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**AN ENHANCED OSPF ROUTING PROTOCOL IN
WIRELESS MESH NETWORKS
WITH RAYLEIGH/RICEAN FADING**

**By
Bengu Bala Balya**

**A thesis submitted to the
Faculty of Graduate Studies and Research in partial fulfillment of the requirements for
the degree of**

Master of Applied Science

**Ottawa-Carleton Institute for Electrical and Computer Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
Carleton University**

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**An Enhanced OSPF Routing Protocol In
Wireless Mesh Networks
With Rayleigh/Ricean Fading**

Submitted by Bengu Bala Balya

In partial fulfillment of the Requirements for the Degree of
Master of Applied Science

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2005**

ABSTRACT

OSPF (Open Shortest Path First) is a link state based interior gateway routing protocol. This study explores the performance of OSPF routing protocol in a fixed wireless network with Rayleigh/Ricean fading. Our topology consists of wireless mesh routers, which are connected to each other via 802.11a links.

During our throughput performance study two types of throughput losses are identified. The first type of throughput loss is a direct consequence of fading, and happens when user traffic is sent during fading depths and lost. The second type of throughput loss is an indirect consequence of fading, and happens when OSPF control traffic is sent during fading depths and lost. This results in router interface shut down and consequent user traffic interruption and route changes.

FA-OSPF (Fading Adapted OSPF) routing algorithm was developed in our study in order to prevent the second type of throughput loss and consequent user traffic interruption and route changes.

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List of Acronyms

ABR	Area Border Router
AODV	Ad Hoc On Demand Distance Vector
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
CDF	Cumulative Distribution Function
dB	Decibel
DSR	Dynamic Source Routing
FAHS	Fading Alert Hello Send
FARHS	Fading Alert Response Hello Send
FA-OSPF	Fading Adapted Open Shortest Path First
FAS	Fading Alert State
FCC	Federal Communications Commission
HSI	Hello Send Interval
HSST	Hello Send Start Time
Hz	Hertz
ICI	Inter Channel Interference
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform

ISI	Inter Symbol Interference
LSA	Link State Advertisement
MAC	Media Access Control
MANET	Mobile Ad Hoc Networks
OFDM	Orthogonal Frequency Division Multiplexing
OSPF	Open Shortest Path First
PDF	Probability Density Function
PER	Packet Error Rate
PHS	Periodic Hello Send
PRDI	Partial Router Dead Interval
PRDIT	Partial Router Dead Interval Timer
PSD	Power Spectral Density
RDI	Router Dead Interval
RDIT	Router Dead Interval Timer
RTO	Retransmission Time Out
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SNR	Signal to Noise Ratio
TCP/IP	Transmission Control Protocol/ Internet Protocol
UDP	User Datagram Protocol
WLAN	Wireless Local Area Network

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Chapter-1

INTRODUCTION

1.1 Introduction

As demand for wireless internet technologies increase so does the need to update previous internet protocols which are not originally designed by taking into account wireless media limitations, such as fading. Our work will study OSPF routing protocol. Enhancements will be made to standard OSPF routing protocol in order to prevent problems caused by Rayleigh/Ricean fading environment.

In this chapter, first the roadmap and motivation for this thesis study will be presented. Then, background information on related technologies and research will be summarized.

1.2 Motivation and Roadmap

OSPF is a link state based interior gateway routing protocol, which is mainly designed for internet [1][2]. OSPF has been widely deployed and successfully operated by network service providers for about a decade. Some of the advantages of using OSPF can be listed as: load balancing between the links, different available cost metrics, ability to find the shortest path by using Dijkstra's algorithm, robustness to link failures and faster convergence than distance vector based routing algorithms or mobile ad-hoc routing protocols.

Although OSPF is a very well known and proven routing protocol, it is not considered first choice as a routing algorithm for new generation of wireless networks. OSPF routers perform periodic link state advertisements, which are broadcasted messages that are flooded within an OSPF area. Link state advertisements give information about link state changes at router interfaces. In a highly mobile environment, connectivity between routers will be changing continuously, resulting in continuous link state advertisements. This will generate huge amount of routing traffic. Mobile ad-hoc networks are the best example to observe this problem. Due to mobility of routers and nodes, topology and connectivity between routers will be changing continuously.

In addition to mobility, wireless fading will be affecting connectivity between routers as well. That is even if routers are fixed, due to other objects moving around them, there will be sudden power level drops, resulting in both user traffic and routing control traffic losses.

Our study will focus on routing in fixed wireless mesh networks where routers are not mobile. This eliminates the negative mobility effects on OSPF routing protocol. On the other hand, since routers are connected with wireless links, there will be wireless fading effects on OSPF. This study will try to find ways of adapting OSPF routing protocol in a wireless Rayleigh/Ricean fading environment. Instead of ruling out using OSPF in wireless networks and pursuing developing new routing algorithms, our study explores

the possible ways to adapt standard OSPF to wireless fading and get the advantage of using a platform independent routing protocol.

There are only a few more studies encountered in the literature, which evaluates the performance of OSPF routing protocol in a mobile or multi-hop wireless environment [3][4]. These studies try to find a wireless interface for OSPF by using techniques such as decreasing number of adjacencies between the routers.

In our study Rayleigh/Ricean fading environment is created as the first step, in order to observe fading effects on upper layer protocols. During UDP throughput analysis study on this platform, two types of throughput losses have been identified. First type of throughput loss occurs when user traffic is sent and lost during fading depths. The second type of throughput loss occurs when OSPF control traffic is sent during fading depths and lost. This results in OSPF to shut down its interface. If there is an alternative link OSPF reroutes traffic, otherwise user traffic is interrupted. This is an undesired behavior of OSPF, since fading depths occurs very temporarily and by the time OSPF finds a new path to the destination fading depth will be over.

Our study focuses on preventing the second type of throughput loss, which is caused by OSPF in a wireless Rayleigh/Ricean fading environment, rather than improving OSPF performance in general. This study does not improve Dijkstra's algorithm or the way standard OSPF calculates and finds best routes [1]. On the other hand, by preventing

unnecessary interface shut downs, corresponding link state changes, consequent link state advertisements, route flapping or moving traffic back and forth between alternative links will also be prevented. Thus, there will be less link state advertisements and OSPF control traffic will decrease significantly. FAOSPF (Fading Adapted OSPF) is developed in our study as a modification to standard OSPF routing algorithm, in order to prevent the second type of throughput loss and consequent problems listed above.

There are studies in the literature that recommends cross layer design techniques, in order to improve routing performance in wireless networks [5][6]. By using cross layer design techniques, routing protocol learns about the change in link state status directly from MAC layer. In our study, instead of using cross layer design, a new technique by sending extra “Hello” messages from router interfaces is used, in order to obtain information about link status.

1.3 Wireless Mesh Networks

Wireless mesh networks [5] consist of mesh clients and mesh routers. Mesh clients can act both as a host and as a router as in the case of mobile ad hoc networks. On the other hand, mesh routers are specialized for only routing. Another difference between a mesh client and a mesh router is that, a mesh client has only one wireless MAC interface. Mesh routers, on the other hand, can have many, such as, 802.11, 802.15, and 802.16. Routers have less power limitations and less mobility and more complexity than mesh clients, and they form the backbone of the wireless mesh networks. Wireless mesh routers can have

interface to PAN, LAN, metropolitan, cellular and sensor networks. They can also have interface with wired networks or act as a gateway to the internet. These features of mesh routers form the main difference between ad hoc networks and mesh networks.

Figure-1.1 Wireless Mesh Network

One of the main issues to be solved in wireless mesh networks is the scalability problem. That is, as the number of nodes increases in a system, performance decreases significantly. Routing protocols may have difficulty in finding a routing path. Transport protocols may lose their connection and MAC throughput may decrease significantly [5].

Therefore, there is a need to further modify routing, transport and MAC layer protocols as well as radio technologies, to overcome scalability problem. Our study will be a valuable step in the solution of scalability problems in wireless mesh or ad hoc networks, and will be explained in the upcoming chapters.

1.4 OSPF Routing Protocol

Each OSPF router has a link state database, which keeps the information obtained from link state advertisements coming from other routers [1] [2]. By using link state database information, OSPF router builds its routing table, by using Dijkstra's algorithm to calculate the shortest path to each destination.

OSPF areas are used to contain flooded link state advertisements within an OSPF area. All routers within the same area will have the same link state database. Routers located at the boundary of OSPF areas, are called ABR (Area Border Router). ABR's have more than one link state databases.

When a router is first powered on, it broadcasts Hello messages from all interfaces [7]. Once two routers exchange Hello messages, and they agree on the information contained in the Hello message, then that means they have formed an adjacency. Hello messages contain information, such as, router id, area id, authentication, network mask, Hello send interval, router dead interval, router priority, optional capabilities, network mask, designated router and backup designated router.

Hello messages are being sent periodically at every Hello message send interval. If a router does not hear from its neighbor for a time interval determined by router dead interval, then this router will assume that the connection with this neighbor is no longer available.

Whenever a router notices a change in state of one of the links, this change is broadcasted to all other routers within the area via link state advertisements [7].

There are seven neighbor states in OSPF, named as: Down, Init, Two-way, ExStart, Exchange, Loading and Full [1]. Neighbors will be in full state if they are fully adjacent and link state databases are identical.

OSPF routing protocol was first developed in 1980's and successfully implemented since then. Our study will be a valuable step in evaluating and improving the performance of OSPF at wireless mesh networks.

1.5 Background Information

According to our literature survey, routing in wireless media research are mainly focused on routing in mobile ad hoc networks [8]. Mobile ad hoc networks are the extreme case of routing in wireless media, where all wireless limitations exist. The advantage of mobile ad hoc networks is that there is no need for an infrastructure and mobile ad hoc clients can act as a router. Network topology is dynamically changing, self-configuring and self-healing. Since topology is dynamically changing, so is the connectivity between nodes and/or routers. This creates huge amount of routing updates and is the main problem of mobile ad hoc networks. Another important limitation is the power constraints on mobile nodes. That is, routing protocols should consider power limitations on each path, as well as link quality and choose paths with less power consumption.

