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Yu-Jung Chu for the degree of Master of Science in Electrical and Computer Engineering presented on May 6, 2016.

Title: Mobility Protocol, Channel Estimation and Modulation Techniques for Hybrid WiFi-FSO (WiFO) WLAN of Femtocells

Abstract approved: _____

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As the price of broadband access service becomes more affordable, the number of homes with WiFi and public WiFi hotspots in the US are projected to increase significantly in the next few years. However, limited capacity of existing WiFi networks fail to provide adequate bandwidth for densely populated areas. Therefore, in this thesis, we describe WiFO, a novel communication system that integrates free space optical communication and WiFi technologies to provide an order of magnitude improvement in wireless capacity. Specifically, the thesis will focus on the mobility protocols and novel modulation and channel estimation techniques in order to provide high bit rates and large coverage.

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Mobility Protocol, Channel Estimation and Modulation Techniques for Hybrid WiFi-FSO (WiFO) WLAN of Femtocells

by

Yu-Jung Chu

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Yu-Jung Chu, Author

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This thesis is dedicated to my beloved family. Without their support and unconditional love, I wouldn't have enough courage to pursue my dream in a foreign country alone.

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I Love OSU! Go Beavers!

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Chapter 1: Introduction

In the past decade, hand-held portable devices increased in both quality and quantity. This improvement in technology makes the prices of these consumer electronics more acceptable. Thus, people tend to own multiple devices for various purposes from work and school to personal entertainment. Thousands of miscellaneous apps for smart phones and tablets are being made everyday. Consequently, future Wireless Local Area Networks (WLAN), such as WiFi, must be able to accommodate such explosive increase in wireless usage. That said, this chapter will discuss the shortcomings of current WiFi and introduce a novel communication system called WiFO. WiFO is a hybrid WiFi Free Space Optical Local Wireless Area Network of Femtocells.

1.1 Motivation

The growing popularity of wireless Internet access and the development of personal devices, such as smart phones and tablets, enable people to get information instantaneously. Thus WiFi has become an indispensable part of people's daily lives. With the rapid growth in wireless communication, better transmission quality is urgently needed. Despite numerous advances in wireless technologies, the shared Radio frequency (RF) spectrum cannot be unboundedly expanded due to the fundamental limitations induced by the laws of physics. Therefore, devices will inevitably compete for the available RF spectrum and it is becoming more important to find new ways of providing sufficient access to wireless Internet.

As an example, IEEE 802.11g, which is the third modulation standard for wireless LANs, has a maximum raw data rate of 54Mbit/s theoretically. But in practice, due to the implementation of access points (AP), MAC protocol overhead and the distances between users and APs, only a fraction of the maximum capacity, e.g, 15-20Mbit/s is achieved. Imagine a scenario that in a big stadium, thousands of fans are watching an NBA baseball game and trying to share the exciting feelings with friends in the halftime simultaneously. Even with 200 people, they would average 100Kbit/s per person which is not acceptable for video streaming applications. Similar examples include conference meetings in hotels or the boarding areas in airport terminals. These examples show that such limited wireless capacities of current WiFi networks fail to provide adequate bandwidth for users in densely populated areas.

In order to utilize RF resources more effectively, there needs to be more advanced and complicated RF circuitry and algorithms to work on temporal and spectrum allocation. On the other hand, recent research in Free Space Optical (FSO) promise a complementary system to enhance wireless capacity with minimal modification on the existing WiFi architecture. This can be achieved because FSO technology does not interfere with RF transmissions. FSO works by utilizing the development of the solid state lighting technology, such as Light-Emitting Diodes (LEDs) and Vertical-Cavity Surface-Emitting Lasers (VCSEL). These devices now have the capability to transmit data at a high bit rate reliably. However, these applications are thus far limited to spot-light, point to point and short distances and have not been well integrated with the existing WiFi networks. Consequently, FSO communication systems are of limited mobility. Thus, the next focus in this research is finding a way to integrate FSO technology with the existing WiFi network system and retain a flexible mobility. In the next section, a prototype of our proposed system, WiFO, will be introduced concisely.

1.2 WiFO

WiFO is a novel communication system, which aims to overcome the shortage of the WiFi capacity problem arising from the competition, among many users, for a limited shared wireless bandwidth by integrating current RF and the recent free space optical technologies seamlessly. Usually, the capacity overload problems are due to the common down-link scenario where most of the users would download contents from the Internet via many wireless applications. The down-link traffic is therefore many times greater than the up-link traffic. Because of this asymmetrical property, only a one-directional FSO channel is needed, that is, data is transmitted from the Internet to the mobile devices via AP. Fig. 1.1 illustrates the typical usage scenarios for indoor applications that include offices, airport terminals, entertainment centers, etc. Users in these environments are often stationary instead of moving around, e.g., sitting at the desk in the office for a while. This way, in addition to the WiFi transmissions, deploying a network of LEDs/VCSELs with the high speed Ethernet infrastructure directly above the appropriate spots can realize local high rate FSO transmissions. The proposed FSO system for indoor applications modulates and demodulates lights from inexpensive LEDs/VCSELs and silicon photodiodes (PDs). Thus, the characteristics of its FSO transmissions are quite different from that of long distance FSO transmissions for outdoor usage. While collaborating with the existing WiFi and high-speed (Gigabit) Ethernet infrastructures, unlike stand alone FSO technology, the WiFO system not only provides high capacity and mobility but also has a unique advantage that it doesn't interfere with the existing WiFi transmissions. Therefore, it enables wireless devices to receive data from both FSO and WiFi channels simultaneously.

The architecture of the proposed WiFO system is shown as Fig. 1.2. The down-link

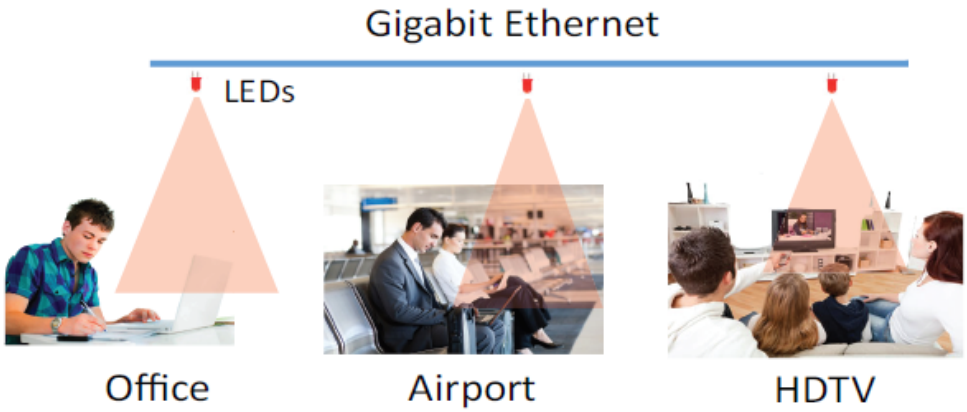

Figure 1.1: Use Scenario

scenarios are realized as below. In a WiFi network, all the data from the Internet to the end users is first passed through the access point (AP). Then for an IP packet of a given flow, the AP will decide whether to use the WiFi or FSO channel to send the data. If the FSO channel is selected to send the data for a particular device or user, the data will be encoded according to the transmission protocol and broadcast on the Gigabit Ethernet network with the appropriate information to allow the corresponding FSO transmitter to receive the packets. Upon receiving the packets, the transmitter relays the data to all the devices (receivers) within its light cone area. The receivers then decode the packets. The packets are discarded if they are not wanted. Otherwise, the data is taken and a feedback/ACK is sent to the AP via the WiFi channel. This ACK message allows the system to adapt effectively to the current network conditions. A closed-loop transmission is then completed. If the AP decides to send the data via the WiFi channel, then it just directly broadcast the packets through the WiFi network as

usual. Thus, the WiFO system is integrated seamlessly with the existing WiFi network and significantly increases the overall wireless capacity through local Free Space Optic transmissions.

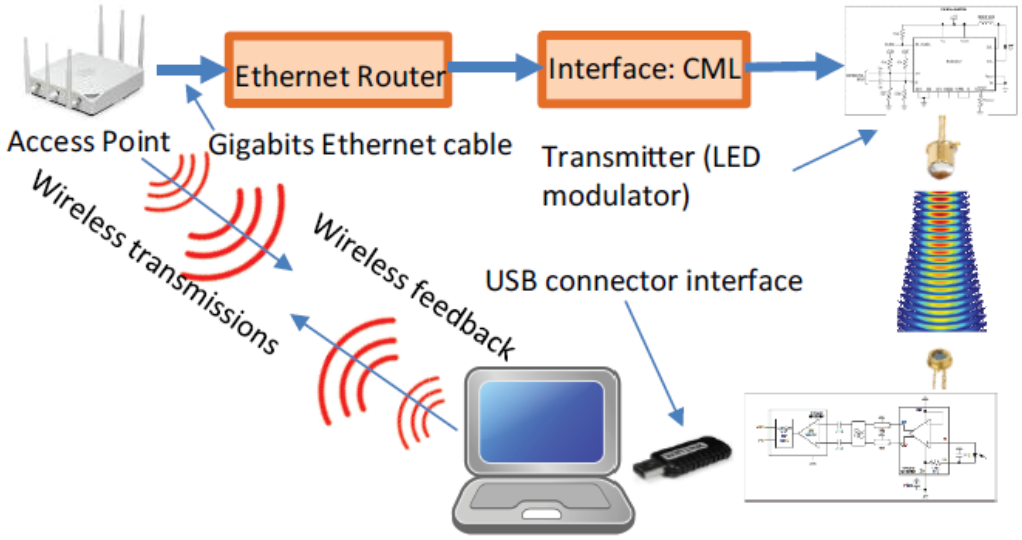

Figure 1.2: WiFO Architecture

1.3 Outline of The Thesis

With the descriptions of the motivation and the prototype of WiFO in the previous two sections, this section is going to briefly go over the following chapters. This thesis is divided into 7 chapters. Related work will be discussed in Chapter 2. It is important to note that the previous work and other excellent researchers' contributions play a key role of inspiring us to have this proposed WiFO system as well. In the Chapter 3, the hardware and software architectures of WiFO will be described briefly. Chapter 4

will define the packet formats for the proposed protocols and elaborate on the proposed transmission and mobility protocols. Chapter 5 will refine the architecture to address the scenario when light cones overlap. The simulation results will be present in Chapter 6 to demonstrate the WiFO's remarkable performance in terms of video demo, latency and bit error rate (BER). The conditions for signal irrecoverability are also simulated and discussed for the scenario of overlapping light cones. Finally, a conclusion will be made in Chapter 7 and some potential future work will be addressed as well.

