State-based channel selection in multi-channel wireless networks

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In this thesis, we present an innovative scheme to favor the selection of $M$ out of $N$ available high-performing channels in multi-channel wireless networks through the application of states to individual channels. One channel selection scheme is random selection, which can lead to poor network performance when one or more data channels are disadvantaged. This is due to the inability of random selection to discriminate between high performing and disadvantaged channels. The novel proposed channel selection scheme is shown to perform nearly as well as the highest performing of $N$ channels when one or more channels are disadvantaged. We develop a Markov-chain-based theoretical model and then present simulation results validating a significant performance increase of the proposed channel selection scheme.
STATE-BASED CHANNEL SELECTION IN MULTI-CHANNEL WIRELESS NETWORKS

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ABSTRACT

In this thesis, we present an innovative scheme to favor the selection of $M$ out of $N$ available high-performing channels in multi-channel wireless networks through the application of states to individual channels. One channel selection scheme is random selection, which can lead to poor network performance when one or more data channels are disadvantaged. This is due to the inability of random selection to discriminate between high performing and disadvantaged channels. The novel proposed channel selection scheme is shown to perform nearly as well as the highest performing of $N$ channels when one or more channels are disadvantaged. We develop a Markov-chain-based theoretical model and then present simulation results validating a significant performance increase of the proposed channel selection scheme.
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### LIST OF ACRONYMS AND ABBREVIATIONS

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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgment Message</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
</tr>
<tr>
<td>CSMA/CD</td>
<td>Carrier Sense Multiple Access with Collision Detection</td>
</tr>
<tr>
<td>CTS</td>
<td>Clear to Send</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MACA</td>
<td>Medium Access Collision Avoidance</td>
</tr>
<tr>
<td>MACAW</td>
<td>Medium Access Collision Avoidance Wireless</td>
</tr>
<tr>
<td>MSG</td>
<td>Data Message</td>
</tr>
<tr>
<td>OQPSK</td>
<td>Orthogonal Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RTS</td>
<td>Request to Send</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>$\beta$</td>
<td>The Transition Threshold</td>
</tr>
<tr>
<td>$C$</td>
<td>The Dynamic Counter</td>
</tr>
<tr>
<td>$\psi$</td>
<td>The Credit Score</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>The Exponential Back Off Timer</td>
</tr>
</tbody>
</table>
The Number of Channel Selection Combinations in an $M \times N$ System

$K$

The Number of Channel Selection Combinations for a State in the Markov Chain in an $M \times N$ System

$K_G$

The Credit Score Threshold

$\kappa$

The Number of Selected Channels

$M$

The Total Number of Channels

$N$

The Number of Good Channels

$N_B$

The Number of Good Channels

$N_G$

Overhead

$\Omega$

The Probability of Successful Transmission

$\rho$

The Improvement Counter

$\Phi$

The Performance in a State of the Markov Chain

$\tau$
EXECUTIVE SUMMARY

In recent years, advances in computing and communication technologies have resulted in smaller, faster, economical and more reliable network devices that enable communication with rapid, efficient information exchange among mobile users. In a tactical or emergency response environment, units require a network that can support data exchange and collaboration on the move. Due to the harsh electromagnetic environment (e.g., weather, terrain features, jamming, interference and manmade obstructions) in tactical or emergency response scenarios, networking challenges include high latency, low bandwidth and poor reliability. Battlefield and emergency response networks have a rapidly changing fluid network infrastructure, where a traditional architecture may not be applicable. The flexibility of wireless networks makes them an attractive networking option for tactical and first responder operations.

Wireless networks do have inherent limitations compared to traditional wired networks, which include bandwidth optimization, power control, transmission quality and limited battery life. Network performance can be impacted unless the network has the flexibility to detect environmental anomalies and recover. A potential scheme of dealing with a harsh environment to increase the rate of successful transmissions for wireless networks is to divide the allocated spectrum into multiple channels. Multi-channel wireless networks can exploit frequency diversity, and capacity is no longer limited to a single channel. As demand for wireless networks in tactical, emergency response and other harsh environments increases, the broad application of multi-channel systems will become more prevalent, along with requirements for increased services.

