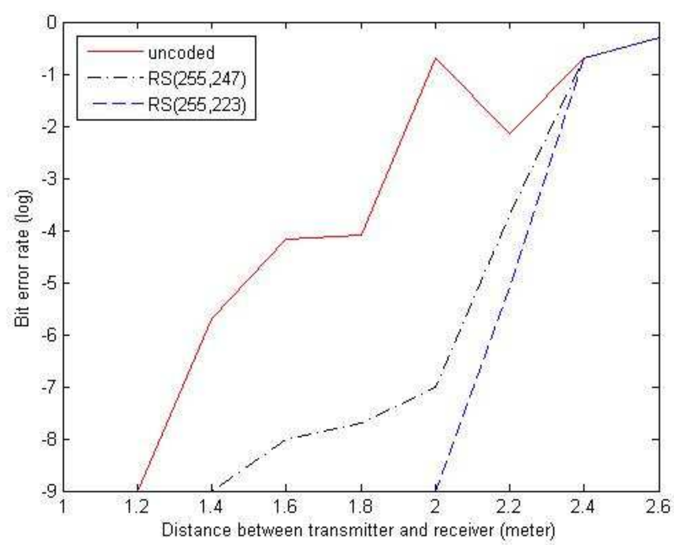

Figure 4.24: BER improvement by applying RS code. Transmitting rate is 40Mbps

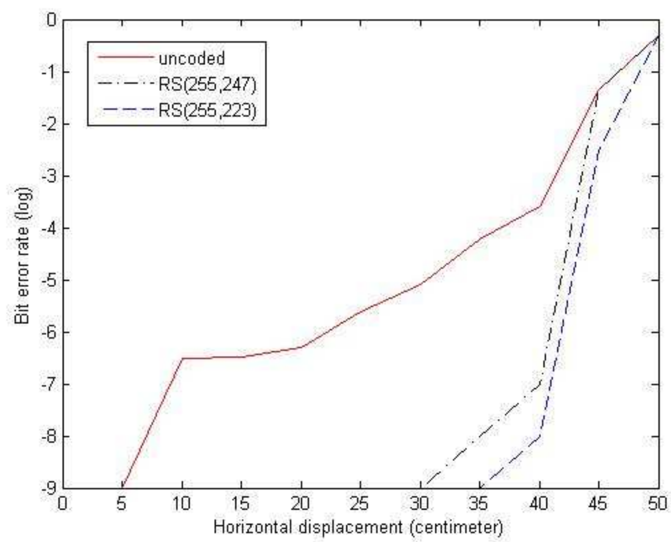

Figure 4.25: BER improvement by applying RS code. Transmitting distance is 1.8 meters

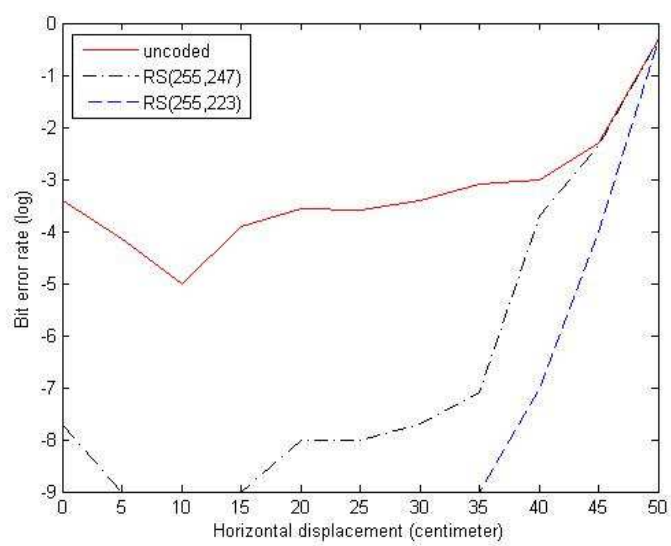

Figure 4.26: BER improvement by applying RS code. Transmitting distance is 2.6 meters

would be critical as well. On the other hand, the figures show that RS code cannot guarantee a low BER transmission if the original BER is larger than 10^{-4}. Either RS(255,247) or RS(255,233) was not capable of reducing BER dealing with received data has BER higher than 10^{-4}. Finally, by applying most widely used RS code (RS(255,223)), the high quality of FSO transmission could be guaranteed.

Chapter 5: Conclusion

In this thesis, we proposed a hybrid system called WIFO which integrates free space optic transmission and existing WiFi techniques. The reason that we want to create WIFO is to meet the increasing demands for wireless communication bandwidth. As a part of WIFO project, this thesis focused on physical features of the FSO channel in WIFO. According to information theory, we cannot design a proper coding method until fully understand the characteristics of a wireless channel.

Practically, we choose measuring bit error rate as an approach to understand the FSO channel. The bit error rate measured in many different settings showed us what the FSO channel is. From the power measurements of LEDs, we have the knowledge that the optic power emitting from LED is Gaussian-like and has additive property. From all the bit error rate measurements sections, we gain the relations between bit error rate and other critical parameters. For instance, the transmitting rate, transmission distance, receivers rotation angle and horizontal displacements are negatively related with the bit error rate.

Most importantly, all these experimental results are solid proofs that FSO transmission is feasible for WIFO system. It also shows that our research direction is correct. I am confident that WIFO is promising and would succeed in the near future.

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