Chapter 2: Related Work and Background

Our cooperative FSO-WiFi network is complementary to the limited shared RF transmissions. FSO/RF has been extensively studied, with some focusing on analyzing throughput and delay for hybrid FSO/RF networks [1], while others research into point-to-point architecture based on board-level and chip-level optical interconnects [2] for super computers. There has also been work on outdoor and long-distance implementations of hybrid FSO/RF communication systems, such as [3] [4] [5] [6]. These hybrid systems were affected by attenuation and fading due to distances, weather conditions and scintillation. Little research effort has been put into indoor free-space optical communications. In [7] [8], the implementation of a physical layer with a large bandwidth is employed to provide high speed data links for a small number of users to the base station. M. Kavehrad [9] also intends to exploit white light emitting diodes (WLEDs) for simultaneous illumination and indoor free-space optical communication. Although this solution is potentially energy efficient, it is not easy to integrate the expensive WLED illumination system with the power system. This system also only offers low bandwidth. In contrast, our proposed WiFO system is novel and feasible, with work focusing on indoor implementation where fading is mainly caused by the geometry of the cone beam. Recent literature on joint optimization of using RF and FSO channels simultaneously have been proposed and studied. For example, the work in [11] [12] [13] [14] [15] and [16] addresses joint coding schemes for both FSO and RF channels. While these works discussed above are impressive, there has not been work on the most imperative issues such as the congestion of WiFi network and dynamic allocation of bandwidth to a large

number of users. Li-Fi [18] by H. Hans et al. is another notable technology using visible light communication that can achieve high data rate for short range communication. To the best of knowledge, the WiFO system [10] [19] is the first system that integrates WiFi and FSO seamlessly with the advantage of low cost using inexpensive components. Meanwhile, it can provide both high capacity and mobility.

Chapter 3: WiFO Hardware and Software Architecture

In this chapter, the hardware architecture and the software design of WiFO will be introduced. The hardware architecture consists of a transmitter, a receiver, an AP server and a receiver laptop. In the section of software design, the OSI (Open Systems Interconnection) model is used to explain the functions of each layer.

3.1 The Hardware Architecture

The goal of the WiFO prototype is to transmit data reliably via FSO channel with a transmission rate of tens of Mbps. WiFO is designed for an indoor-use scenario, which means that we focus on the transmitting distance between one to three meters. To achieve these objectives, a set of transmitter and receiver is responsible for data transmission. An AP server and a receiver laptop are used for processing, modulation/demodulation and use software protocols to simplify and lessen the loading of the transmitter and receiver pair.

There are two components of the transmitter, which are a BeagleBone Black board and a transmitter circuit. The specification of BeagleBone Black include a 1GHz processor, 512M DDR memory and two PRUs (Programmable Real-time Units) that can access on-board GPIO (General Purpose Input/Output) pins at a maximum speed of 200MHz. The beagleBone Black also supports WiFi and 10/100Mbps Ethernet. The CPU of BeagleBone Black passes the data gotten from the AP server to its PRU and the digital output of the PRU is then fed into the transmitter circuit which drives the

blinks of the on-board LEDs to transmit data via the FSO channel. At the receiver, a receiver circuit connected to a photodetector, an amplifier, a comparator and a BeagleBone Black board build the functions of the receiver. The receiver circuit converts weak optical signals received from the FSO channel into 3V peak-to-peak voltages and passes them to the PRU of the BeagleBone Black. The PRU and the CPU of the BeagleBone Black then cooperate to pass the output signals via Ethernet to the receiver laptop which will implement demodulation and software protocols. Fig. 3.1 and Fig. 3.2 show the flowchart and realization of WiFO system.

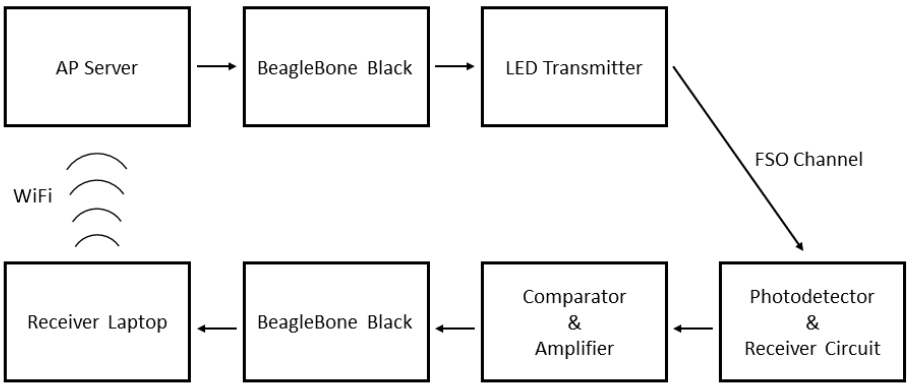

Figure 3.1: WiFO System Flowchart

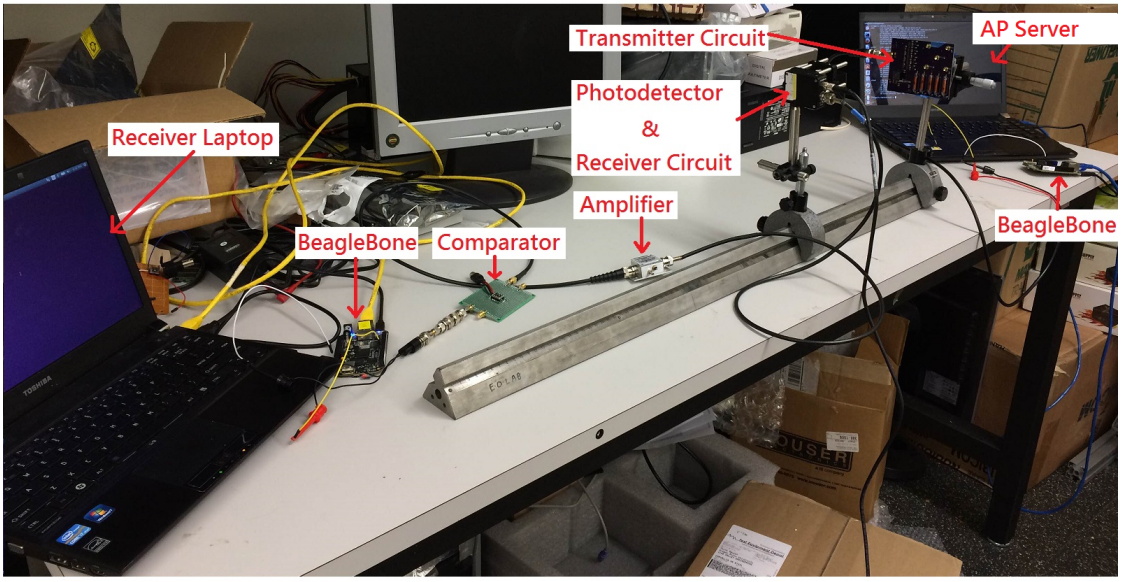

Figure 3.2: WiFO System

3.2 The Software Design

The OSI model consists of seven layers in conceptual network stacks. Here we design the functions used for FSO transmissions in each layer.

- Physical Layer: Manchester Code is implemented here for eliminating DC components. Then the transmitter uses OOK (On-Off Keying) to modulate "0" to low optical intensity and "1" to high optical intensity. When receiving data, the corresponding demodulation is implemented and then four-time oversampling is applied for the Majority decoder in the MAC/Data Link layer.

- MAC/Data Link Layer: A Majority decoder is implemented at the receiver to avoid bit flips. A 32-bit preamble is prefixed to each frame used to distinguish between frames.

- Network Layer: An AP server is used to regulate packet flow. It uses a mechanism to decide whether the FSO or the WiFi channel is used to transmit the packet.

- Transport Layer: Since WiFO is a one-way FSO transmission focusing on the downlink scenario, the ACKs are sent back via the WiFi channel from the receivers to the AP server to implement the retransmission mechanism. Packet IDs are also checked here to examine the order the packets are received and ensure the data are reconstructed correctly in order.

- Session Layer: This layer of WiFO has not been implemented. In the future, this can be addressed with a mechanism for authentication and permission on users connected to each WiFO transmitter.

- Presentation Layer and Application Layer: One of the best advantages of WiFO

is that everything remains the same in the application layer. This means, programmers do not need to make any changes with high level APIs when systems are integrated with WiFO. And WiFO is compatible with all existing network protocols, such as HTTP, FTP, TELNET...ext.

Chapter 4: Protocols of Transmission and Mobility

Since WiFO integrates the FSO technology with the existing WiFi system, it is important that the user can switch between the FSO and WiFi channels seamlessly. Here are the general assumptions: (1)Multiple transmitters are connected to one AP server. (2)Multiple users can be under one light cone. (3) No any two light cones are overlapping with each other, that is, no user is under more than one light cone. (4)Every packet should be acknowledged. (5)Each packet will not be transmitted via the FSO or WiFi channel until timeout or the ack of the previous packet is received at the AP server. Fig. 4.1 is an illustration based on the above assumptions.