The aim of this thesis is to develop, theoretically model, and simulate a novel scheme to favor selection of high-performing channels when selecting $M$ of $N$ or $M \times N$ channels. We call this scheme state-based channel selection, which utilizes channel quality to place channels in either a good or bad state. Channels identified as being in a good state are eligible for selection by the scheme. Channels identified as being in a bad state are not eligible for selection but monitored for improvement.
Other schemes that attempt to address the $1\times N$ channel selection problem were explored in previous research. One scheme explored is random channel selection, where channels are selected in a pseudorandom fashion from the set of all channels without regard to channel quality. When one or more data channels are disadvantaged, random selection performs poorly. Significant improvements in network performance were achieved in this thesis by using state-based channel selection. A theoretical model using a Markov chain was developed to analyze the performance of state-based channel selection. Next, simulation models using MATLAB and QualNet are utilized to validate the performance of the proposed channel selection scheme. Results in this thesis demonstrate that network performance approaches the average probability of successful transmission of the highest performing channels in a system.

We made four major contributions in this thesis. We introduced a novel concept we call state-based channel selection. We introduced the challenge of $M\times N$ channel selection. A theoretical model is developed to analyze the performance of state-based channel selection using a Markov chain for $M\times N$ systems. We validated that state-based channel selection performs better than random channel selection through simulation of $M\times N$ wireless networks.
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor, Dr. Murali Tummala. His mentorship, guidance and knowledge have been invaluable in completing this thesis and my graduate education. His ideas brought significant credibility and refinement to this thesis. He is someone whom I profoundly respect and hope to maintain both a professional relationship and friendship with long after I have completed my master's degree.

I would like to thank my co-advisor, Dr. John McEachen, whose support of my research and knowledge transferred in classes made this thesis possible. This thesis is a reflection of the consistent high standards he sets and the knowledge he imparts on students.

Most of all, I would like to thank my wife, Stephanie, and three children, Brent, Makenzie and Sienna, for their encouragement, understanding and patience over the past several years. Your support has been a blessing and I appreciate it.
I. INTRODUCTION

In recent years, advances in computing and communication technologies have resulted in smaller, faster, economical and more reliable network devices that enable communication with rapid, efficient information exchange among mobile users. The flexibility of wireless networks makes them an attractive networking option for tactical and first-responder operations. In a tactical or emergency response environment, units require a network that can support data exchange and collaboration on the move. Due to the harsh electromagnetic environment (e.g., weather, terrain features, jamming, interference and manmade obstructions) in tactical or emergency response scenarios, networking challenges include high latency, low bandwidth and poor reliability [1], [2]. In particular, ad hoc wireless networks depend on minimal to no established infrastructure; therefore, they can be deployed in harsh and dynamic tactical environments [3]. Battlefield and emergency response networks have a rapidly changing fluid network infrastructure, where a traditional architecture may not be applicable [3], [4].

Compared to wired networks, wireless networks do have inherent tradeoffs, such as bandwidth optimization, power control, transmission quality and limited battery life [4], [5]. Network performance can be impacted unless the network has the flexibility to detect environmental anomalies and recover [3]. A potential scheme of dealing with a harsh environment to increase the rate of successful transmissions for a wireless network is to divide the allocated spectrum into multiple channels [1], [5], [6]. Multi-channel wireless networks can exploit frequency diversity, and capacity is no longer limited to a single channel [1], [2], [6].

As demand for wireless networks in tactical, emergency response and other harsh environments increases, the broad application of multi-channel systems will become more prevalent along with requirements for increased services. We present a novel scheme for establishing states to make channel selection decisions to improve performance in environments where one or more channels are disadvantaged. The
scheme has the potential to increase overall network performance enhancing the ability of tactical and emergency responders to complete their missions.