There are quite a number of algorithms in the literature for mobile ad hoc routing, such as AODV and DSR. The common point in these algorithms is that, they are source initiated and on demand [9][10]. That is, routers do not broadcast routing updates but only do route requests at a time for a particular destination when needed. The disadvantage of these methods is that, when there is a link failure, there will be a delay in requesting and finding a new route. They are not as reliable as route broadcasting method and poor in link failures and connectivity loss.

Our study focuses on wireless mesh networks rather than mobile ad hoc networks. Our topology will consist of fixed wireless routers, and connectivity between routers because

of mobility or power constraints, are not a problem. In wireless mesh networks, mesh routers have less limitations and more complex structures than mobile ad hoc routers [5]. They are specialized just in routing and form the wireless mesh backbone. Wireless mesh routers may have interfaces to different network technologies, such as 802.16 or 802.11a/b networks.

During our literature survey, it has been found out that most of the current research, has an approach to the routing problem, from the graph theory point of view [11]. That is, they focus on the problem of mobility, dynamic topology changes and connectivity between routers [8]. On the other hand, there is very limited research that evaluates the routing performance directly with respect to fading or other physical wireless media characteristics.

OLSR (Optimized Link State Routing) protocol is a link state routing protocol, which is very similar to OSPF [12]. It is designed for mobile ad-hoc networks and based on multipoint relay (MPR) nodes. In this protocol only the nodes that are chosen as MPR can broadcast link state information. The protocol can be further configured to let only MPR nodes to generate information about the links between other MPR nodes. OLSR can reduce the overhead introduced by classical routing protocols, such as OSPF, significantly in a highly dense topology.

Study by Adih, Baccelli and Jacquet, compares OLSR and OSPF algorithms in an ad hoc network [4]. OLSR is found working superior than OSPF, which brings the necessity to define a wireless interface for OSPF. For example DR (Designated Router) concept in OSPF can be replaced by MPR node concept. Another modification can be unreliable transmission of acknowledgement messages. Authors think that, using the same routing algorithm in both wired and wireless networks, will reduce deployment costs and bring seamlessly unified wired and wireless networks under a unique routing solution [4].

In another study a wireless interface is designed for OSPF and found out to be more bandwidth efficient than OLSR, by a factor of two to three folds [3]. Authors performed this study, because OSPF has its own advantages over OLSR (such as variable cost link metrics and route aggregates), and by defining a wireless interface type for OSPF is considered as the best solution for a unified routing algorithm on wired and wireless platforms.

A new link state database exchange mechanism is defined as an OSPF wireless interface extension in [14][15]. This is achieved by a new message, signature message, which is exchanged between the routers. By using signature message, routers will understand if their databases are different with their neighbors, and exchange database information only if it is necessary.

Efficient simulation of Ricean fading, within a packet simulator (NS2), is a study performed by Punnoose, Nikitin and Stancil [13]. In this study, a small scale fading input data set is prepared by generating Gaussian distributed in-phase and quadrature phase components and spectrally shaping these components by using Doppler spectrum. The generated dataset represents a time limited sequence of fading envelop values, and needs to be repeated periodically over and over again, to cover fading values for long time durations. The method presented in this study is used to generate fading input dataset for OPNET simulator in our study.

A practical study was performed, to measure indoor fading at 5GHz band in a university building [16]. According to these measurements, average fade duration, fading crossing rate and Ricean K factor are calculated and tabulated. The authors are planning to use measured values to generate a realistic Markov chain model of an indoor wireless channel.

Markov modeling of wireless fading channel with two states (good and bad) has been implemented in the study of Arauz and Krishnamurty [17]. The authors observed that, with traditional Markov channel modeling, the duration of bad and good states, are not necessarily the same as experimental measurement results.

1.6 Organization of Chapters

Chapter-2 presents the first step of our study. That is the configuration of the router topology, physical, MAC layer and network layer parameters, as well as understanding and implementation of Rayleigh/Ricean fading.

Chapter-3, presents the throughput loss analysis study. OSPF related interface shut down problem is identified and studied in detail.

Chapter-4 presents FA-OSPF algorithm, which is developed in our study to improve OSPF performance under wireless fading environment. Performance comparison of FA-OSPF and OSPF will be performed.

Chapter-5 evaluates the performance of FA-OSPF by using another topology where there are two alternative paths between source and destinations. Performance comparison of FA-OSPF and OSPF protocols will be repeated with this new topology.

Chapter-6 presents the conclusions, overall evaluation of FA-OSPF, thesis contribution and future potential research areas.

Chapter-2

Network Configuration and Fading Input Data Generation

2.1 Introduction

In our study, a wireless mesh network is created, where routers are connected to each other via 802.11a (OFDM) channels. Each router interface is associated with a transmitter/receiver pair, which is responsible for physical layer wireless signal transmitting and receiving. The first part of this chapter presents the network topology and configurations used in our study, such as MAC layer configurations, IP addressing schemes and overall topology.

Wireless channels are characterized by several factors, such as path-loss, shadowing, fading and interference from unwanted sources. In our model, all parameters but fading were chosen to be constant, in order to be able to observe fading effects on our routing protocol, independent of other parameters. The second part of this chapter will present the configuration of all these parameters and the assumptions that are made.

Received power levels will change according to a time varying fading envelope, in order to observe fading effects in our system. The last part, of this chapter, will focus on generating fading input data set.

2.2 Network Topology and Configuration

An infrastructure/backbone wireless mesh network topology is created as shown in Figure-2.2.1a and Figure-2.2.1b. Four wireless mesh routers form the backbone of our wireless mesh network.

Figure-2.2.1a Configuration of WLAN parameters

Router-1 and Router-2 will have interface to workstations via 100 Mbps links. On the other hand Router-3 and Router-4 are totally backbone routers. The manual MAC layer configuration of our network, such as channel frequency, bandwidth and BSS identifiers are shown in Figure-2.2.1a.

Figure-2.2.1b Network Topology

Table-2.1 Configuration of router interfaces

Router-1	Router-2	Router-3	Router-4
Interface-0 IP : 191.16.10.01/24 100BaseT Ethernet	Interface-0 IP : 191.16.20.01/24 100BaseT Ethernet	Interface-0 IP : 191.16.30.01/24 100BaseT Ethernet	Interface-0 IP : 191.16.40.01/24 100BaseT Ethernet
Interface-1 IP : 191.16.12.01/24 BSS12, 802.11a Freq: 5180 MHz	Interface-1 IP : 191.16.12.02/24 BSS12, 802.11a Freq: 5180 MHz	Interface-1 IP : 191.16.13.02/24 BSS13, 802.11a Freq: 5240 MHz	Interface-1 IP : 191.16.14.02/24 BSS14, 802.11a Freq: 5300 MHz
Interface-2 IP : 191.16.13.01/24 BSS13, 802.11a Freq: 5240 MHz BW: 16.6 MHz	Interface-2 IP : 191.16.23.01/24 BSS23, 802.11a Freq: 5200 MHz BW: 16.6 MHz	Interface-2 IP : 191.16.23.02/24 BSS23, 802.11a Freq: 5200 MHz BW: 16.6 MHz	Interface-2 IP : 191.16.24.02/24 BSS24, 802.11a Freq: 5260 MHz BW: 16.6 MHz
Interface-3 IP : 191.16.14.01/24 BSS14, 802.11a Freq: 5300 MHz BW: 16.6 MHz	Interface-3 IP : 191.16.24.01/24 BSS24, 802.11a Freq: 5260 MHz BW: 16.6 MHz	Interface-3 IP : 191.16.34.01/24 BSS34, 802.11a Freq: 5220 MHz BW: 16.6 MHz	Interface-3 IP : 191.16.34.02/24 BSS34, 802.11a Freq: 5220 MHz BW: 16.6 MHz

All IP addresses are manually configured as shown in Figure-2.2.1b. Table-2.1 summarizes the information in Figure-2.2.1a and Figure-2.2.1b in a tabulated format. As we see from previous figures, routers have three wireless 802.11a interfaces and each one is used to connect to one of neighboring routers. Fading will be implemented on these links. There are two workstations, one source and the other destination. Source is connected to Router-1 and destination is connected to Router-2, via Ethernet 100Mbps links. Constant packet rate, 1 Mbps, UDP traffic generated at source, will travel through wireless mesh backbone, to reach its destination, workstation-2. The performance of this traffic will be evaluated in the coming chapters. The reason for using Ethernet links instead of 802.11b links is that, our study focuses on performance of 802.11a links. Thus having no other wireless links in our model will be helpful for our purpose.

2.3 Physical layer Configuration

There are several factors, which affect the signal quality in a wireless media, such as, path-loss, shadowing, fading and interference from other sources, as well as, background and thermal noise, transmitter and receiver antenna gains. Our final aim in this study is to observe the behavior of routing protocols and user traffic with respect to wireless fading. The next section gives details about how fading is implemented in our model. In this section, all wireless parameter configurations other than fading will be discussed.

Path-loss occurs in any wireless media because of spreading of electromagnetic power in space as a function of distance [19]. In fixed wireless systems, as in our topology with

fixed routers that are not mobile, path-loss will be constant. For a typical WLAN network topology, with 50 meter distance between transmitter and receiver, large-scale path-loss is calculated as 90dB by the formula given below. This value is set as the default and constant path-loss value in our model as shown in Table-2.2.

Large-scale path-loss is calculated by using the general formula [19]:

$$PL[dB] = 20 \log_{10} \left(\frac{4\pi d_0}{\lambda} \right) + 10n \left(\frac{d}{d_0} \right) = 60 + 30 = 90 \text{ dB} \quad (2.1)$$

Where,

$n= 3$ (propagation exponent for urban areas))

$d_0 = 5 \text{ m.}$ (reference distance)

$d = 50 \text{ m.}$ (Tx-Rx separation)

$\lambda = 0.06 \text{ m.}$ (wavelength in 5 GHz band)

Shadowing is another factor that occurs due to attenuation of signal because of an object located between the transmitter and the receiver. In our channel model, shadowing will not be considered and assumed zero. OFDM (Orthogonal Frequency Division Multiplexing) transmission model is used in IEEE 802.11a networks, in order to reach high data rates of up to 54 Mbps over wireless channels. OFDM technique transforms a frequency selective wideband channel into parallel narrowband flat fading channels [18].

