Performance Analysis of Hybrid FSO/RF Communication System

by

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B.Sc., Sir Syed University Karachi, 2009

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Abstract

In this project we modeled a point-to-multipoint (P2MP) network using discrete time Markov chain. The system being consist of a central node and \( N \) remote nodes. The central node is connected to remote nodes via FSO links and a common shared RF is used as backup link. When an FSO link fails, the RF link is used and for that we have presented an unequal priority protocol, where node 1 has the highest priority for accessing the RF link. Furthermore, the performance metrics of each node are studied, such as throughput from the central node to the remote node, average buffer size, the queuing delay, symbol lost and the efficiency of the system.
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List of acronyms

5G  Fifth generation mobile network
FSO  Free space optics
FIFO  First in, first out
LAN  Local area network
LTE  Long-term evolution
MMW  Milimeter wave length
OWC  Optical wireless communication
P2MP  Point to multi point
SNR  Signal-to-noise ratio
UV  Ultraviolet
VLC  Visible light communication
WISP  Wireless internet service provider
WiFi  wireless fidelity
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In the name of ALLAH, the Most Gracious and the Most Merciful

All praises belong to Allah the merciful for his guidance and blessings to enable me to complete my project. I would like to thank:

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DEDICATION

To my Mother, Father, and to my siblings
Bilal, Maimoona and Shoaib
for their endless support and encouragement
Chapter 1

Introduction

1.1 Background

Optical Wireless Communication (OWC) involves data transmission through an un-guided propagation medium using an optical carrier. An OWC system consists of three main components, which are the transmitter, the propagation channel, and the receiver. In the transmitter, the light source is modulated to carry the data. The light source may be a laser or light emitting diode. At the receiver, a telescope collects the incoming light and focuses it onto a photodetector, which then converts it into electric current. In the case of OWC, the transmitter and the receiver are separated by a propagation channel which is air. The line of sight is indispensable for outdoor OWC [2].

1.2 Literature review and motivation

1.2.1 Free-space optical communications

FSO is an optical communication that uses light propagating in free space to transmit data for telecommunications or computer networking. Free space means air, outer space, vacuum or something similar [3]. FSO offers the capacity to send large amounts of data securely over moderate distances without the expense of fibre optic cable. This technology is very useful where establishing physical connections between a transmitter and a receiver is difficult. An FSO system can be a promising approach to address the broadband access market [4]. These systems have matured to a level where mass produced models are available. An FSO system offers many features, like
low start up and operations cost, rapid deployment and high bandwidth [5].

FSO has gained popularity for implementing point-to-point transmission links because of its high data rate, high transmission security and large unregulated spectrum, in comparison to Radio frequency (RF) [3]. FSO links have been used to connect one local area network to another and also to backbone networks, typically implemented by optical fibres as shown in Fig 1.1 [6].

![LAN-to-LAN FSO connectivity](image)

**Figure 1.1: LAN-to-LAN FSO connectivity [1]**

In Fig. 1.1, the black arrows refer to FSO links, which can also be used as robust outdoor backhaul solutions for small radio cells, such as WiFi, LTE and 5G as shown in Fig. 1.2 [7], where the red arrows are FSO links. Other terrestrial applications of FSO include last-mile applications to connect end users to a broadband network backbone [8], recovery links for networks which are partially disconnected due to natural disasters [9] and wireless video surveillance and monitoring [10]. The FSO transmission system has an optical transmitter and an optional receiver which use the atmosphere as the transmission medium for the optical signal (specifically, a laser beam), as shown in Fig. 1.3.
The optical signal transmitting through atmosphere is affected by fading due to atmospheric conditions [11] [12] [13].

1.2.2 Hybrid FSO/RF implementation

FSO and RF links can be combined using millimeter wavelength (MMW) to form hybrid FSO/RF, which can improve the system performance of the FSO links. This is due to the fact that both FSO and RF links experience different effects when it comes to atmosphere and weather. FSO links suffer from high attenuation in the presence of fog, while rain has no effect. In contrast, RF links are not affected by fog, but rain can increase the attenuation. Similarly, the atmospheric turbulence is the main cause of small scale fading in FSO links [14].