A. RELATED WORK

Single channel and multi-channel wireless networks share many common fundamentals with a few minor differences. Single channel networks must resolve how to share the transmission medium efficiently and fairly. Multi-channel networks must share the transmission medium efficiently and fairly but also must synchronize and select which channel to share. Methods of node coordination and channel selection in multi-channel networks and schemes for channel selection were explored in [6], [7] and [8]. Frequency hopping time division multiple access (TDMA), multi-transceiver and dedicated control channel approaches are used for node coordination [6], [7]. Each of these schemes has protocols for synchronizing a common communication channel between nodes [6], [7], [8]. A common process in each of these protocols is channel selection between nodes, which impacts system performance.

Wormsbecker and Williamson [8] presented three schemes of interest. First, a random channel selection scheme is presented as a method to fairly distribute traffic across all channels. In this scheme, channels are randomly selected from among \(N\) possible channels. Second, a lowest channel available scheme is presented. In this scheme, the lowest channel available is selected and varies with respect to network demand. A challenge that both of these methods suffer from is that they select channels regardless of performance; therefore, the potential of a high retransmission rate exists in cases where one or more channels are disadvantaged. Third, a soft channel reservation scheme, where each node remembers the channel it most recently had a successful transmission, is presented. In this scheme, if the channel that was last used successfully is unavailable, two solutions exist. One solution is to choose an available channel randomly and the other is to select the lowest numbered channel that is available. The soft reservation scheme suffers from the fact that in cases where the last channel selected becomes disadvantaged or when multiple nodes request the same channel, performance degrades to that of random or lowest channel first schemes.
Wormsbecker and Williamson’s three schemes exhibit suboptimal performance due to an inability to discriminate between high performing and disadvantaged channels in a multi-channel wireless network [8]. These schemes consider the challenge of coordinating one of \( N (1 \times N) \) channel selection where one data channel is selected from \( N \) channels. In this thesis, we investigate the challenge of coordinating \( M \) of \( N (M \times N) \) channel selection where \( M \) channels are selected from among \( N \) available channels.

B. OBJECTIVE AND APPROACH

The objective of this thesis is to develop and demonstrate a channel selection scheme that performs better than random channel selection when one or more channels are disadvantaged. We first consider \( 1 \times N \) channel selection and then expand upon our findings and apply the scheme to \( M \times N \) channel selection.

We propose a new scheme called state-based channel selection, which selects high performing channels while ignoring disadvantaged channels in an effort to increase system performance. A theoretical model is developed for both random and state-based channel selection using a Markov chain to analyze system performance prior to implementation. Finally, random selection and state-based schemes are implemented in a series of Rayleigh fading channel simulations.

C. THESIS ORGANIZATION

Medium access control (MAC) considerations are presented in Chapter II their application in single and multi-channel wireless networks are reviewed. The motivation for the development of a new channel selection scheme due to poor performance associated with random selection is introduced in and the proposed scheme, state-based channel selection, is presented in Chapter III. A Markov-chain-based model for state-based channel selection is developed in Chapter IV. Results of state-based channel selection are presented in Chapter V. Results are compared against random selection demonstrating a performance increase by state-based channel selection. The findings of this thesis and recommendations for future research on this topic are discussed in Chapter VI. The appendices include source code for calculations and simulations.
II. MEDIUM ACCESS CONTROL CONSIDERATIONS

The performance of multi-channel wireless networks is evaluated by modifying the MAC layer with the proposed state-based channel selection scheme and comparing the performance to random channel selection. Attenuation, shadowing, jamming and multipath effects due to reflection, refraction and scattering can cause one or more channels to be disadvantaged in a multi-channel network [1], [8]. The multipath effects of reflection, refraction and scattering are affected by the terrain, weather and manmade structures [1], [5]. Jamming can be caused intentionally by an adversary or through interference from friendly capabilities [1], [5]. These channel impairments, which are quite common in tactical or emergency response wireless networks, are illustrated in Figure 1.