In our model, it is assumed that OFDM sub-channels are perfectly orthogonal and ICI (Inter Channel Interference) is negligible. ISI (Inter Symbol Interference) will also be assumed to be zero. In addition highly directional antennas are used in our topology in order to minimize external interference from other sources.

Thermal noise and background noise are also assumed to be constant and the same in all receivers in our topology. Table-2.2 shows the parameters in a wireless channel and their default values in our model [22][23][19].

Table-2.2 WLAN Topology and Parameter Specification

Parameter	Default Value
Transmitter Frequency	5GHz
Channel Bandwidth	16.6 MHz
Multiple Access Scheme	OFDM (802.11a)
Transmitted Power	0.050 Watts (or 17 dBm)
Path-loss	90 dB
Propagation Exponent, n	3.0
Transmitter Antenna (30° Beam-width) Gain	5 dB
Receiver Antenna (30° Beam-width) Gain	5 dB
Noise (Thermal + Background + Accumulated)	-73 dBm
Reception Power Threshold	-95 dBm
Buffer Size	256000 bits
Rayleigh/Ricean Fading: maximum Doppler Frequency	4 Hz

2.3.1 A General Discussion on Wireless Parameters

As we see from Table-2.2, we have set all wireless parameters in our model, other than fading. Fading occurs because of multi-path components, arriving to the receiver by reflections from other objects or due to relative motion of transmitter and receiver. Although we have not implemented fading yet, we can calculate the fading margin by using the values given in Table-2.2. Fading margin, determines the maximum fading that can occur in our model and yet the power of the received signal will be still greater than reception power threshold.

We can calculate fade margin in our model as follows:

$$P_r > -95dBm \quad (2.2)$$

$$P_t - PL + G_{tx_ant} + G_{rx_ant} - Fading > -95$$

$$17 - 90 + 5 + 5 - Fading > -95$$

$$Fading < 32dB$$

We can also calculate the SNR value by using the parameters from Table-2.2. Since fading is not implemented yet, this SNR value will be constant and not reflect fading effects. For simplicity, we will name the SNR before taking into account fading effects as SNR_{base} . According to channel parameters given in Table-2.2, SNR_{base} , can be calculated as follows:

$$SNR_{base}[dB] =$$

$$10 \log (Received_Power(with_nofading) / Background+Accummulated+Thermal_Noise)$$

$$SNR_{base}[dB] = P_t[dBm] - PL[dB] + G_{tx_ant}[dB] + G_{rx_ant}[dB] - Noise[dBm] \quad (2.3)$$

$$SNR_{base} = 17 - 90 + 5 + 5 + 73 = 10dB$$

As we see from the calculation above, SNR_{base} is constant and equal to 10dB in our model. On the other hand, since there is fading, actual SNR, will change in accordance with fading as well:

$$SNR_{actual}[dB] = SNR_{base} + \Delta_{SNR_fading} = 10 + \Delta_{SNR_fading} \quad (2.4)$$

Data rate and modulation types are not set in Table-2.2, because, they will be dynamically changing in our model depending on transmitter data rate.

2.4 Fading Input Data Generation

In order to implement fading functionality in our simulation tool, the first step will be the generation of a time series of fading data set.

The received power stage in our simulation tool is modified in such a way that, this generated fading data set will be used as an input. During the simulation, after the default process of received power calculation of an arrived packet, this calculated received power value will be adjusted according to the fading data value for that specific time.

We will first discuss about Rayleigh and Ricean fading in this section. Then the methodology, for generating the fading input data set, will be explained. Finally, CDF of theoretical and simulated fading data will be compared.

2.4.1 Rayleigh / Ricean Fading in Wireless Networks [19]

Small scale fading is the result of multi-path components of the same signal arriving to the receiver with constructive or destructive additions. Relative transmitter and receiver motion, or reflected components of the signal from the surrounding objects, are the cause of fading.

Fading is called Rayleigh, if all components arrive with equal strength. If there is a line of sight between transmitter and receiver, then there is a signal component arriving to the receiver, which is stronger than the other components. This type of fading is called Ricean fading.

Both Rayleigh and Ricean fading are implemented in our model. A Rayleigh random variable “R” has a distribution as follows:

$$P(R) = \frac{R}{\beta^2} * \exp\left(-\frac{R^2}{2\beta^2}\right) \quad ; R \geq 0 \quad (2.5)$$

On the other hand, a Ricean random variable “r” has the following distribution:

$$P(R) = \frac{R}{\beta^2} * \exp\left(-\frac{R^2 + A^2}{2\beta^2}\right) * I_0\left(\frac{RA}{\beta^2}\right) \quad ; R \geq 0 \quad A \geq 0 \quad (2.6)$$

where, mean is $\beta\sqrt{\frac{\pi}{2}}$ and variance is $\left(2 - \frac{\pi}{2}\right)\beta^2$.

$$\text{Ricean } K = \frac{\text{Power_in_specular_components}}{\text{Power_in_scattered_components}} = \frac{A^2}{2\beta^2} \quad (2.7)$$

If Ricean K is zero, that means there is no line of sight, and it is actually Rayleigh fading. On the other hand, if Ricean K is infinity, that corresponds to the case where there is no multi-path fading.

2.4.2 Fading Input Data Set Generation [13] [20] [19]

In order to generate a fading input data set, the same methodology used by Punnoose and Rahman, will be followed [13] [20]. Once this fading data set is generated and ready, it will be used by the simulator, to calculate the corresponding fading power value for an arriving packet at the router receivers in our model.

There will be only one fading data set generated, for both Rayleigh and Ricean fading. Ricean-K variable in the simulation tool will determine the type of fading. For Rayleigh fading Ricean-K factor will be set to zero.

Fading occurs for a short duration of time and Doppler frequency is a measure of how fast fading changes. Although transmitter and receiver are fixed in fixed wireless

networks, there will be still a Doppler frequency due to relative motion of surrounding objects.

The following steps are followed during fading data input generation:

Step-1: Determination of Doppler frequency and Doppler spectrum. In our study, Doppler frequency of 4 Hz is used. Since we have a fixed wireless network, Doppler spectrum is calculated according to the formula as given below [21]:

$$S(f) = \begin{cases} 1 - 1.72f_0^2 + 0.785f_0^4 & ; |f_0| \leq 1 \\ 0 & ; |f_0| > 1 \end{cases} \quad (2.8)$$

where, $f_0 = \frac{f}{f_m}$ and f_m is the maximum Doppler frequency, 4 Hz.

The calculated Doppler power spectral density by the above formula is shown in Figure-2.4.1.

Figure-2.4.1 Doppler Power Spectral Density (dB)

Step-2: The next step will be to specify the number of points. In our model, it is decided to use 1024 frequency points, which basically determines the time duration of fading waveform as follows [13].

$$Td = \frac{(N-1)}{2 * f_m} = 128 \text{ seconds} \quad (2.9)$$

Step-3: For each frequency point, complex Gaussian random numbers are generated. The numbers are generated in such way that the complex number for a positive frequency point is the complex conjugate of the complex number for the corresponding negative frequency [13] [20].

Step-4: Complex numbers generated for each frequency point are multiplied by the corresponding values of the Doppler power spectra values.

Step-5: The resultant frequency domain data, which is a series of complex numbers, is applied to IFFT (Inverse Fast Fourier Transform), in order to generate a time series of data.

Step-6: Previous steps have been repeated to obtain a second time series of data. These two sets of data summed up to form the in-phase and quadrature phase of multi-path sources.

Step-7: The real and imaginary parts of data set entries, x_1 and x_2 respectively, are normalized. Resultant, normalized values of x_1 and x_2 , are the final fading data set values that are generated, and used by the simulator to calculate fading.

By using the fading data set values, x_1 and x_2 , Rayleigh fading power in linear scale, is calculated as follows.

$$Rayleigh_Fading_Power = \frac{x_{1i}^2 + x_{2i}^2}{2}, \quad (2.10)$$

where, “i” is the index of discrete samples generated by IFFT process. Figure-2.4.2 shows the Rayleigh fading power envelope in dB scale, as calculated and used in our study.

Figure-2.4.2 Rayleigh Fading Power Envelope

It is already shown how to calculate the Rayleigh fading power in equation 2.10. Ricean fading with Ricean K factor can also be calculated as follows using the same fading data set:

$$Ricean_Fading_Power = \frac{(x_{1i} + \sqrt{2 * RiceanK})^2 + x_{2i}^2}{2 * (RiceanK + 1)}, \quad (2.11)$$

As an example, Figure-2.4.3 and Figure-2.4.4 show the Ricean fading power envelopes calculated from the above formula and plotted for Ricean K 2.2 and 5 respectively. If we

compare these figures with the Rayleigh fading power envelope given in Figure-2.4.2, it will be noticed that Ricean fading is not as severe as Rayleigh fading. As Ricean-K variable gets larger, so does the line of sight between transmitter and receiver. Therefore, Ricean $K=5$ case should be less severe than Ricean $K=2.2$ case. The figures show that the results are in accordance with these conclusions.

Figure-2.4.3 Ricean fading power envelope with Ricean $K=2.2$.

Figure-2.4.4 Ricean fading power envelope with Ricean $K = 5$.

2.4.2.1 Example on how to calculate the fading sample index

It is already explained how to prepare the fading input data set values in previous section.

Now the question is, during simulation, how simulator decides on which discrete fading data sample to use.