The nature of FSO and millimeter wavelength (MMW) has resulted in enormous approaches for implementing hybrid FSO/RF data transmission systems. Two main
approaches were presented in implementing hybrid FSO/RF systems. One approach was the switch-over hybrid FSO/RF scheme, which applies hardware switching between FSO and MMW RF links [15]. Another approach was the use of both FSO and RF links for data transmission all the time [16] [17].

This work is based on previous work, which was, when an FSO link had poor quality, the central node used the RF link to communicate with remote nodes on an equal priority basis [1]. On the other hand, in this project, when an FSO link has poor quality, the central node will use shared RF link to communicate on an unequal priority basis.

The Hybrid FSO/RF system 1) improves communication system reliability 2) prevents generation of unnecessary RF interference to the environment 3) uses RF on an unequal priority basis 4) benefits from higher data rate, provided by FSO links most of the time.

1.2.3 Point-to-multi-point transmission

The motivation behind using point-to-multi point (P2MP) FSO is its interesting and unique features, and most of the literature is bound to point-to-point data transmission with FSO technology. FSO can also be used for multiuser scenarios to support P2MP topologies [18]. A P2MP topology has a network architecture for outdoor wireless communication, which can connect multiple users to a central location. In the P2MP network, the transmission is wireless, such as in the WiFi LAN or the Worldwide Interoperability for Microwave Access (WiMAX) network [19]. The mechanism of Wireless internet service provider (WISP) connection involves users being connected at the edge of the network using a client device which is normally mounted on the roof of a house. The central base station is mounted on a higher elevation where the line of sight is clear. Since literature on P2MP is not abundant, this yet again is the motivation behind proposing P2MP hybrid FSO/RF network in multiuser scenarios. In the proposed scheme, the P2MP hybrid FSO/RF network consists of remote nodes which are connected to the central node via an FSO link. A common RF link is shared among all the remote nodes. Using a common RF link will have benefits such as 1) sharing the RF spectrum 2) preventing the generation of unnecessary RF interference and 3) conserving RF transmission power.
1.3 Project contributions

1. The FSO/RF network is modelled and the performance of the system is studied using Markov chains

2. Unequal priority protocol is proposed for a central node that will use the shared RF link to communicate to a remote nodes

1.4 Project organization

This project has four chapters. A summary is presented as follows.

Chapter 1 introduces the reader to the subject and the scope of the research. The motivation of the research and the contributions are discussed.

In Chapter 2, a P2MP network has been presented and analyzed that uses number of FSO links for data transmission from the central node to the remote nodes. The network is modelled using discrete time Markov chain. Furthermore, by considering the transmission from the central node to remote nodes, an unequal priority protocol has been proposed and various performance metrics have been studied, such as throughput from the central node to the remote node, average buffer size, average queuing delay, packet loss probability and efficiency of the queueing system.

Chapter 3 shows results and plot graphs of throughput, average buffer size, average queuing delay, packet loss probability and efficiency.
Finally, the project is summarized in Chapter 4 and some future work is suggested.
Chapter 2

Cross Layer Analysis of Point-to-multi-point hybrid FSO/RF network

This chapter is based on a previous work [1], where P2MP network is considered, which consists of remote nodes and the central node. Each remote node is connected to the central node via an FSO link. A common RF link is shared among all the remote nodes as a back up, and all nodes had an equal priority to access the RF link if the FSO link failed, a simple switch over hybrid FSO/RF is adopted. Furthermore, the performance of a single remote node had been studied, such as throughput from the central node to the remote node, average buffer size, average queuing delay, packet loss probability, and the efficiency.

In this work, the nodes have an unequal priority for accessing the RF link if any of the FSO link fails, and the performance metrics of all the nodes have been studied.
2.1 P2MP hybrid FSO/RF network modelling

Figure 2.1: General Block diagram of a P2MP Hybrid FSO/RF network [1]

Figure. 2.1 [1] is the general block diagram of a P2MP hybrid FSO/RF System. It has a central node and multiple remote nodes and also a shared RF back-up link. Following assumptions are made

1. The system has $N$ remote nodes.
2. Optical and RF channels have fading.
3. When more than one FSO link fails, the central node uses RF link to communicate.
4. The nodes will access the RF link on an unequal priority protocol. Node 1 being the highest priority and node $N$ has the lowest priority.
5. Non-saturated traffic condition is assumed. Specifically, the central node may or may not have data symbols for transmission to $N$ remote nodes in each time step.