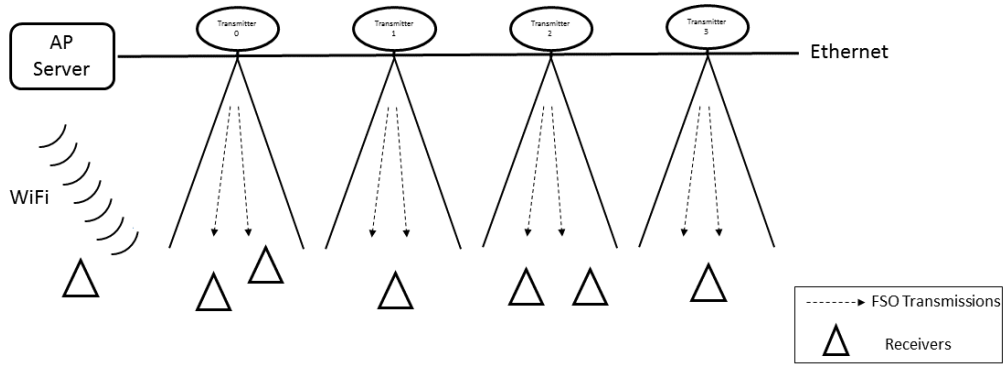

Figure 4.1: Prototype of protocols

This chapter is going to define the packet formats used to implement the transmission and mobility protocols of an FSO system. Then, the proposed protocols of transmission

and mobility are depicted in detail.

4.1 Packet Format

In the WiFO system, three types of packets have been designed to implement the transmission and mobility protocols. There are data packet, beacon packet and ack packet. The following three subsections will introduce each kind of packet formats separately.

4.1.1 Data Packet

The format of the data packet consists of five parts - cone ID, IP address, packet ID, date length and data payload. The lengths of data packets are not fixed because of the variable length column. Fig. 4.2 can help us to understand the packet format easily. Each part of the data packet will be introduced as following.

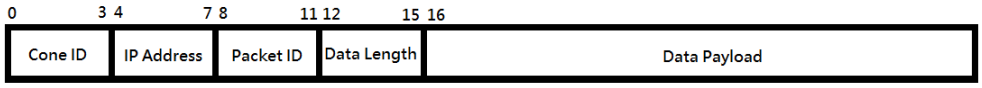

Figure 4.2: Data Packet

- Cone ID: 4 bytes. Each transmitter connected to the AP server gets a unique ID assigned by the server. Negative value is invalid.
- IP Address: 4 bytes. This stands for the destination IP address of the packet. Negative value is invalid.
- Packet ID: 4 bytes. Each data packet has a unique packet ID that the server can track via the ack packet if the data is received by the receiver successfully. Negative value is invalid.
- Data Length: 4 bytes. This column indicates how many bytes there are in the data payload. Negative value is invalid.
- Data Payload: The plain data that has not applied any modulation and coding schemes. The length of data payload is indicated in the column of data length.

4.1.2 Beacon Packet

Beacon packets are similar to data packets. They are broadcasted by the transmitters intermittently to all the users under the light cones. Beacon packets collaborating with ack packets (subsection 4.1.3) distinguish the users' locations. Each beacon packet only consists of 8 bytes including two parts - a cone ID and an identifier. The format of beacon packets is illustrated in Fig. 4.3.

- Cone ID: 4 bytes. Same as the cone ID introduced in the data packets. Negative value is invalid.
- Identifier: 4 bytes. Here we use a specific negative number to distinguish the IP address in the data packets.

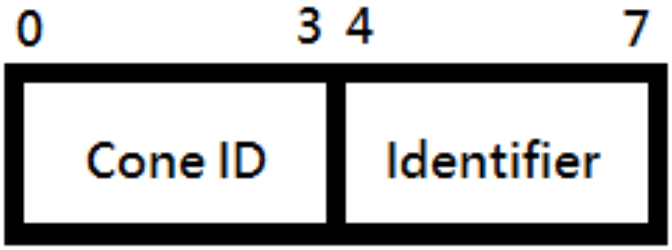

Figure 4.3: Beacon Packet

4.1.3 Ack Packet

Ack packets have two main functions. One is to have the AP server follow if the data packets are received successfully by the receivers. The other is to have the AP server recognize the locations where the receivers are at. Both data and beacon packets are acknowledged by ack packets. Fig. 4.4 shows the format of ack packets.

- Current Cone ID: 4 bytes. The cone ID received from the data/beacon packet it is acknowledging now. Negative value means that the data is from the wifi transmissions.

- Previous Cone ID: 4 bytes. The cone ID received from the last data/beacon packet it was acknowledging. Negative value means that the data was from the wifi transmissions.

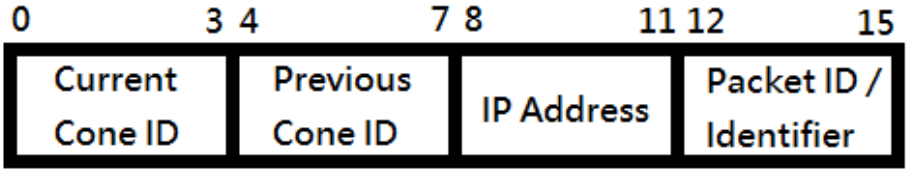

Figure 4.4: Ack Packet

- IP Address: 4 bytes. The IP address of the receiver. Negative value is invalid.
- Packet ID/Identifier: 4 bytes. If the receiver is acknowledging a data packet, this column is the same as the packet ID in that data packet; If the receiver is acknowledging a beacon packet, this column is the same as the identifier in that beacon packet.

4.2 Proposed Protocol of Transmission

In order to promise a stable and reliable transmission via the FSO channel, several mechanisms are applied to accomplish this goal. These mechanisms include preambles, Manchester coding, oversampling and majority decoding. We will introduce these four schemes respectively and explain how they work together to retain a stable transmission over the FSO channel.

- Manchester Coding: Due to some hardware limitations, the DC component is un-

wanted in the WiFO transmissions. One of the Manchester coding's characteristics is to eliminate DC components of signals. Manchester coding is also a line code where each bit of the signals to be encoded is either low ("0") or high ("1"). This is exactly the same as the current WiFO settings. There are two conventions for Manchester coding to represent data - *G. E. Thomas* and *IEEE 802.3*. We adopt IEEE 802.3 convention, which represents a logical "0" as a high-low signal sequence and a logical "1" as a low-high signal sequence. That said, each "0" is encoded into "10" and each "1" is encoded into "01". The disadvantage of Manchester coding is that it doubles the size of data as two bits are used to represent each bit. Fig. 4.5 [17] is an example of Manchester coding.

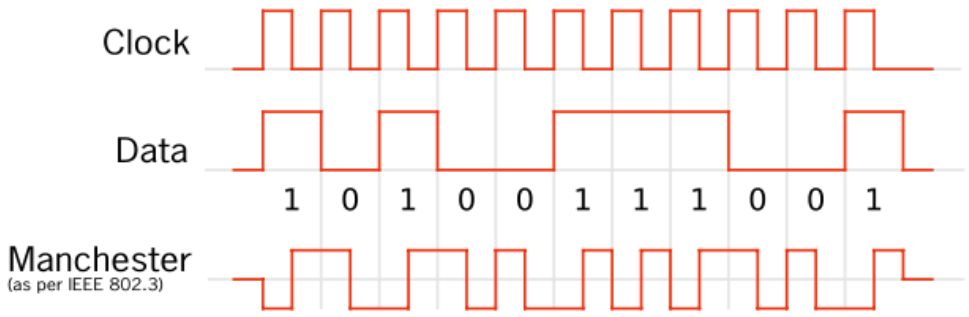

Figure 4.5: Manchester Code

- Preamble: The preamble is a 32-bit particular pattern to distinguish packets from

each other. For every packet transmitted through the FSO channel, *i.e.* data packets and beacon packets, a preamble is attached prior to it. Preambles are transmitted at a lower transmission rate to signal the receiver to receive the following packet. Although preambles are transmitted at a lower rate, it is not processing Manchester coding, so it doesn't require double bandwidth compared to normal packets.

- Oversampling and Majority Decoding: At the receiver, each bit period is sampled four times. Oversampling and majority decoding are applied to correct bit flips. For example, a bit "0" goes through a 4 time sampler and the output is "0001". Since majority decoding is applied and there are more zeros than ones, the original bit "0" is decoded correctly from "0001".

Fig. 4.6 is a block diagram illustrating the the transmission protocol. At the transmitter, when a data/beacon packet is encapsulated, it is fed into a Manchester encoder. Then a preamble is added prior to the coded packet. The FSO channel is operated at two different transmitting rates in turns. One is at the rate 1 Mbps for transmitting the preamble. The other is operated at 2 Mbps to transmit the coded packet. The receiver is operated in a corresponding way where it waits for the preamble. Then the receiver over samples each bit received 4 times. The sampled outputs are fed into a majority decoder to correct bit flips, if any. Finally, A Manchester decoder is implemented to get the raw data and a transmission is completed.