The number of time domain points generated by IFFT process, determines the total number of fading sample points within the fading envelope duration of 128 seconds. There should be enough fading samples in our model, so that there will be a separate corresponding fading value for each packet arriving to the receiver in a short period of time. The number of fading samples in our model is determined by taking into

consideration the limitations of our simulation tool, processing power and Matlab tool. In our model this total number of discrete fading sample points is chosen as $2^{18} = 262144$.

Since the fading envelope duration is 128 seconds, with 262144 total fading samples, inter-sample time will be 0.488 ms. This 128 second long data set will be used repeatedly during simulation. As an example, let us consider the case when a packet arrives to receiver at 500.2716 seconds. The corresponding Rayleigh fading value for this particular packet will be, 116.2716 seconds in Figure-2.4.2, as calculated by the formula below:

$$\text{Corresponding_fading_data_time} = 500.2716 \pmod{128} = 116.2716 \text{ seconds} \quad (2.12a)$$

It is possible to calculate the corresponding discrete fading data value index, “i” as well, as follows:

$$\text{fading_data_sample_index} = [500.2716\text{sec} * (1/ 0.488 \text{ msec})] \pmod{262144} = 237714 \quad (2.12b)$$

Therefore, 237714'th discrete fading sample at the output of IFFT should be used, for the packet arriving at time 500.2716.

2.4.2.1 Fading Model Verification.

If the instantaneous Rayleigh fading power is P , then the probability density function of instantaneous fading power is calculated as follows [20]:

$$f_P = \begin{cases} \frac{1}{P} \exp\left(-\frac{P}{\overline{P}}\right) & ; P \geq 0 \\ 0 & ; P < 0 \end{cases} \quad (2.13)$$

In this formula average envelope power, is given by $\bar{P} = \sigma_r^2$, which is the variance of Rayleigh variable [20]. CDF of the instantaneous power is also calculated by:

$$F_p = \begin{cases} 1 - \exp\left(-\frac{P}{\bar{P}}\right) & ; P \geq 0 \\ 0 & ; P < 0 \end{cases} \quad (2.14)$$

The theoretical CDF as calculated by the above equation and the simulated CDF of Rayleigh fading power envelope, are both plotted together as shown in Figure-2.4.5. As we see from this figure, simulated values are the same as the theoretical ones.

Figure-2.4.5 Comparison of theoretical and simulated CDF of Rayleigh fading power

The CDF of Ricean and Rayleigh fading power envelopes are plotted as shown in Figure-2.4.6. As we see from this figure, as Ricean K factor increases, fading becomes less severe. Rayleigh fading, a special case of Ricean fading with Ricean K factor equal to zero, has no line of sight and therefore has the most severe fading case within the all three.

Figure-2.4.6 CDF comparison of Rayleigh and Ricean fading power.

Chapter 3

THROUGHPUT LOSS ANALYSIS

3.1 Introduction

The purpose of this chapter is to make an overall analysis, and to get an insight into problems occurring in wireless mesh networks due to fading. The direction of this thesis is determined after the analysis results of this chapter.

During UDP throughput analysis unexpected, severe and temporary throughput losses have been detected which are randomly occurring during our simulations. We have studied this unexpected and random behavior of throughput losses and concluded that, it is related with the randomness of the OSPF configuration in our model. That is, the random start time of sending Hello messages from router interfaces. The proof of this observation is presented in this section. As a result of this analysis, two different types of throughput losses are identified. The first type of throughput loss will be user/network data packet loss as a direct consequence of fading, which is naturally expected and continuously occurring during our simulations. The second type of throughput loss will be user/network data packet loss due to OSPF as an indirect consequence of fading. This type of throughput loss is unexpected, temporary and can be more severe than the previous one. It occurs only when OSPF shuts down its router interface when consecutive OSPF Hello messages are lost due to fading.

As a final study of this chapter, we have compared throughput performance with different SNR values. As a result of this analysis, it has been concluded that both types of throughput losses occur more often for lower SNR values.

3.2 UDP Throughput with Rayleigh/Ricean Fading

A basic wireless mesh network topology is created with two routers connected to each other via 802.11a links as shown in Figure-3.2. Router configurations are the same as explained in chapter-2. This is the topology that will be used throughout this chapter. Traffic is generated at source node, workstation-1 and routed by router-1 and router-2, to its destination, workstation-2.

Figure-3.2 Two-router topology

Constant packet rate, 1 Mbps, UDP traffic is generated and throughput statistics are compared for different fading scenarios in this section.

Figure-3.2.1 shows the comparison of WLAN throughput measurements at router-2 for all fading scenarios. As we see from this figure, Rayleigh fading scenario has the lowest throughput. Ricean fading scenario is better than Rayleigh fading case but worse than no fading scenario. Another important observation from the figure is that, there are severe temporary throughput losses, at times, 468, 7200, 7632 and 9864 seconds. These throughput losses will be explained in detail in the coming sections.

Figure-3.2.1 Comparison of WLAN Data Traffic with All Fading Scenarios

3.3 Throughput Loss Analysis

In Figure-3.2.1 in previous section, four unexpected severe throughput losses have been observed at times 468, 7200, 7632 and 9864 seconds. In this section, we will explore these severe throughput losses and find out why and how they occur.

We have repeated simulations for the same configuration, topology and traffic as in Figure-3.2.1. It has been observed that, these severe throughput losses were not happening at the same time instants, for each repeated simulation. In order to find the reason behind this random behavior, the configuration of our topology has been checked. It has been found out that, OSPF start time parameter was the random parameter in our model, and this parameter was randomly assigned between 5 and 10, at the beginning of each simulation. OSPF start time determines the time, at which the first Hello message and following periodic ones were sent from router interface. In this section, we will examine the relation between severe throughput loss occurrences and OSPF start time (or Hello send start time) parameter.

3.3.1 Hello Send Start Time (HSST) versus Throughput Loss.

In order to see the relation between HSST and throughput loss, throughput measurements have been performed for different HSST values, as shown in Figure-3.3.1. As we see from this figure, severe throughput losses occurred at different times and for different number of times, for each HSST value, within an hour of simulation duration. For

example, for HSST 16 seconds, there are two severe throughput losses at 727 and 3261 seconds. On the other hand, for HSST 21 seconds, it didn't happen at all.

Figure-3.3.1 Throughput for different Hello Send Start value

In order to be sure that, changing HSST value is the only reason behind these changes in time location of severe throughput occurrences, we have repeated all the simulations in Figure-3.3.1. For each repeated simulation for a particular HSST value, severe throughput losses occurred exactly at the same time instants. This result shows that, there is not another random variable in our model, which affects time and number of severe

throughput occurrences other than HSST. We have summarized our observations in Table-3.1.

Table-3.1 Hello Send Start (HSST) versus Severe Throughput Occurrences

OSPF Start Time (seconds)	Severe Throughput Occurrences		Simulation Repeated by:
	Number	Time (seconds)	
16	2	750, 3240	3
19	1	800	3
22	1	1400	3
21	0	N/A	3

3.3.2 Explanation of OSPF and Throughput Loss Relation

In this section we will discuss about how HSST might be affecting the severe throughput loss occurrences.

OSPF routing protocol is the only routing protocol used in our model. Let us first give some information about OSPF protocol. There are two basic parameters in OSPF, which are closely related with our study [1]:

-HSI (Hello Sent Interval): Default value is every 10 seconds

-RDI (Router Dead Interval): Default value is 40 seconds

Each router will send a Hello message to its neighbors at every 10 seconds periodically. If no Hello messages arrive from the neighbor within 40 seconds, then the router will assume that, the neighbor is down. As a result, it will not forward any traffic to its neighbor and basically the router interface to this neighbor is closed.

Relative start time of sending Hello messages to the fading envelope, determines when the router neighbor close downs happen. That is, if four consecutive Hello messages are sent by chance during fading depth durations, they will be lost. The router that couldn't get these Hello messages will assume that the neighbor is down. In other words, OSPF routing protocol will shut down its interface to this neighbor, and no traffic can be forwarded in between until new Hello messages are re-exchanged.

Let us consider two routers that have wireless interfaces, and these interfaces will have exactly the same fading power envelope. That is, wireless links at both interfaces will go through the same fading depths over time. The first router sends Hello messages at 16, 26, 36, 46, 56 seconds and so on. The second router sends Hello messages at 3, 13, 23, 33, 43 seconds and so on. It is perfectly possible for the first router to have fading related OSPF interface shut downs, and corresponding throughput losses, whereas, the second router to have no problem at all. Since, relative timing of sending Hello messages to fading depths, are different at both routers.

3.3.3 Proof of Relation Between OSPF and Throughput Loss

In the previous section, it was explained that, severe throughput losses occur, when router shuts down its interface due to lost Hello messages within an RDI interval. In this section, we will check if this argument is really true. For this purpose, we will examine the two severe throughput losses occurring approximately at times 740 and 3270 seconds, as shown in Figure-3.3.2.

Step-1:

As the first step, we have checked the RDI timer expirations at both routers. RDI timer expires on a router, if that router could not get four consecutive Hello messages from its neighbor.

Figure-3.3.2 Mean throughput measurement over time (Hello Send Start = 16 sec)

Table-3.2 shows the two RDI expirations occurred at router-1, for the corresponding two severe throughput losses in Figure-3.3.2. Router-1 has RDI timer expirations at 727.568998 and 3261.682736 seconds, which initiate OSPF interface shut downs by router-1. These timings are exactly just before we observe severe throughput losses in Figure-3.3.2.

Table-3.2 RDI Expirations at Router-1

Router-1	Neighbor Address = 191.16.12.2	RDI Expire Time= 727.568998 seconds
Router-1	Neighbor Address = 191.16.12.2	RDI Expire Time= 3261.68273 seconds

Step-2:

As the second step, we have checked the previous four Hello messages that were sent just before these RDI timers expired. Our aim is to show that they were sent during fading depths and therefore, lost and never arrived at router-1. Table-3.3 shows the times when these previous four Hello messages have been sent by router-2 to router-1, for the first RDI expiration on router-1. Similarly, Table-3.4 shows the times when these previous four Hello messages have been sent by router-2 to router-1, for the second RDI expiration on router-1.