2.1.1 Fading model for optical and RF channels

The data transmission from the central node to all the remote nodes is done on an unequal priority protocol, so we will study all the remote nodes. For the central node,
we derive the probability that there is a link available between the central node and the remote node. We define $a$ to be the probability when an FSO link becomes poor and can not be used for data transmission from the central node to the remote node, which is given by [1]:

$$a = Pr[\gamma_{FSO} < \gamma_T] = F\gamma_{FSO}(\gamma_T) \quad (2.1)$$

where $\gamma_{FSO}$ is the instantaneous signal-to-noise ratio (SNR) of the FSO receiver, and $\gamma_T$ is the SNR threshold.

Furthermore, we define $b$ to be the probability that an RF link is a poor quality and can not be used for data transmission between the central node and the remote node, which is given by [1]:

$$b = Pr[\gamma_{RF} < \gamma_T] = F\gamma_{RF}(\gamma_T) \quad (2.2)$$

where $\gamma_{RF}$ is the instantaneous SNR of the RF receiver, and $\gamma_T$ is the SNR threshold.

We consider that when an FSO link fails between the central node and the remote node, a back-up RF is used. As mentioned earlier, either the FSO link or the RF link will be used, and they both need to be in good quality to be used. Moreover, the RF link is used on an unequal priority basis. For example, if the FSO link of node 2 fails, the central node will use the RF link to establish a link, when node 1 is not using the RF link.

### 2.2 Analysis of node 1

We define $p_1$ as the probability that there is a data link available from the central node to the highest priority node, which is given as:

$$p_1 = (1 - a) + a(1 - b) \quad (2.3)$$

where $(1 - a)$ is the probability of using the FSO link and $a(1 - b)$ is the probability that the FSO is in poor quality and the RF link is good to use. Node 1 according to the proposed protocol has the highest priority of accessing the RF link, in case the FSO link is failed.
2.2.1 Markov chain state transition probabilities of the first transmit buffer of central node

A Markov chain is a stochastic process that satisfies the Markov property, which is also referred to as a memoryless property. A process satisfies the Markov property, if predictions can be made of the future based only on its present state [20]. Since we are studying the transmit buffer of the central node, therefore it can be modeled using discrete time Markov chain.

The central node assigns a first-in-first-out (FIFO) transmit buffer of size $B$ symbols for every remote node. The number of symbols stored in the transmit buffer represent the state of the buffer. The buffer is in state $s_i^{(1)}$ when there are $i$ symbols in the buffer (i.e., in the queue) ready for transmission. The future state of the buffer depends only on its current state and the change from one state to another will occur at discrete time values corresponding to symbol arrival and departure events. Therefore, we can use the discrete time Markov chain to model the states of the transmit buffer for the remote nodes [20].

We define $\omega$ as arrival probability that a symbol arrives at the buffer within time step. The resulting Markov chain is single-arrival, single-departure queue. The state transition diagram is shown in Fig. 2.2, where $f_o = 1 - \omega + \omega p_1$, $v = \omega(1 - p_1)$, $u = (1 - \omega)p_1$, $f = 1 - (u + v)$ and $f_B = 1 - u$ are the state transition probabilities.

![State Transition Diagram](image)

Figure 2.2: The state transition diagram of the first transmit buffer of central node [1].

The steady state distribution vector $s^{(1)}$ corresponding to Fig. 2.2 is given by:

$$s^{(1)} = [ s_0^{(1)} \ s_1^{(1)} \ \cdots \ s_B^{(1)} ]^t$$

(2.4)

where $s_i^{(1)}$, $0 \leq i \leq B$, is the probability that the transmit buffer of node 1 is in state
\( s_i^{(1)} \), satisfying the condition:
\[
\sum_{i=0}^{B} s_i^{(1)} = 1 \tag{2.5}
\]
at steady state, the distribution vector \( s \) settles down to a unique value and satisfies the following equation [20]:
\[
P_1 s^{(1)} = s^{(1)} \tag{2.6}
\]
the solution of this set of difference can be given in general form as [20]:
\[
s_i^{(1)} = \rho^i s_0^{(1)}, \quad 0 \leq i \leq B
\tag{2.7}
\]
where
\[
\rho = \frac{v}{u} = \frac{\omega(1 - \rho_1)}{(1 - \omega) \rho_1} \tag{2.8}
\]
the solution for \( s_0^{(1)} \) is obtained by substituting (2.7) in (2.5) which gives:
\[
\sum_{i=0}^{B} \rho^i s_0^{(1)} = 1 \tag{2.9}
\]
After some algebraic manipulations of (2.9), we can obtain \( s_0^{(1)} \) as: [20]:
\[
s_0^{(1)} = \frac{1 - \rho}{1 - \rho^{B+1}} \tag{2.10}
\]
Combining (2.7) and (2.10) the steady state distribution for the other states is given by [20]:
\[
s_i^{(1)} = \frac{(1 - \rho)\rho^i}{1 - \rho^{B+1}}, \quad 0 \leq i \leq B \tag{2.11}
\]