![Figure 1. Effects of propagation and interference in wireless networks that can negatively impact performance (After [5]).](image)

In traditional single channel networks, the MAC layer coordinates when a node may access the medium, whereas in multi-channel networks nodes, must also synchronize the channel they will communicate on [6], [7]. Selecting and synchronizing the channel nodes communicate on poses a challenge in multi-channel networks and can
drastically impact network performance [6], [7]. In the following sections, we discuss single and multi-channel MAC protocols which are used to mediate access to the wireless medium. Our discussion of multi-channel MAC protocols will include multiple transceiver, frequency-hopping, time-division and dedicated control channel approaches [6]. Given these approaches of node synchronization, we apply random and state-based channel selection schemes to compare their performances in subsequent chapters. We conclude the chapter by introducing the concept of a Gilbert-Elliot channel, which we will apply in order to create the state-based channel selection scheme.

A. SINGLE CHANNEL MEDIUM ACCESS PROTOCOLS

The wireless medium is a shared broadcast medium and requires a mechanism to mediate access. A wireless channel is time-varying and asymmetric due to multipath propagation and fading [1], [9]. Accordingly, the wireless medium can be thought of as a set of half-duplex links [9]. The links are error prone and susceptible to burst errors [2], [4]. MAC protocols negotiate which node has the ability to transmit on the medium at any given time.

Traditionally, in networks MAC protocols are established for negotiating access to one shared channel. MAC protocols are either contention based whereby nodes compete for usage of the medium or are contention-free whereby a centralized node negotiates rules that dictate how nodes use the medium. The most notable single channel contention based MAC protocols are ALOHA [10], Slotted Aloha [11], Carrier Sense Multiple Access (CSMA) [12], Multiple Access with Collision Avoidance (MACA) [13], and MACA Wireless (MACAW) [14]. The most notable contention-free MAC approaches for single channel systems are time-division multiple access (TDMA), frequency-division multiple access (FDMA), code-division multiple access (CDMA) and space-division multiple access (SDMA) [1], [9]. Each of these MAC protocols are discussed in detail in [1], [2], [3] and [9]. In the next section we will discuss methods of node coordination which use these protocols in multi-channel wireless networks.
B. MULTI-CHANNEL MEDIUM ACCESS CONTROL PROTOCOLS

Multi-channel networks add a degree of freedom to wireless communications networks [6], [7]. The immediate benefit that can be reaped is an increase in spatial reuse by accommodating simultaneous transmissions [7]. Multi-channel wireless networks can also exploit frequency diversity, and capacity is no longer limited to a single channel [6], [7]. However, challenges surface with the use of multiple channels. In single channel networks, MAC protocols only need to decide when the channel is suitable for communication to reduce the likelihood of collisions between nodes in the medium [5], [7]. When multiple channels are available, a source-destination pair must select and be synchronized to a common idle channel before attempting a transmission [6], [7]. This is due to a hardware limitation where a transceiver cannot be tuned to more than one channel simultaneously [7]. The goal of coordinating nodes is to minimize collisions during data transmission to avoid delay and unnecessary energy usage during transmission.

There are four main approaches to handle coordination of multiple channels amongst multiple nodes. First, in frequency-hopping schemes, devices hop between frequencies to coordinate which nodes use which channels given a shared strategy [6]. Second, in time-division approaches, nodes use allotted time slots to communicate based upon a shared scheme [6]. Third, there are multiple transceiver approaches in which nodes can receive on multiple channels simultaneously [6]. Finally, in dedicated control channel approaches, one channel is continuously monitored for control packets to coordinate nodes [6], [7].

1. Frequency-Hopping Approach

In this approach, a device has only one half-duplex transceiver. Devices exchange data by cycling through all channels synchronously. In proposed frequency-hopping solutions, a pair of devices will stop hopping as soon as they make an agreement for transmission [15], [16]. The devices rejoin the hopping pattern after transmission ends [6], [7]. These schemes require a tight clock synchronization which is the common disadvantage of these approaches. Synchronization can be challenging and requires
network resources to be maintained [1], [2]. In this thesis, we will not analyze how frequency-hopping approaches operate; but assuming that synchronization can occur, we assume that these systems are appropriate for $M \times N$ channel selection.