Table-3.3 Hello Messages Sent by Router-2, before first RDI expiration

Router-2	Interface Address= 191.16.12.2	Time= 697.914557 seconds
Router-2	Interface Address= 191.16.12.2	Time= 708.000498 seconds
Router-2	Interface Address= 191.16.12.2	Time= 718.095022 seconds
Router-2	Interface Address= 191.16.12.2	Time= 728.955120 seconds

Table-3.4 Hello Messages Sent by Router-2, before second RDI expiration

Router-2	Interface Address= 191.16.12.2	Time= 3221.682394 seconds
Router-2	Interface Address= 191.16.12.2	Time= 3232.550044 seconds
Router-2	Interface Address= 191.16.12.2	Time= 3242.899530 seconds
Router-2	Interface Address= 191.16.12.2	Time= 3253.613977 seconds

The fourth Hello message is sent at 728.955120 seconds, and it is actually not before, but just after the first RDI expiration. This is mainly because, the previous Hello messages are not sent at exactly 10 seconds but with some delay. We will talk about this observation more in the next chapter. For now, we can say that three lost Hello messages, instead of four, may be enough to cause RDI expiration.

Step-3:

Our last step will be to check throughput statistics, measured at the times when Hello messages, listed at Table-3.3 and Table-3.4 were sent. Our aim is to show that these Hello messages are being sent during low throughput durations. If this is the case, we can conclude that these Hello messages were indeed being lost, causing those RDI expirations listed in Table-3.2.

Figure-3.3.3 shows throughput measurements for the first Hello message in Table-3.3, which was sent at 697.91 seconds. As we see from the figure, throughput was zero right at 697.91 seconds. Therefore, this Hello message was indeed lost.

Figure-3.3.3 Throughput at when first Hello message sent (of first RDI expiration).

The corresponding throughput plots, for the rest of the other Hello messages listed in Table-3.3 and Table-3.4, are shown in Appendix-1. As we can conclude from all these figures, Hello messages listed in Table-3.3 were lost and caused the first RDI expiration shown in Tale-3.2. The last Hello message in the table is an exemption case, since it was delayed and actually sent after first RDI expiration.

Similarly, all Hello messages listed in Table-3.4 were lost, and caused second RDI expiration shown in Tale-3.2.

3.4 Throughput Loss Analysis

We have talked about the relation between OSPF interface shut downs and severe temporary throughput losses in the previous sections. It has been already concluded that severe throughput losses occur as a result of OSPF interface shut downs, which are initiated depending on relative position of Hello message send times with respect to fading depths. We will call this kind of throughput loss as second type of throughput loss or, *Throughput _Loss_{ospf}* in our study.

Second type of throughput loss, *Throughput _Loss_{ospf}* occurs temporarily and initiated by OSPF control traffic loss and consequently leads to user traffic loss.

In this section, we will define another type of throughput loss, *Throughput _Loss_{fading}*, which is shown in Figure-3.4.1. As we see from this figure, there is an average constant amount of difference in throughput, between the traffic sent and the traffic received (around 100000 bits/sec). In addition, this constant amount of data difference between sent and received data, is the same for all scenarios. We will call this kind of throughput loss, as the first type of throughput loss, or *Throughput _Loss_{fading}*. Throughput in the no-fading scenario is assumed to be equal to data sent by source, since the no-fading scenario does not have any losses.

Figure-3.4.1 Two Types of Throughput Loss

First type of throughput loss, $Throughput_Loss_{fading}$, is not related with OSPF interface shut downs and happens as a direct consequence of fading. That is when user data packets are sent during fading depths and lost on their way.

Based on previous discussions, it is concluded that, the total throughput loss can be expressed as a combination of both factors as follows:

$$Throughput_Loss = Throughput_Loss_{fading} + Throughput_Loss_{ospf}$$

Although the amount of fading is not constant and continuously changing during the simulation, it changes so fast that, we can see the on average effect of fading on user data, as a constant amount of throughput loss. This is the case in Figure-3.4.1, which shows throughput measurements, for three hours time duration. This figure is good to see an overall picture. On the other hand, we need to collect per packet statistics also in our study. For example, Figure-3.4.2 shows a throughput plot, where statistics were collected for each and every arriving packet. However when we work in a very small time period, it is not easy to differentiate between the two types of throughput losses. For example, as we can see in Figure-3.4.2, throughput becomes zero for two short time periods. The question that we would like to ask now is, which type of throughput loss is that? The answer for this question is to check the duration of the time interval where throughput is zero. If it is less than one second, as in the case of Figure-3.4.2, then it is the first type of throughput loss. The second type of throughput loss, *Throughput_Loss_{ospf}*, will last longer than one second. This is mainly because, Hello messages are sent at every 10 seconds, and there should be a Hello message exchange between the two routers, before throughput will be normal again.

Figure-3.4.2 First type of throughput loss

In the previous section, two OSPF related interface shut downs, at around times 740 and 3270 seconds, were shown in Figure-3.3.2. The corresponding RDI timer expirations for these interface shut downs were listed in Table-3.2. In the following figures, we will show the per-packet statistics collected for the corresponding throughput measurements for these interface shut downs. Figure-3.4.3 shows the throughput for the first interface shut down and Figure-3.4.4 shows for the second one. As we see from both figures, throughput is zero for 10-20 seconds of durations, which is much longer than the ones in previous figure, Figure-3.4.2, which were around 100-200 seconds.

Figure-3.4.3 Throughput loss associated with 1'st OSPF interface shut down.

Figure-3.4.4 Throughput loss associated with 2'nd OSPF interface shut down.

3.5 SNR versus Throughput Loss Analysis.

In previous chapter, SNR is expressed as follow:

$$SNR_{actual}[dB] = SNR_{base} + \Delta_{SNR_fading} = 10 + \Delta_{SNR_fading} \quad (3.1)$$

where,

$$SNR_{base} = 10 \log \frac{\text{Received_Power}(\text{without_taking_into_account_fading})}{(\text{Thermal} + \text{Accumulated} + \text{Interference})\text{Noise}}$$

Even tough SNR_{base} is constant and equal to 10dB, SNR_{actual} will not be constant, because of the continuously changing fading power. However, we have no control on fading power and fading power effect on SNR. In addition, SNR changes due to fading power will be too fast (in milisecond scale) and will not be of any value for us to observe OSPF interface shut downs, which occur in larger time durations (10-20 seconds scale).

In this section, we want to see, how throughput will be affected by different SNR_{base} values. For example, it can be assumed that, there is less background noise in our model, or transmitter powers are higher. Then the receivers will be less sensitive to fading, since SNR will be higher. In order to perform this study, we will introduce an adjustment value to SNR_{base} in Equation-3.1, as follows:

$$SNR_{actual}[dB] = SNR_{base} + \Delta_{SNR_fading} = 10 + \Delta_{SNR_fading} + \Delta_{SNR_base} \quad (3.2)$$

SNR_{base} is set to a constant value at the beginning of each simulation run and will stay constant during that simulation. Therefore, SNR_{actual} will be changing because of $\Delta_{SNR_{base}}$ in between different simulation runs, however, because of $\Delta_{SNR_{fading}}$ within a simulation run.

As we see from Figure-3.5.1, throughput decreases with decreasing SNR_{base} levels as expected. As SNR_{base} gets lower, there will be an average constant throughput loss, $Throughput_Loss_{fading}$, as explained in the previous sections.

Figure-3.5.1 Throughput on 802.11a link with 10, 8 and 5.5 dB SNR_{base}

Another observation is that, as SNR_{base} becomes 8 dB, there are three severe temporary throughput losses observed at times 1584, 2016, 2448 seconds. These severe throughput losses are the second type of throughput loss, $Throughput_Loss_{aspf}$. Therefore, we can conclude that as SNR_{base} gets lower, both types of throughput losses become more severe.

Although we have changed SNR_{base} values in this section in order to see its effects on throughput, SNR_{base} will be constant and equal to 10dB for the rest of our study, unless it is explicitly stated otherwise.

Chapter 4

FA-OSPF, FADING ADAPTED OSPF ROUTING ALGORITHM

4.1 Introduction

According to the observations made in the previous chapter, OSPF unnecessarily shuts down its interface when consecutive Hello messages are lost due to fading. This problem is a natural result of OSPF, which is not designed for wireless networks. When “Hello” messages are lost in a wireless fading media, as they are sent during temporary fading depths; OSPF considers them lost as a sign of a permanent problem. As a result, OSPF shuts down its interface whether or not there is an alternative link available. If there is an alternative link available, OSPF will reroute traffic on that link. If there is not any available, then traffic will stop. In either case, this problem will cause an increase in OSPF control traffic and throughput losses in user traffic. This will be explained in detail in this chapter.

The described problem is further analyzed and a new routing algorithm, FA-OSPF, is developed as a solution. FA-OSPF is a simple, but yet very effective and scalable solution, which will adapt standard OSPF to wireless fading environment. Performance comparison of FAOSPF and OSPF routing algorithms shows that, FAOSPF performs the same or much better in all scenarios.

4.2 Summary of Observations from Previous Sections.

There are two types of throughput loss. The first one is directly associated with fading. Whenever the received power level drops because of fading, so does the SNR that results in an increase in BER and loss in throughput. We consider this type of throughput loss as a natural result of fading. If OSPF changes its route decision based on this kind of throughput loss, this will be a desired behavior.

The second type of throughput loss happens when OSPF shuts down its router interface, when consecutive OSPF Hello messages are sent and lost by chance during fading depth intervals. Relative timing of sending Hello messages to the fading occurrences, determines whether the consecutive Hello messages will happen to be lost during fading depths. Duration of this type of throughput loss can be up to 10-20 seconds. Fading depth intervals are temporary and for very short time durations. If OSPF shuts down its interface due to lost Hello messages, this will be an undesired behavior. Since:

- Fading depth occurs for a very short time period and although Hello messages happen to be sent during fading depth interval, fading will be over soon while OSPF is still trying to find new routes.
- It will result in this router to calculate new routes to the destination and perform link state advertisements. As a result, there will be extra OSPF traffic in the network, which will use extra bandwidth.
- Traffic will be stopped until the router converges to a stable point again.