2.3 Analysis of node 2

The central node will have a data link available for second remote node either when the FSO link is good to use, or the RF link is available. The RF is available to the second node when three events take place:

1. The FSO link is bad
2. The RF link is good to use
3. The RF link is not being used by remote node node 1 with probability \( x_1 \)
We define $p_2$ as the probability of data link availability from the central node to the second remote node, which is given as:

$$p_2 = (1 - a) + a(1 - b)x_1$$  \hspace{1cm} (2.12)

where $x_1$ as the probability of node 1 not accessing the RF link, which is given as:

$$x_1 = s_0^{(1)}(1 - \omega) + s_0^{(1)}\omega(1 - a) + s_0^{(1)}wab + (1 - s_0^{(1)})(1 - a) + (1 - s_0^{(1)})ab$$  \hspace{1cm} (2.13)

where the term $s_0^{(1)}(1 - \omega)$ on the RHS is the probability that the first buffer of the central node is empty and the packet has not arrived. The term $s_0^{(1)}\omega(1 - a)$ is the probability that the buffer is empty and the packet has arrived and the FSO link is good to use. The term $s_0^{(1)}wab$ is the probability that the buffer is empty and the packet has arrived and the FSO and RF link is not good to use. The term $(1 - s_0^{(1)})(1 - a)$ is the probability that the buffer is not empty and the FSO link is good to use. The term $(1 - s_0^{(1)})ab$ is the probability that the buffer is not empty and the FSO and RF link is not good to use.

2.3.1 Markov chain state transition probabilities of the second transmit buffer of central node

The transition state probabilities and distribution vector $s_0^{(2)}$ and $s_1^{(2)}$ can be found in a same way as mentioned in Subsection 2.2.1.

2.4 Analysis of node 3

We define $p_3$ as the probability of data link availability from the central node to the third remote node:

$$p_3 = 1 - a + a(1 - b)x_1x_2$$  \hspace{1cm} (2.14)

where $x_2$ is the probability of node 2 not accessing the RF link, and is given as:

$$x_2 = s_0^{(2)}(1 - \omega) + s_0^{(2)}\omega(1 - a) + s_0^{(2)}wab + (1 - s_0^{(2)})(1 - a) + (1 - s_0^{(2)})ab$$  \hspace{1cm} (2.15)
For node 3, we consider the same conditions, where in addition to node 1, node 2 can also be considered as a potential candidate for accessing the RF link.

The transition state probabilities and distribution vectors $s_0^{(3)}$ and $s_i^{(3)}$ can be found in a same way as mentioned in Subsection 2.2.1.

### 2.5 Analysis of node 4

We define $p_4$ as the probability of data link availability from the central node to the fourth remote node:

$$p_4 = 1 - a + a(1 - b)x_1x_2x_3$$  \hspace{1cm} (2.16)

where $x_3$ is the probability of node 3 not accessing the RF link and is given by an equation similar to (2.13) and (2.15).

The transition state probabilities and distribution vectors $s_0^{(4)}$ and $s_i^{(4)}$ can be found in a same way as mentioned in Subsection 2.2.1.