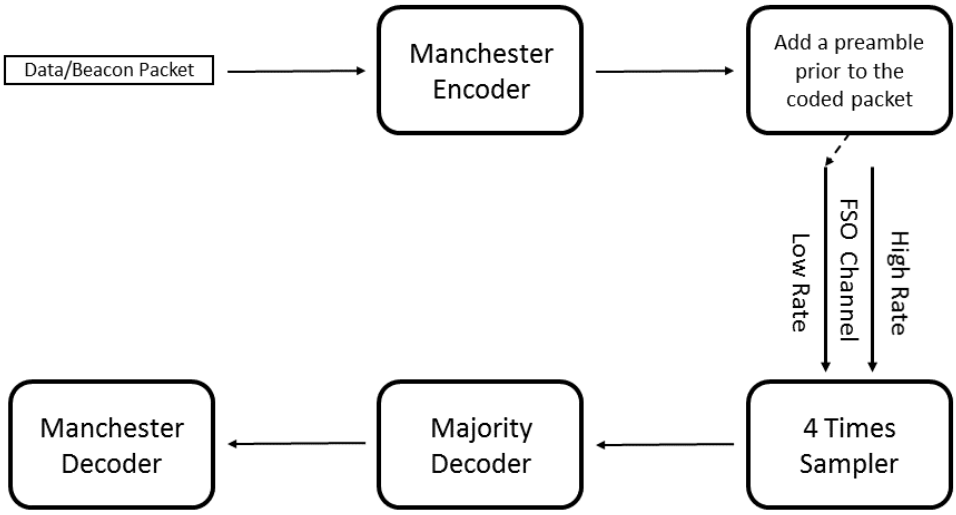

Figure 4.6: Transmission Protocol

4.3 Proposed Protocol of Mobility

In addition to providing complementary bandwidth capacity to the existing WiFi system, WiFO retains a high level of mobility. In a WiFO communication system, users can move from one light cone to another. If a user moves out of a light cone, the pre-existing WiFi system will automatically continue transmitting data without packet loss. This feature is implemented by having each WiFO transmitter send beacons to all of the receivers within its light cone. Each beacon packet contains the beacon ID which corresponds with the specific transmitter. When a user receives a beacon packet, it sends an ACK with the beacon ID via WiFi to the AP server. The server then updates a table recording the users IP address and which light cone the user belongs to. If the user moves out of a light cone, it stops receiving the beacons, stops sending ACKs to the AP server, and after a specific time period, the AP server removes the user/beacon ID table entry. When the data comes in to the AP server, the server searches the table for the destination IP address. If it can be found, then the data is sent to the corresponding WIFO transmitter to broadcast to its users, otherwise, the data is sent via WiFi as normal. And there is a timeout mechanism to trigger retransmission avoiding packet loss.

Let's look into the protocol more closely with an example. Assume two transmitters exist with cone ID "0" and "1". At the beginning, there is no user under any light cones. The system is idle but keeps sending beacons. Here we use "-5" as the identifier in the beacon packets. The table maintained at the server is empty as shown in Fig. 4.7.

Later a user with IP address "192.168.1.1" moves into light cone 0. One user with IP address "192.168.1.2" and the other with IP address "192.168.1.3" both move into light cone 1. These three users receive beacons from the two transmitters respectively and

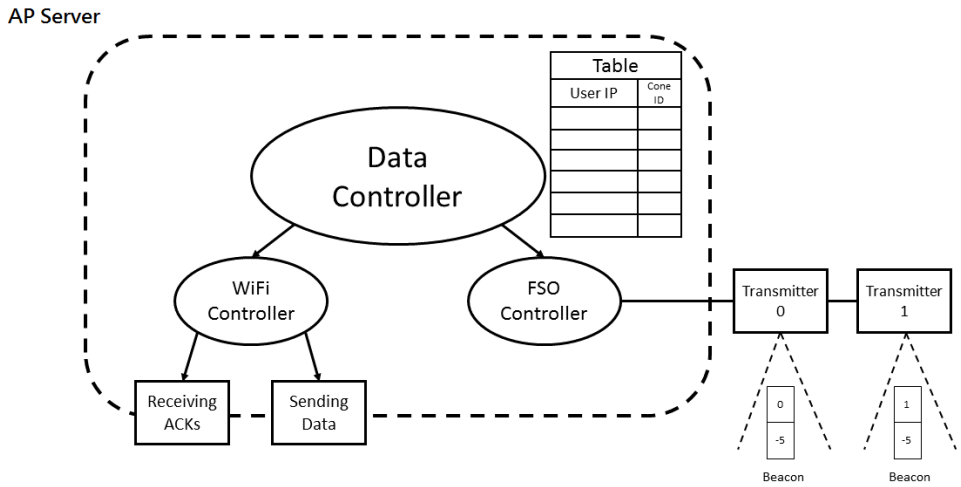

Figure 4.7: Mobility Example (1)

send the acks via WiFi to the AP server. The server then update its table with the acks it received. Fig. 4.8 shows the ack packets and the corresponding table entries. Here we use "-1" to represent the previous cone ID is not from any light cone.

Now a data stream to the IP address "192.168.1.2" is coming to the AP server. The data controller of the server divides the data stream and encapsulates it into data packets with corresponding packet numbers. It then searches the table with the destination IP address. If the IP is found and the FSO channel is not congested, the data packets are then sent to the FSO controller, otherwise, the data packets are sent to the WiFi controller. In this example, the data packets are sent to the FSO controller to be broadcasted via transmitter 1. Both the two users under light cone 1 receive the data packets, but the user with the IP address "192.168.1.3" ignores and discard the packets. The user with the IP address "192.168.1.2" received the data packets and sends the ack back to

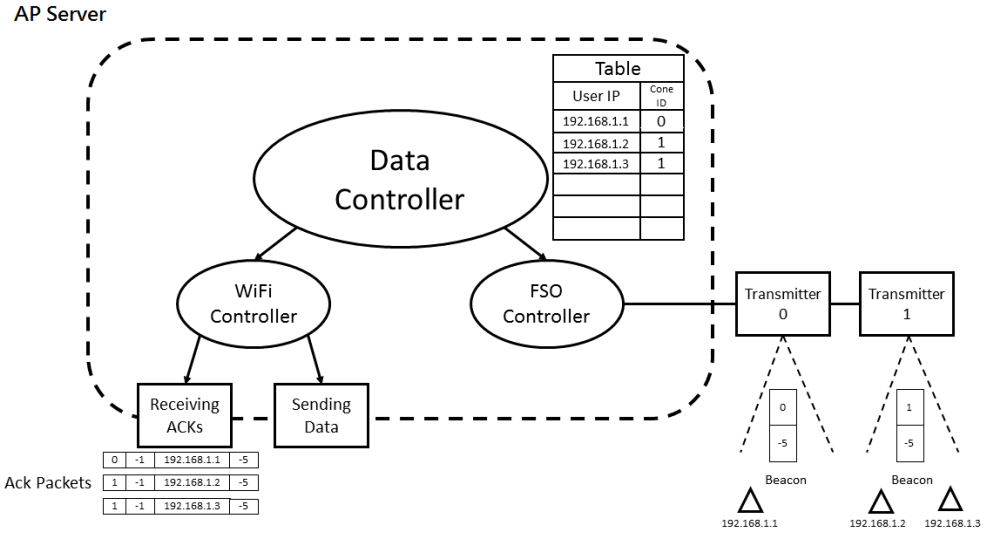

Figure 4.8: Mobility Example (2)

the AP server via WiFi. Note that the users keep staying under the light cones, so the previous cone IDs change from -1 to 0 and 1 in Fig. 4.9.

If the user with the IP address "192.168.1.2" moves out from the cone light, it stops receiving both beacon and data packets. So it also stops sending acks back to the server. The server will be aware of the loss within a period of time (timeout) and switch to the WiFi controller to send the rest of data packets. The user with the IP address "192.168.1.2" is deleted from the table as well. The user with the IP "192.168.1.2" sends acks back to the server after receiving data packets from the WiFi controller. Fig. 4.10 illustrates the description above.

Other than the timeout mechanism, the AP server can also recognize the locations of users by the current and previous cone IDs from the ack packets. Table 4.1 shows the corresponding user locations and server actions according to the current cone IDs and

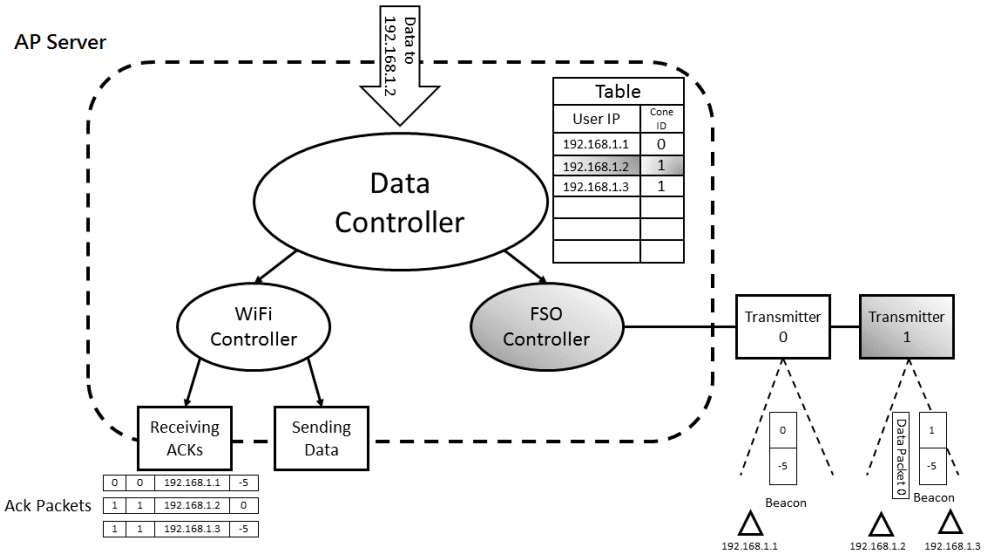

Figure 4.9: Mobility Example (3)

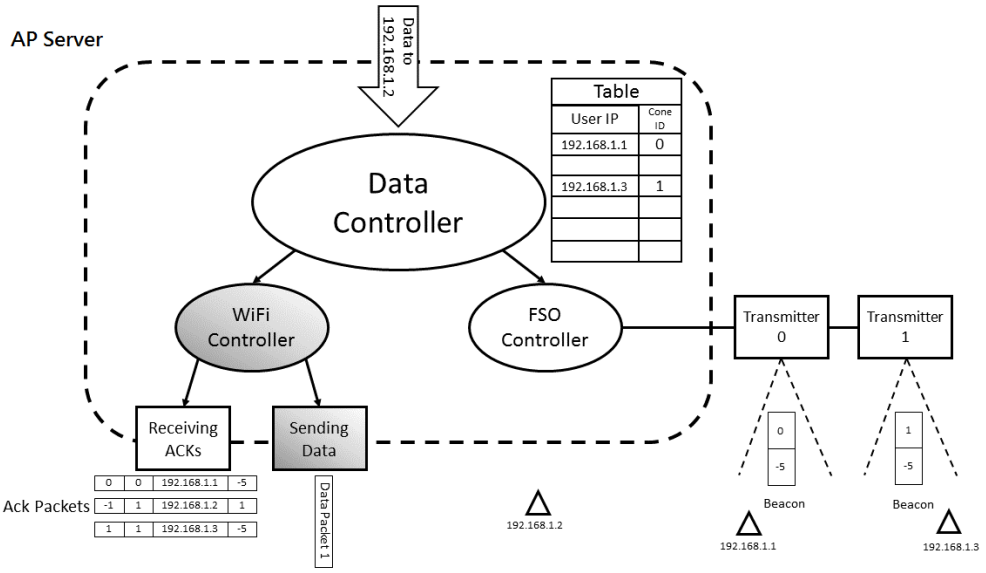

Figure 4.10: Mobility Example (4)

previous cone IDs from the ack packets.