4.3 Standard OSPF Algorithm

Figure-4.3.1 shows a scenario, when four consecutive Hello messages sent by router-2 to router-1 are lost in wireless media. Hello send interval is 10 seconds and router dead interval is 40 seconds.

Figure-4.3.1 OSPF Performance in Fixed Wireless Media with Fading.

OSPF protocol by default works as follows: Whenever a Hello message arrives from a neighbor, router resets its RDIT (Router Dead Interval Timer) for that neighbor. In our example, RDIT is reset at time 16 seconds and will expire 40 seconds later at 56 seconds.

If any other Hello message arrives within 40 seconds, then RDIT will reset again. In our study, these periodically send Hello messages will be named as PHS (Periodic Hello Send). In standard OSPF protocol all Hello messages are PHS. If no Hello messages are being received during RDI interval, RDIT expires and the router shuts down its interface. As we see from the above figure, four consecutive Hello messages that are sent from Router-2 to Router-1, by chance occur at the same time as fading depths and lost on their way. This happens exactly at times, 26, 36, 46 and 56 seconds. As a result, RDI timer expires at 56 seconds and the neighbor goes to down state. After this point routers will not be able to communicate until they re-exchange new Hello messages. For simplicity in this example, no Hello messages, sent by router-1 to router-2 will be lost.

Hello messages are being sent periodically by the router interfaces, and interfaces may have more than one neighbor connected to this interface. In our topology, each router has only one neighbor per interface. Therefore, when we say the neighbor is down, this actually also means interface to this neighbor is shut down, a valid statement for our topology.

If we return to the example, given in Figure-4.3.1, it is possible for RDIT to expire with only three lost Hello messages instead of four. This will happen if the Hello message sent at 56 arrives, after RDI expires at router-1. RDIT is set when the first Hello message that is sent at time 16 seconds. If any of the following Hello messages sent at times 26, 36 or 46 seconds has a delay, Hello message sent at time 56 will be delayed too. As a result,

this Hello message will be received by Router-2, unfortunately milliseconds after RDIT expiration. Therefore, it is possible for RDIT to expire after 3 consecutive lost Hello messages, instead of 4 consecutive lost Hello messages, depending on link delays.

As we see in this section, if the router doesn't get four consecutively send Hello messages sent by its neighbor, it shuts down its interface, whether the Hello messages are lost due to optical link congestion or wireless fading. It has been explained in the previous section that, if the source of the problem is wireless fading, for this router to shut down its interface is an undesired behavior.

4.4 Solution Proposal: Introduction of PRDI Timer.

In this section, a modification to OSPF routing algorithm will be developed in such a way that, OSPF will know the reason why OSPF messages are being lost. That is, either because of link congestion, or because of fading. If it is because of link congestion, there will be no change in the way OSPF works. If it is because of fading, OSPF will not expire its RDI timer and will not close down its neighbor. This will be achieved as follows:

Each router will have PRDI (Partial Router Dead Interval) timer in addition to RDI (Router Dead Interval) timer. PRDI timer will be usually set to half or three quarters of normal RDI timer. Whenever a Hello message is received, OSPF will reset PRDI timer in addition to RDI timer. If "Hello" messages get lost, then PRDI timer will expire before RDI timer. This will give to the router some time to take action before shutting down its

interface. The router, at which PRDI expires, sends extra Hello messages other than periodic ones to take the attention of the other router that's not being heard of. Other router will respond by sending a Hello message back right away. This will reset the RDI timer and will prevent the interface from being shut down.

On the other hand, if there is no fading but link congestion, then, both routers or one of them, will not get the extra Hello message and RDI timer will expire at its normal time and the interface will be shut down. If previous Hello messages are being lost because of fading, then the Hello message will arrive at its destination since the probability of this additional Hello message being sent during a fading depth interval in addition to previous ones, is very low.

RDI interval is fixed and the same at both neighbors, once OSPF communication is up and running. Hello messages contain HSI and PRDI values, to make sure that routers are using the same OSPF timings. In our solution, PRDI value will be determined based on HSI and RDI values. Therefore, there is no need for routers to share PRDI value as well. As a result, there will be no change in the Hello message format with our solution.

The time difference between RDIT and PRDIT is the time interval that our solution should work to prevent OSPF shutting down its interface. In our formula, PRDIT is chosen, as close as possible to RDIT, but far enough to have enough time to prevent down state of neighbors. The reason to choose PRDIT as close as possible to RDIT is

that, we would like to give our system enough waiting time for receiving Hello messages, before starting the fading alert state. By choosing PRDIT as three quarter of RDIT in our formula, our model has a chance to check 3 consecutive Hello messages sent by the other neighbor. In our formula, one fifth of HSI is also added to this PRDIT interval, which is 2 seconds for 10 seconds of HSI. This safety margin is introduced in case 3rd Hello message is delayed because of link delays.

The following formula will be used to determine PRDI:

$$\text{PRDI} = (\text{RDI} * 3 / 4) + (\text{HSI} * 1 / 5); \quad (4.1)$$

For example, for typical HSI=10 seconds and RDI=40 seconds, PRDI will be:

$$\text{PRDI} = 40 * 3 / 4 + 10 * 1 / 5 = 30 + 2 = 32 \text{ seconds.}$$

PRDI can be calculated by any other formula, as long as, PRDI is a function of RDI and is less than RDI. On the other hand, the reason we decided to use the above formula specifically can be explained as follows:

- PRDI should be less than RDI, so that router will have a warning before RDI expires.
- PRDI should be large enough so that, router will get as many periodic Hello messages as possible, before PRDI expires. Therefore, PRDI will be in sleep mode and have no effect on the system unless it is necessary.
- PRDI is a function of HSI as well as RDI in our formula. If we didn't add one fifth of HSI, in our calculation, then PRDI would have expired exactly at the same time as when the third Hello message is received. By adding (HSI/5) amount of delay in PRDI

expiration, it will ensure that PRDI will not expire if third Hello message will be received.

Although there is one neighbor per router interface in our study, there may be more than one in a broadcast topology. Therefore, if the router can't get four consecutive Hello messages, it will close that neighbor, but will continue to send Hello messages to other neighbors from this interface. So, our solution has no control on and can't change the time of sending periodic Hello messages from this interface in accordance to OSPF protocol given in IETF standard, RFC 2328. If we did otherwise, we would be changing normal behavior of OSPF protocol.

Another important factor, to be considered in our solution model, is the relative timing of sending Hello messages from each router. That means both routers can send Hello messages either at the same time, or delta time apart. Our solution should work in all conditions independent of delta.

Finally, our solution should consider the more complicated case, when Hello messages from Router-2 to Router-1 also get lost because of fading.

4.5 Solution Implementation: FA-OSPF Algorithm

Figure-4.5.1 shows how our solution works. A new timer, PRDIT, is introduced, which is set in accordance to formula given in Equation 4-1. Our model works as follows:

If Router-2 does not hear from Router-1 for PRDI amount of time, PRDIT expires. Router-2 will schedule two extra Hello messages to be sent within the next (RDI-PRDI) time interval. These two extra Hello messages will have exactly the same message format as regular periodic Hello messages. Although, they have the same message format, they will be treated differently, according to their arrival time. For simplicity, we will call them as FAHS (Fading Alert Hello Send) messages.

Whenever a Hello message is received, routers will check if this is a PHS or FAHS. The only way for Router-1 to understand the difference between PHS and FAHS is to check the time difference between the previous and current Hello receive times, if it is less than HSI or not. In other words, check if more than one Hello message is received within a single HSI. If this is the case, Router-1 will know that, its neighbor has sent an extra Hello message to warn about no Hello messages have been received recently. Router-1 will schedule two response Hello messages, FARHS (Fading Alert Response Hello Send), independent of whether it got only one or both FAHS messages.

Figure-4.5.1 FAOSPF, Modified OSPF for Fixed Wireless Media with Fading.

In other words, Router-2 will schedule two response messages, once it gets the first FAHS message. These response messages will be scheduled as follows:

1'st FARHS message will be sent right away.

2'nd FARHS message will be scheduled as a back up to 1'st FARHS as follows:

After (1'st FARHS sent + $(HSI / 5)$) and before (next scheduled PHS time – $(HSI / 5)$)

The reason of adding $(HSI / 5)$ seconds after 1'st FARHS is that, there will be a safety gap between the two. That is, if one of them gets lost because of a fading depth, there will still be the second one. Each message has its own chances to arrive to Router-2 independent of each other.

The reason for subtracting $(HSI / 5)$ from next scheduled PHS time for determining the upper time limit of sending 2'nd FARHS is a safety gap to make sure that 2'nd FARHS will arrive to Router-2, before RDI expires. RDIT at Router-2 will expire approximately at the same time as the next scheduled PHS time at Router-1.

The reason for sending two FAHS and FARHS messages is that, in case one gets lost because of fading, there will be the second one to do the job. FAHS and FARHS, messages are extra messages scheduled by the neighbor and have nothing to do with periodic Hello messages scheduled by the interface. Periodic Hello messages will continue to be sent periodically unaware of the existence of FAHS and FARHS.

4.5.1 *Fading Alert State Flag*

It has been already explained how routers will differentiate PHS and FAHS messages. However, there is still the problem of how routers will differentiate between FAHS and FARHS messages. For example, let us consider the case when Router-2 PRDIT expires. Then, Router-2 will send two FAHS to Router-1. In return Router-1 will send two FARHS messages. There are two possible ways for Router-2 to continue:

- Assume that these are FARHS messages as a response to FAHS messages that have been sent before. Then, Router-2 will reset its PRDIT and RDIT timers as planned.
- Assume that these are FAHS messages sent by Router-1 to warn about fading conditions. In this case, Router-2 will schedule two response messages. Once Router-1 gets FAHS messages, Router-1 has two possible ways to continue. If Router-1 assumes that, these are FAHS messages it will schedule two FARHS messages. This is a loop condition, which will result in an infinite number of Hello messages sent back and forth between the two routers.