2. Time-Division Approach

In this approach, only a single transceiver is needed. Time is divided into an alternating sequence of control and exchange phases [6]. During a control phase, all nodes tune to the control channel and make negotiations for channels to be used during the following data exchange phase [6]. During the data exchange phase, all nodes that have been assigned data channels transmit on corresponding channels [6]. All channels can be available for transmission in the data exchange phase. The advantage of this approach is that it requires only one radio per node; however, it requires time synchronization, which is a challenge [6]. This approach also suffers from the same problem it does in a single channel approach, namely, at low normalized throughputs it is quite inefficient [6], [9]. In this thesis we will not explore how time-division approaches operate, but assuming that a centralized node can synchronize nodes in wireless networks, we assume that these systems are appropriate for $M \times N$ channel selection.

3. Multiple Transceiver Approach

In this approach, each node is equipped with two or more transceivers. One transceiver is dedicated to exchanging control messages and the others to data messages [7]. It is assumed that the number of channels is equal to the number of transceivers on each node. Control messages are sent on the control transceiver, and data channels are negotiated between nodes. The key drawback of this approach is the requirement of more than one transceiver on each node increasing both the cost and size of nodes [7]. This approach is largely impractical given constraints that are often placed on the cost and size of network devices. In this thesis, we will not investigate how multiple transceiver approaches operate, but assuming that nodes with multiple transceivers exist, these systems are appropriate for $M \times N$ channel selection.
4. **Dedicated Control Channel Approach**

In a dedicated control channel approach, nodes have one tunable transceiver and a channel is dedicated to the transmission of control packets. Channels used for transmitting data are negotiated between nodes on this channel. The major advantages of these approaches are that they do not require time synchronization, require no centralized coordination of nodes and no additional hardware [6], [7]. The disadvantage is that it requires a dedicated control channel, decreasing spectral efficiency when few channels are available, and if the control channel is not working, the entire system may fail [7]. We will describe this approach as a frame of reference for our work and assume that the scheme can be applied for $M \times N$ channel selection. The next two sections provide a description of a dedicated control channel approach and its operation.

**C. DEDICATED CONTROL CHANNEL**

1. **Physical Layer**

The physical layer used by a multi-channel wireless network with a dedicated control channel has one control channel and $N$ data channels. A visual of depiction of a multi-channel wireless network spectral band with a dedicated control channel is shown in Figure 2. The control channel is used to pass control messages for the coordination of nodes. The data channels are agreed upon through the passing of messages in the control channel, tuned to and used for information exchange in a session.

![Multi-channel network spectral band with a dedicated control channel and $N$ data channels.](image)

Figure 2. Multi-channel network spectral band with a dedicated control channel and $N$ data channels.
2. Medium Access Control Layer

Consider a multi-channel wireless network in which nodes implement a packet-based protocol shared over $N$ radio frequency (RF) channels in a half-duplex manner. One of these channels is used solely as a control channel, and $N$ other channels are used only for data [17], [18]. The behavior of a transaction sequence of events between nodes that coordinate communication between them referred to as a session is displayed in Figure 3 [17]. A successful session consists of four sequential operations. First, the data source node transmits a Request-to-Send (RTS) packet on the control channel after first assuring the control channel is not in use by another node [17], [18]. The RTS packet, containing both the receiver’s addressing information and a selected data channel assignment, is received by all receiving nodes in range including the desired destination node. A channel selection request can be made for $M \times N$ data channels. Once transmission of the RTS is complete, the source node waits to receive on the control channel.

![Figure 3](image)

Figure 3. A transaction sequence of events in a multi-channel wireless network for a session (From [17]).

Next, the destination node (whose address matches that provided in the RTS packet) switches from receive mode to transmit and transmits a Clear-to-Send (CTS) packet on the control channel. This packet is received by the source node, indicating that the destination node has heard the transmission request and is switching over to the assigned data channel(s) to receive the actual data. Once transmission of the CTS is complete, the destination node switches immediately to receive and tunes to the assigned data channel(s) [17], [18].

The source node, upon receiving the CTS packet, tunes to the assigned data channel(s), switches to transmit mode, and begins sending Message Data (MSG) packets.
that contain the data. The MSG packet is of variable length, depending on the quantity of data. Included in the MSG packet is a packet size descriptor, which allows the destination node to determine when the MSG is complete. Once MSG is complete, the source node switches immediately to receive on the assigned data channel(s) [17], [18].