Cone IDs	User's Location	Server's Action
Current Cone ID ≥ 0, Previous Cone ID < 0	moving into a light cone	Register the user to the table
Current Cone ID < 0, Previous Cone ID ≥ 0	moving out from a light cone	Delete the user from the table
Current Cone ID ≥ 0, Previous Cone ID ≥ 0, Current Cone ID = Previous Cone ID	staying in the cone	N/A
Current Cone ID ≥ 0, Previous Cone ID ≥ 0, Current Cone ID ≠ Previous Cone ID	moving from a cone to another cone	Update the table
Current Cone ID < 0, Previous Cone ID < 0	staying outside of cones	N/A

Table 4.1: Cone IDs and Users' Locations

Chapter 5: Dense Deployment of FSO Transmitters

In Chapter 4, we assume that no any two light cones are overlapping with each other, however, in practical applications, it is common that a user can receive signals from two or multiple transmitters simultaneously. That is, optical light cones might overlap with each other. This chapter will talk about the different scenario where a user is under overlapping light cones from the perspective of mathematical models. The theoretical optimal thresholds for recovering signals from multiple transmitters will be derived.

5.1 Scenario of Light Cones Overlapping

Fig. 5.1 shows the disadvantage to the light cones not overlapping each other. A user might be at a location which is not covered by any light cones. This can be fixed by moving transmitters closer to each other but this results in overlapping light cones. The advantage to this set up is that a user can receive signals simultaneously from two transmitters when it is under the overlapping area as shown in Fig. 5.2(b).

Pulse Amplitude Modulation (PAM) is a scheme where signals of more than two intensities can be transmitted. In this subsection, we build a mathematical model for the scenario that a user can receive signals simultaneously from multiple transmitters with PAM. Using PAM, an FSO transmitter sends a signal in discrete amplitudes, i.e., discrete light intensity levels. The signal at the receiver will be attenuated according to its distance from the FSO transmitter and the center of the light cone. Moreover, there will be noise added to the received signal. The following subsections will describe how

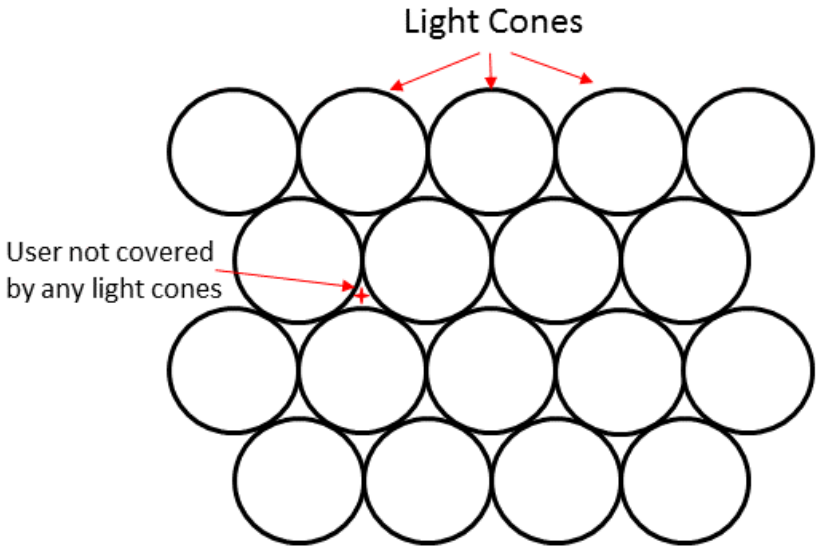

Figure 5.1: Light Cones Not Overlapping

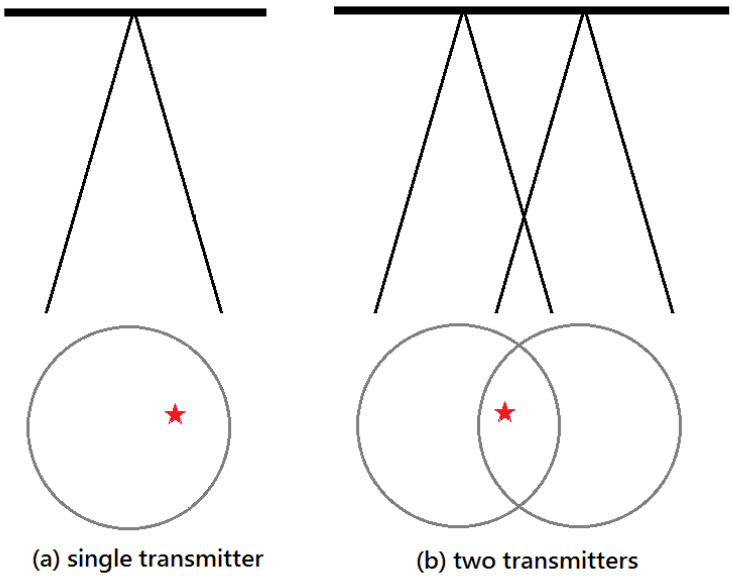

Figure 5.2: Single/Multiple Transmitters Scenario

to determine the attenuation factor, and use them to determine the original signal. To help with the problem formulation, we use the following notations.

- m : The maximum magnitude of signals (light intensity) that a transmitter can send. For simplicity, we assume $m \in \mathbb{N}$.
- n : The number of transmitters associated with a receiver. $n \in \mathbb{N}$.
- k : The number of different training sequences. $k \in \mathbb{N}$.
- y_i : The ith received signal. $i \in \mathbb{N}$.
- $\underline{\mathbf{y}}^{k\times 1}$: The vector of k received signals. $\underline{\mathbf{y}}^{k\times 1} = (y_1, y_2, \cdots, y_k)^T$.
- x_i : The transmitted signal from transmitter i. $x_i = 0, 1, 2, \ldots m$.

- x_{ij} : The ith transmitted signal from transmitter j. $i \in \mathbb{N}$. $j \in [1, 2, \cdots, n]$.
- $\underline{\mathbf{x}}_i^{n\times 1}$: The ith transmitted signal set from n transmitters.
  $\underline{\mathbf{x}}_i^{n\times 1} = (x_{i1}, x_{i2}, x_{i3}, \cdots, x_{in})^T$.
- $\mathbf{X}^{k\times n}$: $(\underline{\mathbf{x}}_1, \underline{\mathbf{x}}_2, \ldots, \underline{\mathbf{x}}_k)^T$.
- n_i : The ith channel noise. $n_i \backsim$ i.i.d.
- $\underline{\mathbf{n}}^{k\times 1}$: k independent channel noise. $\underline{\mathbf{n}}^{k\times 1} = (n_1, n_2, \cdots, n_k)^T$.
- f : The probability density function of the channel noise.
- α_j : The channel attenuation parameter of the transmitter j. $0 < \alpha_j \leq 1$.
  $j \in [1, 2, \cdots, n]$.
- $\underline{\boldsymbol{\alpha}}^{n\times 1}$: Vector of n transmitters' intensity. $\underline{\boldsymbol{\alpha}}^{n\times 1} = (\alpha_1, \alpha_2, \cdots, \alpha_n)^T$.
- h_i : The ith threshold to be determined.

Due to short distance and line of sight transmission, if the receiver is in the transmission cone of only one transmitter as shown in Fig. 5.2(a), the received signal y_i from a transmitter j can be modeled as:

$$y_i = \alpha_j x_j + n_i, \tag{5.1}$$

where x_j, n_i, and α_j denote the transmitted signal, noise, and attenuation factor, respectively.

More generally, if a receiver is in the overlapping light cones of n transmitters, and receives simultaneous transmissions from n transmitters as shown in Fig. 5.2(b), then

$$y_i = \sum_j \alpha_j x_{ij} + n_i = \underline{\mathbf{x}}_i^T \underline{\boldsymbol{\alpha}} + n_i. \tag{5.2}$$

We note that with n transmitters and m+1 signal levels available from the transmitter's side, the received signal y_i could have $(m+1)^n$ levels. For example, with m=2 and n=2, we could have 9 possible received levels as shown in Fig. 5.3. In addition, the FSO channel is rather static, i.e., α_i's do not change much since the receiver is typically stationary with respect to the transmitters. And thus, we discuss how α_i's can be estimated effectively in the next subsection.