In order for routers to differentiate between FAHS and FARHS messages, FAS (Fading Alert State) flag will be used. Router-2 will set FAS flag to “ON” state, once its PRDIT timer expires. This flag will return to “OFF” state automatically independent of other messages, at $((\text{RDIT expiration time as scheduled}) + (\text{HSI} / 5))$. Here $(\text{HSI}/5)$ is a safety margin, to ensure that second FARHS is received before, FAS returns to “OFF” state.

Although RDI expiration time is used to determine FAS flag return to “OFF” state time, RDI may not expire and just get reset. Whatever happens to RDI, FAS state will go to “OFF” state as scheduled.

Router-1 will set its FAS flag to “ON” state, once it gets the first FAHS message. If this message gets lost on its way, then FAS flag will be on at arrival of second FAHS message. This flag will return to “OFF” state automatically at:

Time at next PHS scheduled + (HSI / 5)

FAS flag will be triggered to be “ON” depending on fading. On the other hand, returning to “OFF” state is automatic independent of fading. Another important point is that, this flag can be set to “ON” only if it was previously “OFF”. This feature will make routers differentiate between FAHS and FARHS messages. That is, the router will respond to extra Hello messages only if it is in FAS “OFF” state. Once it schedules FAHS or FARHS messages, the router will set FAS flag to “ON” state and will ignore the Hello messages coming thereafter, until FAS is “OFF” again.

Although routers will ignore Hello messages from fading mechanisms during FAS “ON” state, PRDI and RDI timers will continue to be reset at each Hello arrival. In other words, PRDI and RDI timers will reset independent of the source of Hello message, whether it is PHS, FAHS or FARHS.

4.5.2 Scheduling of Fading Alert Hello messages

It has been mentioned before that our model should work independent of the relative time positions of Hello messages sent by two routers. The relative position of Hello messages can be measured with “delta” amount of separation between them. If both routers are powered on at the same time and their OSPF protocols start at the same time with same HSI, then delta will be zero. Delta can be at most close to HSI. The reason for considering delta in our solution is to be able to send FAHS messages as apart as possible from PHS message. This way, the robustness of our system will increase against fading and the probability of one of these Hello messages, that is two FAHS and one PHS, arriving to the destination increases. This is the same analogy as, not to put all your eggs into one basket.

As explained before, the time interval for FAHS messages to be scheduled in, will be as follows:

After PRDI expiration and before (Time at RDI scheduled - $(HSI/5)$)

On the other hand, when two FAHS messages to be scheduled within this interval has not been explained yet. By considering delta, FASH scheduling will be as follows:

Case-1:

If next scheduled PHS is before than (Time at PRDI expired + $(HSI/3)$) then:

- 1'st FAHS is scheduled at $(\text{Time at PRDI expired} + (\text{HSI}/3) + (\text{HSI}/10))$
- 2'nd FAHS is scheduled at $(\text{Time at PRDI expired} + (\text{HSI}/3) + (\text{HSI}/5))$

Case-2:

If next scheduled PHS is before than $(\text{Time at PRDI expired} + (\text{HSI}/2))$ and not case-1, then:

- 1'st FAHS is scheduled at $(\text{Time at PRDI expired} + (\text{HSI}/5))$
- 2'nd FAHS is scheduled at $(\text{Time at PRDI expired} + (\text{HSI}/2) + (\text{HSI}/10))$

Case-3:

If next scheduled PHS is before than $(\text{Time at PRDI expired} + ((\text{HSI}/5)*4))$ and not case-1 or not case-2, then:

- 1'st FAHS is scheduled at $(\text{Time at PRDI expired} + (\text{HSI}/5))$
- 2'nd FAHS is scheduled at $(\text{Time at PRDI expired} + ((\text{HSI}/5) * 2))$

Case-4:

If not case-1, case-2 and case-3 then:

- 1'st FAHS is scheduled at $(\text{Time at PRDI expired} + (\text{HSI}/5) + (\text{HSI}/10))$
- 2'nd FAHS is scheduled at $(\text{Time at PRDI expired} + ((\text{HSI}/5) * 3))$

4.6 Performance Evaluation of FA-OSPF

4.6.1 FA-OSPF Performance with respect to Hello Send Start Times

Figure-3.3.1 in previous chapter presented throughput plots for different HSST (Hello Send Start Time) scenarios, by using default OSPF. The same scenarios plus additional ones (for HSST 16, 17, 18 19, 22) are repeated in this section by using FAOSPF. It has been observed that, severe throughput losses due to OSPF interface shut downs are eliminated by %100 at all scenarios, if FAOSPF is used instead of OSPF. That is, FA-OSPF works successfully to prevent unnecessary interface shut downs and consequent throughput losses. As an example, HSST=16 seconds scenario is shown in Figure-4.6.1

Figure-4.6.1 Throughput comparison with OSPF and FA-OSPF (HSST 16 seconds)

4.6.2 FA-OSPF Performance with respect to SNR

As can be seen from Figure-4.6.2a, $Throughput_Loss_{ospf}$ is totally eliminated at SNR_base 8 dB, by using FA-OSPF method. Figure-4.6.2b shows that, although not totally eliminated, $Throughput_Loss_{ospf}$ is eliminated %76 percent of the cases. As we see from Figure-4.6.2a and Figure-4.6.2b, as SNR decreases the efficiency of using FA-OSPF rather than OSPF increases.

Figure-4.6.2a Throughput with OSPF and FA-OSPF for 8 dB SNR_base

Figure-4.6.2b Throughput with OSPF and FA-OSPF for 5 dB SNR_base

4.6.4 Comparison of OSPF Statistics with FA-OSPF & OSPF

Figure-4.6.4a shows the router convergence time for both OSPF and FAOSPF. Router convergence time measures the time it takes for a router to update a routing update, calculate a new preferred route and forward traffic in that new route. In our study we are not interested in the router convergence times, but the total number of convergence activities performed. Number of router convergence activities, shows the number of OSPF interface shut downs happening in our model. For example in Figure-4.6.4a, OSPF has 18 route convergence activities, whereas FAOSPF has only 4. We didn't count the points before 150 seconds, since traffic is generated starting from 150 seconds in our model. As a result of this analysis, we can conclude that, FAOSPF has %75 less interface shut downs at SNR_base 5 dB.

Figure-4.6.4b shows the increase in FA-OSPF control traffic due to sending extra Hello messages. As we see from this figure, the increase in FAOSPF traffic is only 15 bits/sec, which can be considered completely negligible.

Figure-4.6.4a Router-1 Convergence Duration with OSPF and FA-OSPF

Figure-4.6.4b Router-1 OSPF traffic with OSPF and FA-OSPF

Chapter-5

ROUTING WITH OSPF AND FAOSPF

5.1 Introduction

In this chapter, a new topology with four routers connected to each other via 802.11a links, will be used. By using this topology, two more routers will be introduced and there will be two alternative paths between traffic source and destination. Therefore, routers will be able to route traffic on either path depending on link quality. Our purpose is to evaluate the performance of FA-OSPF with respect to OSPF by using this new topology.

5.2 Four Router Topology

Four routers topology is shown in Figure-5.1. There are two paths between traffic source and destination. Path-1 consists of wireless links, Link-1 and Link-2. Path-2 consists of wireless links, Link-3 and Link-4.

The same fading pattern is applied on all four links. Therefore, from routing point of view, all links and all paths are potentially equal. However, each wireless link and each direction for that link, is associated with a fading offset value. Fading offset value associated with a router interface, together with simulation time, will determine, the corresponding fading value on the 128 msec fading waveform. Therefore, each link will have a different fading value for a particular time. This way routing protocol may choose any one of the paths depending on link quality for that particular time. IP and MAC

address configurations of routers, as well as BSS configurations, are already given in chapter-1. On the other hand, randomly chosen fading offset values are configured in this section as given in Table-5.1. Only two WLAN interfaces per router are being used in our topology as showed in Figure-5.1.

Figure-5.1 Topology with four routers.

Table-5.1 Randomly assigned fading offset values at router interfaces.

	<i>Router-1</i>	<i>Router-2</i>	<i>Router-3</i>	<i>Router-4</i>
<i>Interface-1</i>	NA	NA	150000	40000
<i>Interface-2</i>	10000	50000	160000	4000
<i>Interface-3</i>	100000	200000	NA	NA

Constant packet rate and 1 Mbps UDP traffic is generated. UDP, MAC layer and routing protocol related statistics are measured to compare performance of OSPF and FA-OSPF protocols. For studies presented in this chapter, the following OSPF parameters are being used:

Table-5.2 OSPF Parameters

<i>OSPF Parameters</i>	
Start Time	5 seconds
Reference Bandwidth	1000Mbps
Hello Interval	10 seconds
Router Dead Interval	40 seconds
Interface Transmission Delay	1 second
Retransmission Interval	5 seconds

5.2.3 UDP Throughput with OSPF and FA-OSPF

Figure-5.2a and Figure-5.2b show end-to-end UDP throughput for OSPF and FAOSPF respectively. As we see from these figures $Throughput_Loss_{fading}$ is the same in both figures. On the other hand, $Throughput_Loss_{ospf}$ becomes a problem in OSPF scenario at 15 dB. Figure-5.2b shows that, $Throughput_Loss_{ospf}$, is totally eliminated in FAOSPF scenario. We have repeated the same throughput measurements for the same topology but with Link-4 failure. The resultant throughput plots for FAOSPF and OSPF are shown in Figure-5.3a and Figure-5.3b respectively. Link-4 scenario is shown in Figure-5.7.