### 2.6 Analysis of node $n$

Above equations follow a certain pattern, therefore, the generalized form of the equation to find the probability of central node accessing a node in a hybrid FSO/RF system can be written as:

$$p_n = (1 - a) + a(1 - b)\prod_{j=0}^{n-1} x_j$$  \hspace{1cm} (2.17)

$x_0 = 1$, and $x_j$ is the probability node $j$ not accessing the RF link, and given as:

$$x_j = s_0^{(j)}(1 - \omega) + s_0^{(j)}\omega(1 - a) + s_0^{(j)}wab + (1 - s_0^{(j)})(1 - a) + (1 - s_0^{(j)})ab$$  \hspace{1cm} (2.18)
2.7 Performance metrics for the nodes

2.7.1 Throughput from central node to the remote nodes

Throughput $Th_n$ for node $n$ can be calculated as:

$$Th_n = \omega p_n s_0^{(n)} + p_n \sum_{i=1}^{B} s_i^{(n)}$$

(2.19)

the first term on the right hand side is the probability that a packet leaves the buffer when the buffer is empty, and the second term on the RHS is the probability when a packet leaves the buffer when it is not empty, so the equation now becomes as follows [20]:

$$Th_n = p_n [1 - s_0^{(n)} (1 - \omega)]$$

(2.20)

2.7.2 Average buffer size

The average buffer size $Qa_n$ is the average number of symbols in the buffer [20]:

$$Qa_n = \sum_{i=0}^{B} i s_i^{(n)}.$$  

(2.21)

queue size is measured in units of packets. Using (2.10) the average queue size is given by:

$$Qa_n = \frac{\rho[1 - (B + 1)\rho^B - B\rho^{B+1}]}{(1 - \rho)(1 - \rho^{B+1})}$$

(2.22)

2.7.3 Average buffer queuing delay

The average queue delay $Tq_n$ is the average number of time a symbol spends in the buffer before being transmitted, this delay is given by [20]:

$$Tq_n = \frac{(Qa)_n}{(Th)_n}$$

(2.23)
2.7.4 symbol loss probability

A symbol is lost, when the queue is full and packet arrives but does not leave. The packet loss probability $PL_n$ is given by [20]:

$$PL_n = \omega s_B (1 - p_n) \quad (2.24)$$

2.7.5 Efficiency of the queue

The efficiency of the queue $\eta_n$ is defined as the ratio of probability a packet leaving the buffer relative to the probability a packet arriving at the buffer. this can be expressed as [20]:

$$\eta_n = \frac{(Th)_n}{\omega} = \frac{p_n [1 - s_o^{(n)} (1 - \omega)]}{\omega} \quad (2.25)$$
Chapter 3

Results

3.1 Matlab simulation of numerical results

We have used Monte Carlo methods to do the numerical simulations. Monte Carlo methods refer to a broad class of computational algorithms, that make use of repeated random number sampling to generate numerical results. Monte Carlo methods generally follows the same procedure as described below [21]. Algorithm 3.1 explains the steps we have used to verify our model.

1. Steps 1 and 2 define the input parameters.
2. Steps 4 and 6 generate random inputs distributed over the simulation time.
3. Steps 7-21 perform deterministic computations.
4. Steps 22-26 aggregate the final results.
Algorithm 3.1 Numerical Simulation Pseudocode

1: procedure MonteCarlo
2:     Input: a, b, B, T, N, $\omega_{\text{min}}$, $\omega_{\text{max}}$
3:     Node Buffer $L \leftarrow 0$
4:     Generate random channel states over time domain
5:     for $\omega = \omega_{\text{min}}$ to $\omega_{\text{max}}$ do
6:         Generate random symbols
7:         for $t=1$ to $T$ do
8:             for $n=1$ to $N$ do
9:                 if $L > B$ then
10:                     $\text{lostflag} = 1$
11:                 else
12:                     Add symbol to Node Buffer
13:                 end if
14:             if $L > 0$ and FSO is good then
15:                 update symbol
16:             end if
17:         if $L > 0$, RF is good, FSO is poor and RF$\neq 1$ then
18:             update symbol
19:             $RF \leftarrow 1$
20:         end if
21:     end for
22:     calculate Throughput
23:     calculate Average buffer size
24:     calculate Average delay
25:     calculate Packet loss
26:     calculate Efficiency
27: end for
28: end for
29: end procedure
3.2 Numerical results and discussion

Figure 3.1: Throughput (Th) with $a = 0.99$, $b = 0.2$ and $B = 10$ symbols. (a) Analytical simulation (b) Numerical simulation