	$\alpha_1 = 0.3$	$\alpha_2 = 0.9$	$\underline{x}_i^T \underline{\alpha}$
$\underline{x}_9$	2	2	2.4
$\underline{x}_8$	1	2	2.1
$\underline{x}_7$	0	2	1.8
$\underline{x}_6$	2	1	1.5
$\underline{x}_5$	1	1	1.2
$\underline{x}_4$	0	1	0.9
$\underline{x}_3$	2	0	0.6
$\underline{x}_2$	1	0	0.3
$\underline{x}_1$	0	0	0

$m = 2 \quad n = 2$

Figure 5.3: The received levels

5.2 Channel Estimation

In WiFO, we use training sequences to estimate $\alpha_1, \alpha_2, \cdots, \alpha_n$ simultaneously. Specifically, sending k training signals from the n transmitters, we have:

$$\underline{\mathbf{y}} = \mathbf{X}\underline{\boldsymbol{\alpha}} + \underline{\mathbf{n}}, \tag{5.3}$$

where $\mathbf{X}$ is a $k \times n$ matrix consisting of k training sequence for each transmitter. Multiply $\mathbf{X}^T$ on both sides of the equation, we have:

$$\mathbf{X}^T\underline{\mathbf{y}} = \mathbf{X}^T\mathbf{X}\underline{\boldsymbol{\alpha}} + \mathbf{X}^T\underline{\mathbf{n}} \tag{5.4}$$

We then take expectation on both sides of the equation.

$$E[\mathbf{X}^T\underline{\mathbf{y}}] = E[\mathbf{X}^T\mathbf{X}\underline{\boldsymbol{\alpha}}] + E[\mathbf{X}^T\underline{\mathbf{n}}] \tag{5.5}$$

$$\mathbf{X}^T E[\underline{\mathbf{y}}] = \mathbf{X}^T\mathbf{X}\underline{\boldsymbol{\alpha}} + \mathbf{X}^T E[\underline{\mathbf{n}}] \tag{5.6}$$

$$\mathbf{X}^T(E[\underline{\mathbf{y}}] - E[\underline{\mathbf{n}}]) = \mathbf{X}^T\mathbf{X}\underline{\boldsymbol{\alpha}} \tag{5.7}$$

The estimated channel parameters are equal to:

$$\underline{\hat{\boldsymbol{\alpha}}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T(E[\underline{\mathbf{y}}] - E[\underline{\mathbf{n}}]) \tag{5.8}$$

We note that we should choose the training sequences such that $\mathbf{X}^T\mathbf{X}$ is invertible. In addition, typically $E[\underline{\mathbf{n}}] = 0$.

5.3 Optimal Thresholds

After determining α, the next step is to attempt to recover the transmitted signal x_j at the transmitter j based on the received signal y_i. Depending on the values of α_i's, it is possible to recover multiple transmitted signals x_j's with only one y_i. We will characterize this region of α value shortly. For now, we describe the threshold decoding procedure.

For illustrative purpose, assume that each transmitter can only send 0 or 1 ($m = 1$), and there are $n = 2$ transmitters. One transmitter has α_1 equal to 0.3 and α_2 equal to 0.9 in Eq. (5.2). As shown in Fig. 5.4, there are 4 possible input combinations which produce 4 possible outputs. The outputs are ordered from largest to smallest. If there is no noise, a receiver can reconstruct the bit patterns that were sent by the transmitters by comparing the y_i with the thresholds h_1, h_2, h_3 as depicted in Fig. 5.4. For example, (1,0) was sent if $h_1 \leq y_i < h_2$.

If the noise is large enough to move y_i across a threshold, then there will be a bit error rate. Thus, $h_1, h_2, \ldots$ must be selected to minimize the average bit error. This is the goal of the proposed PAM decoding scheme.

The other example has $m = 1$ and $n = 3$ shown in Fig. 5.5. Here, the $\underline{\boldsymbol{\alpha}} = (0.5, 0.7, 0.9)^T$. Just like the previous example, a variety of values are created and specific threshold values must be picked to allow for the most noise possible while still retaining the integrity of the signal.

Theorem 5.1. *When source signals are uniformly distributed, the optimal thresholds, $h_1, h_2, \cdots, h_n$, must satisfy the following equation:*

$$f(h_i - \underline{\mathbf{x}}_i^T \underline{\boldsymbol{\alpha}}) = f(h_i - \underline{\mathbf{x}}_{i+1}^T \underline{\boldsymbol{\alpha}}), \tag{5.9}$$

	$\alpha_1 = 0.3$	$\alpha_2 = 0.9$	$\underline{x}_i^T \underline{\alpha}$
$\underline{x}_4$	1	1	1.2
$\underline{x}_3$	0	1	0.9
$\underline{x}_2$	1	0	0.3
$\underline{x}_1$	0	0	0

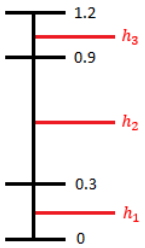

Figure 5.4: The example with m=1 and n=2

	$\alpha_1 = 0.5$	$\alpha_2 = 0.7$	$\alpha_3 = 0.9$	$\underline{x}_i^T \underline{\alpha}$
$\underline{x}_8$	1	1	1	2.1
$\underline{x}_7$	0	1	1	1.6
$\underline{x}_6$	1	0	1	1.4
$\underline{x}_5$	1	1	0	1.2
$\underline{x}_4$	0	0	1	0.9
$\underline{x}_3$	0	1	0	0.7
$\underline{x}_2$	1	0	0	0.5
$\underline{x}_1$	0	0	0	0

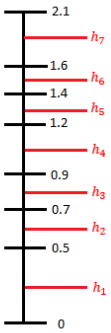

Figure 5.5: The example with m=1 and n=3

where $f(\cdot)$ is the probability density function of the noise.

Proof. With n transmitters and m+1 uniformly transmitted levels, the probability of receiving each level at the receiver would be $\frac{1}{(m+1)^n}$. We then have the probability error as

$$P(\varepsilon) = \frac{1}{(m+1)^n} \sum_{i=1}^{(m+1)^n-1} (p(n_i > h_i - \underline{\mathbf{x}}_i^T \underline{\boldsymbol{\alpha}}) + p(n_{i+1} < h_i - \underline{\mathbf{x}}_{i+1}^T \underline{\boldsymbol{\alpha}})) \tag{5.10}$$

Because the additive noise is i.i.d, we can rewrite Eq. (5.10) as

$$P(\varepsilon) = \frac{1}{(m+1)^n} \sum_{i=1}^{(m+1)^n-1} (\int_{h_i - \underline{\mathbf{x}}_i^T \underline{\boldsymbol{\alpha}}}^{\infty} f(\tau)\, d\tau + \int_{-\infty}^{h_i - \underline{\mathbf{x}}_{i+1}^T \underline{\boldsymbol{\alpha}}} f(\tau)\, d\tau) \tag{5.11}$$

By differentiating $P(\varepsilon)$ with respect to h_i and setting the equation to zero, we can find the optimal h_i to minimize $P(\varepsilon)$.

$$P'_{h_i}(\varepsilon) = \frac{1}{(m+1)^n}(-f(h_i - \underline{\mathbf{x}}_i^T \underline{\boldsymbol{\alpha}}) + f(h_i - \underline{\mathbf{x}}_{i+1}^T \underline{\boldsymbol{\alpha}})) = 0 \tag{5.12}$$

$$\Rightarrow f(h_i - \underline{\mathbf{x}}_i^T \underline{\boldsymbol{\alpha}}) = f(h_i - \underline{\mathbf{x}}_{i+1}^T \underline{\boldsymbol{\alpha}}) \tag{5.13}$$

□

Figs. 5.6 and 5.7 show two examples for finding the thresholds h_i graphically from the two different noise distributions. Both examples use n=1 and m=1. As seen, h_i is obtained by looking for the specific positions that make $f(h_i - 0 \cdot \alpha) = f(h_i - 1 \cdot \alpha)$.

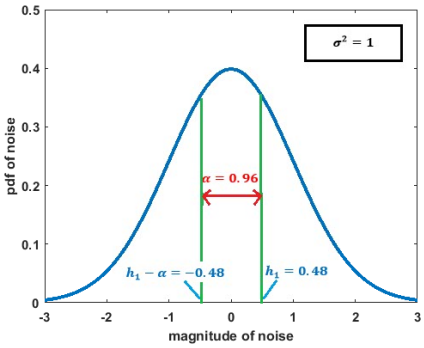

Figure 5.6: Optimal thresholds for Gaussian noise using two transmitters

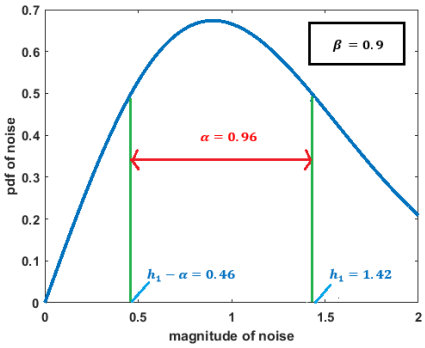

Figure 5.7: Optimal thresholds for Rayleigh noise using two transmitters

5.4 Conditions for Signal Irrecoverability

We note that even when there is no noise, certain α values will guarantee errors in decoding. Specifically, when two or more input patterns map into a single output value. Therefore, it is important to determine what α values make two signals indistinguishable. In order to solve this problem, first it's observed that two received signals can be expressed as y and y' where

$$y = x_1\alpha_1 + x_2\alpha_2 + ... + x_n\alpha_n \tag{5.14}$$

$$y' = x'_1\alpha_1 + x'_2\alpha_2 + ... + x'_n\alpha_n \tag{5.15}$$

Even with infinite precision from the receiver, y and y' still can not be distinguished if $y = y'$. Note, this can happen even if the transmitted signal sets x_i and x'_i are different.

In order to avoid the situation mentioned above, $y - y'$ must not equal 0. If the difference is 0, then the signals are indistinguishable. This can be expressed as follows:

$$y - y' = (x_1 - x'_1)\alpha_1 + (x_2 - x'_2)\alpha_2 + ... + (x_n - x'_n)\alpha_n = 0 \tag{5.16}$$

let $b_i = x_i - x'_i$,

$$y - y' = b_1\alpha_1 + b_2\alpha_2 + ... + b_n\alpha_n = 0, \tag{5.17}$$

$$b_i \in [-m, \cdots, -1, 0, 1, \cdots, m]$$

The variable b_i ranges from -m to m because $b_i = x_i - x'_i$ where x_i and x'_i both range from 0 to m. Therefore the minimum value is $0 - m = -m$ and the maximum value is $m - 0 = m$.