Figure-5.2a UDP Traffic Received at Destination by using OSPF

Figure-5.2b UDP Traffic Received at Destination by using FA-OSPF

Figure-5.3a Link-4 Scenario: UDP Traffic Received at Destination by using OSPF

Figure-5.3b Link-4 Scenario: UDP Traffic Received by using FA-OSPF

As we see from previous figures, OSPF performs worse in terms of *Throughput_Loss_{ospf}*, in link-4 failure. This is an expected observation, because there is no alternative path available in link failure scenario, to forward traffic during OSPF interface shut downs. As we see from the last figure, FAOSPF does not suffer as much as OSPF does, since FAOSPF eliminates the OSPF interface shut down problem and does not need to forward traffic to an alternative path.

We can summarize our observations as follows:

- FA-OSPF improves UDP traffic about (5% at SNR_base 17dB and 17% at SNR_base 15dB) when there is no alternative path available to forward traffic.
- FA-OSPF improves UDP traffic (about 3% at SNR_base 15dB) when there is alternative path available.
- FA-OSPF never performs worse than OSPF, in any scenario. It either performs the same or better.
- FA-OSPF does not change the way it performs with link failure or without link failure. Therefore, FA-OSPF is more robust to link failures than OSPF. On the other hand, OSPF will cause oscillations by moving traffic back and forth between the paths.
- FA-OSPF behaves more predictable. Since it does not change routes unnecessarily.

In the previous figures, end-to-end traffic performance was observed without being aware of which path/paths were used by routers to route traffic during simulation.

Figure-5.4a and Figure-5.4b show the WLAN throughput at two interfaces on router-2, for OSPF and FAOSPF protocols respectively. These figures give us an idea about which paths were used to carry traffic. While FA-OSPF needs route changes only two times per hour, OSPF needs route changes seventeen times per hour. This gives a great advantage for using FA-OSPF over OSPF, since FA-OSPF will perform better than OSPF when there are no alternative links. Even if there are alternative links available, routing updates and link state advertisements will be minimized. This can be a considerable advantage, especially as the number of routers increase within the network.

Figure-5.4a WLAN throughput by using OSPF

Figure-5.4b WLAN throughput by using FA-OSPF

5.2.4 OSPF Statistics with OSPF and FA-OSPF

As we see from previous figures, FA-OSPF can prevent unnecessary route changes and improve UDP throughput especially for low SNR values. These route changes happen because of OSPF interface shut downs. In this section, the total number of OSPF shut downs will be compared for both FA-OSPF and OSPF for different SNR values, as shown in Figure-5.5. As we see from this figure, at 25 dB SNR_base, no interface shut downs are observed with both algorithms. On the other hand, at 20dB SNR_base OSPF has eight and FAOSPF has none. Therefore, at 20dB SNR FAOSPF prevented all interface shut downs. FAOSPF prevents unnecessary OSPF interface shut downs by up to

%90 at 17dB SNR_base. This is a considered a very serious improvement and shows that FAOSPF will perform superior than OSPF for SNR values lower than 20dB.

Figure-5.5 Total number of OSPF and FAOSPF Interface Shut Downs

Figure-5.6 shows the total OSPF and FAOSPF control traffic sent. Although FAOSPF algorithm is designed to send extra Hello messages, as we see from the figure, FAOSPF has less FAOSPF traffic. This is mainly because, FAOSPF prevents unnecessary OSPF interface shut downs, and consequent LSA and route updates. At 15 db SNR, FAOSPF sends %37 less traffic than OSPF according to the figure.

Figure-5.6 Total OSPF and FAOSPF Control Traffic Sent

5.3 Link Failure Scenario

In the previous section, we have already discussed about UDP throughput with both topologies, with and without link failure. Link failure topology is shown below in Figure-5.7, where one of the links, Link-4, has a link failure. Therefore, routers will not be able to route traffic by using Path-2.

Total number of OSPF and FAOSPF interface shut downs are shown in Figure-5.8. As we see from this figure, FAOSPF prevents all interface shut downs at SNR 17dB and 20dB. FAOSPF prevents interface shut downs by 73% for SNR 15dB.

Figure-5.7 Link Failure Scenario

Figure-5.8 Total number of OSPF and FAOSPF Interface Shut Downs

Chapter 6

CONCLUSIONS

6.1 Introduction

OSPF routing protocol was not originally designed for wireless networks and therefore, it does not consider wireless media limitations, such as fading. In our study, we have adapted OSPF in a wireless Rayleigh/Ricean fading environment. Our topology consists of wireless mesh routers connected to each other via 802.11a links.

In this chapter, an overall evaluation of our results, thesis contribution and potential research areas will be presented.

6.2 Summary of Results

OSPF can determine any change in link states by sending Hello messages periodically with constant intervals. When these Hello messages are sent by chance during fading depths OSPF shuts down its interface, assuming the link is congested or totally down. OSPF interface shut downs will result in user traffic interruption, increase in OSPF control traffic, unnecessary route changes and traffic oscillations between alternative paths.

FA-OSPF is developed in our study to prevent unnecessary OSPF interface shut downs. FA-OSPF does not change the way standard OSPF works, but makes some additions,

which will not conflict with standard OSPF. In this method, before router interface is shut down, the routing algorithm gets a warning, PRDI timer expiration. When PRDI expires, FA-OSPF will send extra Hello messages to prevent RDI expiration and interface shut down. If the source of the problem is wireless link fading, then, FA-OSPF prevents RDI expiration at most of the times. PRDI timer durations or scheduling of extra Hello messages can be modified according to network needs dynamically.

The disadvantage of our algorithm will be extra processing power to have additional new timer and state flag. We consider this problem negligible, considering the high processing power of routers. In addition, the processing power wasted in finding a new route and forming and advertising new LSA's without this new feature will be much more.

FA-OSPF does not introduce any new messages or states to IETF defined OSPF standard.

This will bring easy deployment and interoperability as follows:

- If two neighboring routers are running FA-OSPF, then both routers will be using the advantages of FA-OSPF.
- If one of the routers is using FA-OSPF and the other one is using OSPF, then both routers will run as if both of them were using OSPF. None of the routers will be able to use the advantages of FA-OSPF. The router, which runs FAOSPF, will be sending FAHS messages to the other router as a warning of fading, but they will have no effect on the other router, other than resetting RDI timer.

In summary, FA-OSPF is a very simple but yet effective solution, which improves the network performance under wireless fading environment. The advantages of our algorithm can be summarized as follows:

- There will be no OSPF message format change with our algorithm.
- OSPF interface timers do not change.
- Unnecessary route changes due to fading will be prevented.
- Our algorithm does not bring extra traffic load to the system, since sending four more OSPF Hello message will not cause considerable increase in traffic.
- FAOSPF actually decreases the OSPF control traffic, by preventing OSPF interface shut downs and consequent LSA and route updates.
- Our algorithm will not cause any problem if one of the routers has this new feature but the other not. This will bring easy deployment.
- FAOSPF adapts itself dynamically to changes in OSPF timers.
- Our solution is not interface based but neighbor based. Therefore, it is applicable to any kind of OSPF interfaces, such as point-to-point, point to multipoint or broadcast.
- Efficiency of using FAOSPF increases at lower SNR values, when there are more OSPF interface shut downs.

6.3 Contribution of Thesis

- * According to our study, FA-OSPF prevents total number of OSPF interface shut downs by up to %70-100. As a result consequent LSA and route updates are eliminated resulting in %16-37 decrease in total OSPF control traffic. This is considered a very significant improvement. One of the biggest challenges in future wireless mesh networks is the scalability problem [5]. That is as number of nodes increases, the performance of the network decreases drastically. We are considering our algorithm, FAOSPF, a very important step in solving scalability problem of future wireless mesh networks.
- * FAOSPF is more stable and reliable than OSPF, by preventing router interface shut downs, and consequent oscillations in traffic, caused by moving traffic back and forth between alternative paths.
- * FAOSPF improves throughput by preventing OSPF interface shut downs and consequent packet loss, especially when there is no alternative path available to forward traffic.
- * Although 802.11a links are used in our study, FA-OSPF can be effectively used with any other underlying physical layer technology. In addition, other routing algorithms, which use keep-alive messages like OSPF does, can benefit from FAOSPF technique.

6.4 Future Research Areas

- * During our study, it has been observed that, with Rayleigh/Ricean fading, the MAC layer delays increase considerably, as a result of high queue lengths and packet drops. It is anticipated in our study that there is a potential to increase network performance under fading by improving queuing techniques.

- * In our study, network topologies with either two routers or four routers have been used. It will be interesting to observe FA-OSPF performance with a larger network that consists of a larger number of routers.

- * Our study evaluates FA-OSPF performance in fixed wireless environment. It will be interesting to observe how it performs in a mobile wireless environment where fading will be much more severe.

- * Although 802.11a links are used in our study, we believe in that FAOSPF is applicable to any wireless media with wireless fading. Therefore, it will be interesting to evaluate the performance of FAOSPF in other wireless technologies, such as 802.16 or cellular. In addition, our algorithm can be adapted to any other routing protocol other than OSPF, as long as, both routers send periodic keep-alive messages to each other.

* FA-OSPF provides a tool for network engineers or service providers to obtain information about the network condition by observing statistical behavior of PRDI and RDI expirations. For example, observation of an increase in the number of PRDI expirations can be a warning on the increase in wireless fading or mobility. The information that can be obtained from PRDI and RDI timers may have a tremendous effect on future heterogeneous networks that we can't even forecast today.

APPENDIX-1

Throughput and BER Plots at Times When Hello Messages Got Lost.

Figure-A1 Throughput at when 2'nd Hello message sent (of first RDI expiration).

Figure-A2 Throughput at when 3'rd Hello message sent (of first RDI expiration)

Figure-A3 Throughput at when first Hello message sent (of 2'nd RDI expiration).

Figure-A4 Throughput at when 2'nd Hello message sent (of 2'nd RDI expiration)

Figure-A5 Throughput at when 3'rd Hello message sent (of 2'nd RDI expiration).

Figure-A6 Throughput at when 4'th Hello message sent (of 2'nd RDI expiration)

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