Figure 3.1 shows a plot of analytical and numerical simulations of throughput versus arrival probability for nodes 1 to 4. The graph goes through three phases viz. linear, dipping and saturation. The linear phase occurs at lower values of $\omega$, while the saturation phase occurs for high values of $\omega$. The dipping phase is seen between the lines and shows the access probability of the nodes. Node 1 shows the highest throughput because it has the highest priority of accessing the RF link. On the other hand, node 4 has the lowest priority of accessing the RF link, so it shows the lowest throughput. The numerical simulation shows the similar result as of analytical simulation, which proves that our Markov chain model is accurate.
Figure 3.2: Average buffer size \((Q_a)\) with \(a = 0.99\), \(b = 0.2\) and \(B = 10\) symbols. (a) Analytical simulation (b) Numerical simulation

Figure 3.2 shows the plot of analytical and numerical simulations of average buffer size \(Q_a\) versus arrival probability \(\omega\) for nodes 1 to 4. Node 1 has the highest priority of accessing the RF link. Node 4 in the graph has the lowest priority of using the RF link, so the buffer size for this node increases. Node 1 has the highest priority and the buffer is transmitting the packet immediately after receiving them, so it does not increase the buffer size. For small \(\omega\) average buffer size increases with increase in \(N\). The average buffer size \(Q_a\) saturates at maximum buffer size \(B\), as expected.

Figure 3.3: Average queueing delay \((T_q)\) with \(a = 0.99\), \(b = 0.2\) and \(B = 10\) symbols. (a) Analytical simulation (b) Numerical simulation

Figure 3.3 shows the plot of analytical and numerical simulations of average queue-
ing delay $T_q$ versus arrival probability $\omega$ for nodes 1 and 4. Node 1 in the graph has the highest priority, meaning that this node will get preference while accessing the RF link. On the other hand, node 4 line has the lowest priority of accessing the RF link. The behaviour of average queuing delay shows that, it initially increases as packets arrive at the node and it then saturates. Node 4 has the highest queuing delay, because it has the lowest probability of accessing the RF link, while the node 1 in the graph has low queuing delay.

Figure 3.4: Packet lost probability ($P_L$) with $a = 0.99$, $b = 0.2$ and $B = 10$ symbols. (a) Analytical simulation (b) Numerical simulation

Figure 3.4 shows the plot of analytical and numerical simulations of packet loss probability $P_L$ versus arrival probability $\omega$ for nodes 1 and 4. The loss probability goes into two phases viz. zero loss and linear. The zero loss phase occurs at low values of $\omega$. The linear phase occurs at higher values of $\omega$. Node 1 in the graph has the highest priority of accessing the RF link, so the packet loss probability of this node is low. Node 4 has the highest packet loss, this is because it has the least probability of accessing the RF link.
Figure 3.5: Efficiency ($\eta$) with $a = 0.99$, $b = 0.2$ and $B = 10$ symbols (a) Analytical simulation (b) Numerical simulation

Figure 3.5 shows the plot of analytical and numerical simulations of efficiency $\eta$ versus the arrival probability $\omega$ for nodes 1 to 4. The efficiency graph goes into two phases viz. unity efficiency and decreasing efficiency. The unity efficiency occurs at the low values of $\omega$. And the decreasing efficiency occurs at the high value of $\omega$. Node 1 in the graph shows the highest efficiency, because this node has the highest priority of accessing the RF link, which means packets are continuously transmitting. However for the node 4 in the graph has the unity efficiency for low values of $\omega$, but as the packet arrival rate increases, its efficiency goes down due to its low probability of accessing the RF link.
Chapter 4

Conclusion and future work

4.1 Conclusion

This work is the continuation of the previous work of Cross Layer analysis of Point-to-multi-point hybrid FSO/RF Network, where a scheme has been proposed which implements hybrid FSO/RF to improve the FSO links. According to the proposed idea, a back-up RF link will be used when the FSO link fails from the central node to the remote nodes, and the RF link will be used on equal priority basis. The idea proposed here is that, when a RF link is used for transmission from the central node to the remote node, it establishes link or sends data on an unequal priority basis, having node 1 as the highest priority of accessing the RF link. After this, the performance metrics of all remote nodes are studies, such as throughput from the central node to remote nodes, Average buffer size, Average queuing delay, packet loss probability and the efficiency of the remote nodes.

4.2 Future work

In Chapter 2 we have assumed that when an FSO link fails from the central node to the remote node, it uses back-up RF link, which uses a priority protocol. Using other protocols such as round robin protocol, random delay protocol and delay aware scheduling will effect the Markov chain modelling and can be considered as the future work.
Bibliography