Now, by plugging all the permutation of b_i into Eq. (5.17), a matrix equation (5.18) is formed that can be used to find all the relationships among α_i's such that the receiver will not be able to distinguish between two signals.

$$\underbrace{\begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{(2m+1)^n 1} & \cdots & b_{(2m+1)^n n} \end{bmatrix}}_{\mathbf{B}} \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix} \tag{5.18}$$

The matrix $\mathbf{B}$ has a column for each transmitter with each row representing all possible permutations of the available signals. The matrix is of dimension $(2m+1)^n \times n$ because there are n transmitters and $(2m+1)^n$ possible permutations. Fig. 5.8 shows how to construct the matrix $\mathbf{B}$ for $m = 1$ and $n = 2$.

The following procedure can now be implemented to attain rows of the matrix $\mathbf{B}$ which have the potential of making Eq. (5.18) equal to 0. First, construct $\mathbf{B}$ with rows from all the permutations of x_i, as in Fig. 5.8(a). Then delete all rows with all positive or all negative values which results in Fig. 5.8(b). Treat 0 as both positive and negative. These rows would require negative α_j's which are not in the irrecoverable range. Finally, delete all rows that are multiples of each other. This is because these rows have the same relationships between α_j's. What's left is a unique set of ratios that represent all values of α_i's for which two different transmitted signals would result in an identical received signal, as shown in Fig. 5.8(c). Therefore, any values of α_1 and α_2 that make the equation $\alpha_1 - \alpha_2$ equal 0 will make the two different transmitted signals indistinguishable at the receiver. Fig. 5.9 shows the lines that represent all pairs of α_1 and α_2 values that satisfy the equation sets, and therefore transmitted signals cannot be recovered at the receiver

even without noise.

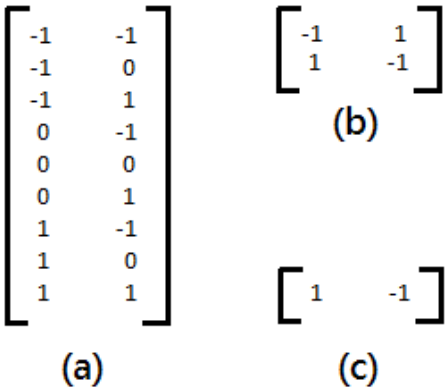

Figure 5.8: Example of steps for constructing the matrix **B**.

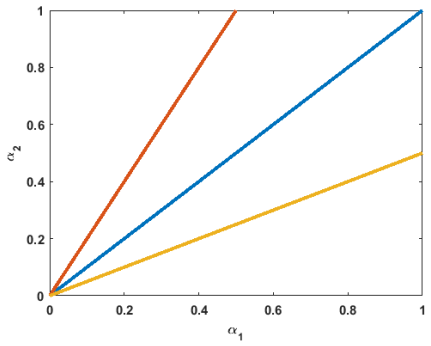

Figure 5.9: Matrix **B** and invalid alpha values with m=2 and n=2

We summarize the procedure to obtain to obtain matrix **B** in Algorithm 1.

Algorithm 1 Determining Matrix **B**

1: **for** each $i \in [1, (2m+1)^n]$ **do**
2: initialize each row of **B** with all permutations of $(b_1, b_2, \cdots, b_n)$;
3: **end for**
4: **for all** rows of **B do**
5: delete rows with all positive/negative elements;
6: **end for**;
7: **for** remaining rows of **B do**
8: delete rows which are multiples of other rows;
9: **end for**

Chapter 6: Simulation and Discussion

In this chapter, we show a video demo and numerical results to verify our proposed schemes in Chapters 4 and 5.

6.1 Video Demo

We successfully demonstrated that transmitting a video file at a 2Mbps rate through the FSO channel is achievable. The demonstration can be found in the following link.

$$https://www.youtube.com/watch?v = LdeHSHbfi - E$$

In the video, we can see that the film is played via the FSO channel with a good quality both in vision and audio. Also, when the channel is blocked, the film gets distorted and stops playing for a short period of time. Fig. 6.1 and Fig. 6.2 are the screen shots showing the channel getting blocked and the film distortion.

While streaming a video, re-buffer occurs when the playback time of a packet is earlier than its receiving time. At this moment, the video player will stop and wait for a buffer time. This buffer time allows the receiver to receive additional packets. Next, the video player starts playing back again if the next packet is available. The process continues until the end of the streaming session. To evaluate the streaming performance of the WiFO system and current WiFi systems, Fig. 6.3 shows the number of re-buffers as a function of buffer time for WiFO and WiFi systems respectively during the heavy

Figure 6.1: Blocking the Channel

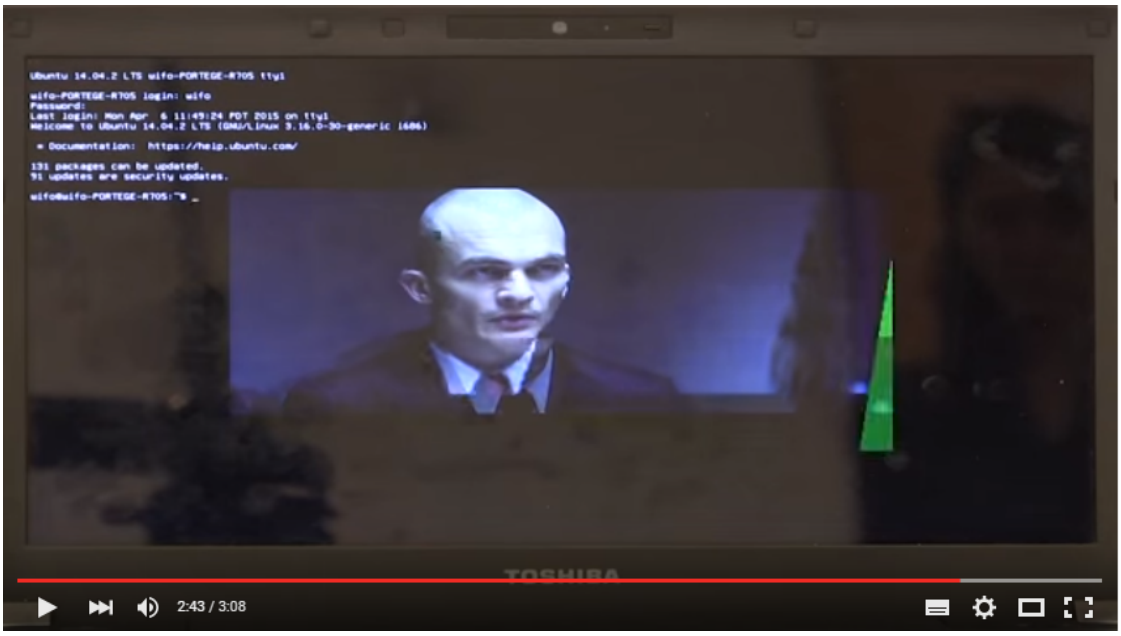

Figure 6.2: Film Distortion

traffic background. As seen, the larger buffer time will result in a smaller number of re-buffers.

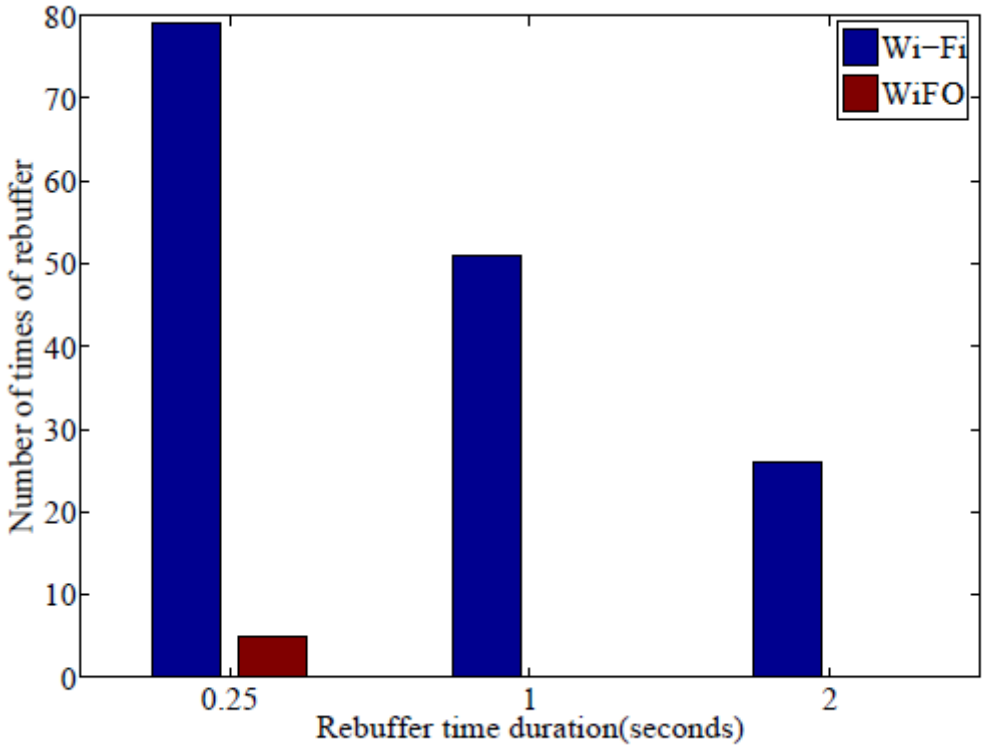

Figure 6.3: Number of re-buffers for different buffer time of WiFO and WiFi systems

6.2 Simulation and Discussion

The round trip delay is defined as the elapsed time from the moment a packet is sent on the FSO channel until it is acknowledged at the transmitter. Fig. 6.4 shows the histogram of round trip delay for the FSO channel. We note that the ACK packets are

sent on the WiFi channel. As seen, the average round trip time is sufficiently small such that a simple protocol like Stop-and-Wait (a protocol that sends the next packet only when an ACK of the previous packet is received) will provide a very high throughput on the FSO channel.

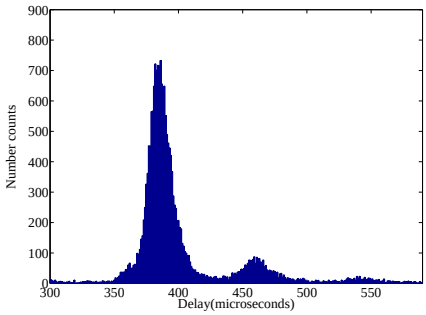

Figure 6.4: Histogram of the round trip delay for FSO channel

Fig. 6.5 shows the total throughput of FSO and WiFi channels. As seen, the WiFi throughput varies according to the background traffic which starts at around 100 second and ends at around 370 second. On the other hand, the throughput on the FSO channel is roughly constant since there is no competing traffic.

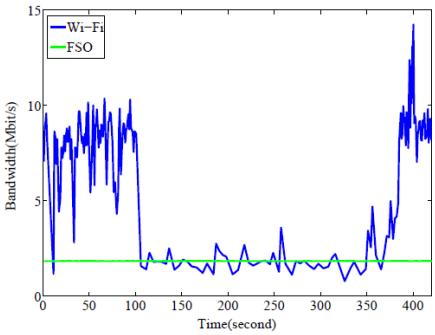

Figure 6.5: Throughputs of FSO and WiFi channels

We show numerical results to verify our proposed scheme presented in Chapter 5.

First, Fig. 6.6 shows the irrecoverable ranges for α_1 and α_2 as indicated by the points on the lines. This figure was generated by using Algorithm 1 with $m = 3$ and $n = 2$. Fig. 6.6 assumes that the receiver can differentiate any two real numbers. In practice, a receiver has finite precision arithmetic, i.e., it can represent a real value with finite number of bits. In that case, it is difficult for a receiver to distinguish two values that are close to each other. As a result, the range of α_1 and α_2 for which the perfect reconstruction is not possible will be enlarged. Fig. 6.7 shows such irrecoverable range of α_1 and α_2 for $m = 3$ and $n = 2$. Notice that the lines in Fig. 6.7 are much thicker than those of Fig. 6.6.

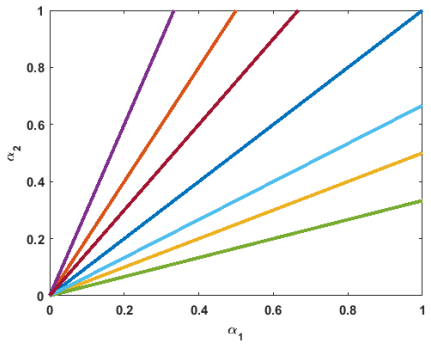

Figure 6.6: The range of α_1 and α_2 values for which perfect signal recovery is not possible, with m=3 and n=2.

We now show the bit error rates for symmetric and un-symmetric noises. Specifically, Fig. 6.8 shows the bit error rate for Gaussian noise as a function of its variance. As seen, as the variance increases, the bit error rate increases accordingly. Similarly, Fig. 6.9 shows the bit error rate for Rayleigh noise as a function of its mode. The bit error rates increase with the noise variance as predicted.

We now examine the bit error rates as a function of a receiver position for two transmitters. In particular, we consider the scenario where the receiver is moving from

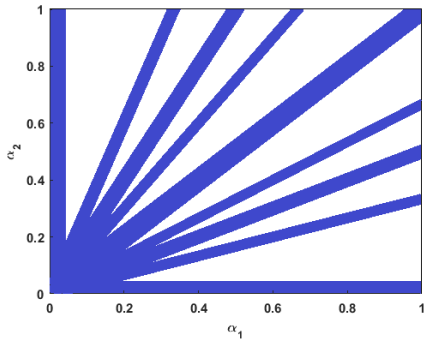

Figure 6.7: The range of α_1 and α_2 values for which perfect signal recovery is not possible, with m=3 and n=2.

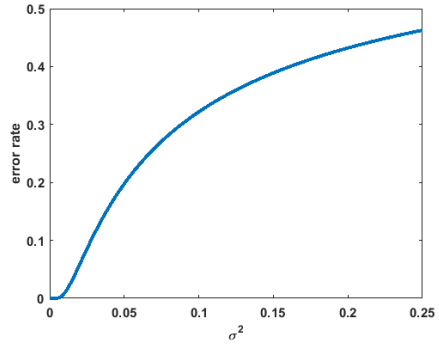

Figure 6.8: Bit error rates using optimal PAM decoding scheme for Gaussian noise as a function of its variance. $m = 1, n = 2, \alpha_1 = 0.5, \alpha_2 = 1$

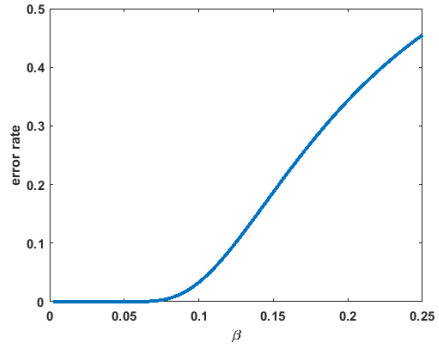

Figure 6.9: Bit error rates using optimal PAM decoding scheme for Rayleigh noise as a function of its mode. $m = 1, n = 2, \alpha_1 = 0.5, \alpha_2 = 1$

the center of transmitter 2 to the center of transmitter 1. In this case, α_1 will increase while α_2 will decrease. Thus, we can plot the bit error rate vs. the ratio α_1/α_2. When the ratio = 1, i.e., $\alpha_1 = \alpha_2$, the receiver is at equal distances from both transmitters.

Fig. 6.10 to Fig. 6.12 show the bit error rates as functions of α_1/α_2 for under Gaussian noise with different variances. In all these figures, the bit error rates are 0.25 when $\alpha_1/\alpha_2 = 1$. This is intuitively plausible since the transmitted patterns 01 and 10 cannot be distinguished at the receiver. On the other hand, the patterns 11 and 00 can be distinguished easily since the thresholds for these symbols are quite far apart. As a result, we have the bit error rate of roughly 0.25, assuming the transmitted patterns is uniformly distributed. It is also noted that the bit error rate is large when α_1/α_2 is small. This is because the transmitted patterns 00 and 10 results in similar received signal. Similarly, the transmitted patterns 01 and 11 will also result in the similar received signal.

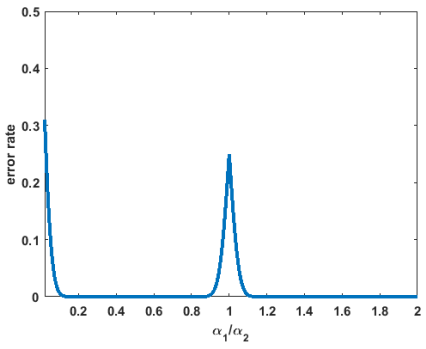

Figure 6.10: Bit error rate vs the ratio of α_1/α_2. $\sigma^2 = 0.0001$

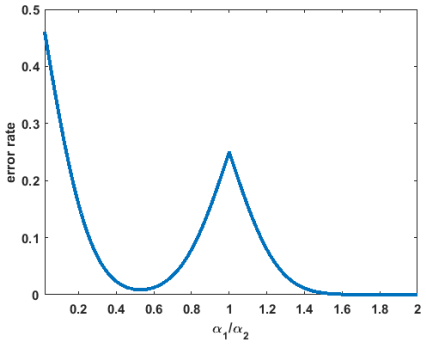

Figure 6.11: Bit error rate vs the ratio of α_1/α_2. $\sigma^2 = 0.0025$

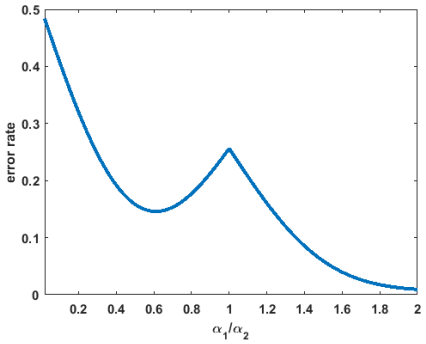

Figure 6.12: Bit error rate vs the ratio of α_1/α_2. $\sigma^2 = 0.01$

Chapter 7: Future Work and Conclusion

In Chapters 5 and 6 , a preliminary work of overlapping light cones is derived from mathematical models and simulation. However, there is still much potential work and research worthy to be further discussed. This chapter will talk about some future work and a conclusion is made to summarize the previous chapters.

7.1 Future Work

Analyzing the channel characteristics and interference is one of the next steps to decide how to deploy the transmitters in a space. That is, using the fewest transmitters to serve the most receivers. Distributing data to WiFi and FSO channels with variable rates is another important issue. The AP server should have the ability to control the rates dynamically when either channel is congested. Besides, different Forward Correction Codes (FEC) can be applied to the WiFO system as well.

7.2 Conclusion

In this thesis, transmission and mobility protocols of WiFO system are proposed and realized. A video demo successfully verify the feasibility of this novel system. Besides, a reformed system for the scenario of overlapping light cones is addressed by mathematical models. Optimal thresholds to recover the transmitted signals and conditions for signal irrecoverability are discussed via simulations. Although there is still some future work

awaiting, with these preliminary results, we believe that the WiFO system is able to make up the deficiency of the limited RF bandwidth. And a potential transmission rate of hundreds Mbps is expectable in WiFO technology.

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