Finally, the destination node, upon completion of MSG reception, switches to transmit mode and transmits an Acknowledgement (ACK) packet on the assigned data channel, indicating successful reception. Once transmission of the ACK is complete, the destination node switches immediately to receive and tunes back to the control channel to await/initiate further transactions. Once ACK is received by the source node, it tunes back to the control channel in receive mode as well [17], [18]. Once the ACK is received, the source node considers the transmission a success and can begin its next session when it has data to send. In the next section we introduce Gilbert-Elliot channels, which can be applied to multi-channel systems.

D. GILBERT-ELLIOIT CHANNELS

A Gilbert-Elliot channel is a channel that can either exist in various defined states. The Gilbert-Elliot channel is modeled using a Markov chain with between two and $L$ states. The generalized Markov chain of a Gilbert-Elliot channel where $p_{si}$ is the probability of a successful transmission and $p_{fi}$ is the probability of a failed transmission. The relative values of $p_{si}$ and $p_{fi}$ control the transition rates between the states is illustrated in Figure 4.

![Figure 4. Generalized Markov chain of a Gilbert-Elliot channel of $L$ states demonstrating the ability to transition to and from various states.](image-url)
We applied the Gilbert-Elliot channel assuming \( L = 2 \) to multi-channel networks with \( N \) channels. Illustrated in Figure 5 is a model of the Gilbert-Elliot channel for \( L = 2 \). We refer to the two states of the Gilbert-Elliot channel as good and bad, representing a burst-noise binary channel [19]. In the good state, transmission is almost error-free, and in the bad state the channel has a small probability of transmitting successfully [19]. When the channel is in the good state it transitions to the bad state with a probability that is equal to \( p_f \) or stays in the good state, with a probability equal to \( p_s \) [19]. When the channel is in the bad state, there is a probability of staying a bad state equal to \( p_f \) and a probability of transitioning to the good state with a probability equal to \( p_f \) [19]. State-based channel selection uses this concept to place \( N \) channels in either the good or bad state to make selection decisions.

![Markov chain of a Gilbert-Elliot channel assuming \( L = 2 \) with defined states as good and bad (From [19]).](image)

In this chapter, we first discussed single channel MAC protocols highlighting their purpose to negotiate which node can access the channel at the right time. We then highlighted that multiple channel wireless networks must not only resolve the proper timing of channel usage but must also select and synchronize which channels are used between nodes. Four coordination approaches, namely frequency hopping, time division, multiple transceiver and dedicated control channel, were then briefly discussed as potential solutions for \( M \times N \) channel selection systems. Finally, we introduced the concept of Gilbert-Elliot channels, which can be applied to make channel selection decisions. In subsequent chapters, we will explore the inefficiency of random channel selection, present a new scheme, state-based channel selection, and compare the relative performances.
III. STATE-BASED CHANNEL SELECTION

The centerpiece of the research effort of this thesis is the proposal of an innovative approach to wireless channel selection that is rooted in the notion of favoring selection of high performance channels in a multi-channel wireless network. We formally introduce the novel, state-based channel selection scheme in this chapter.

To lay the groundwork for the state-based approach, we begin by identifying the channel selection requirements in a multi-channel wireless network. We then examine the performance of random channel selection and demonstrate that it performs poorly in environments where one or more channels are disadvantaged. Next, we introduce the novel scheme state-based channel selection. Finally, we present flow charts codifying the state-based channel selection scheme to facilitate implementation. In later chapters, we will present both theoretical modeling and simulation results of this new channel selection scheme.

A. MULTI-CHANNEL MEDIUM ACCESS CONTROL CHANNEL SELECTION REQUIREMENTS

We begin the examination of channel selection requirements in a multi-channel wireless network. Recall from Chapter II that the scheme can be applied to frequency-hopping, time-division, multiple transceiver and dedicated control channel approach systems. A multi-channel wireless network MAC can select $M$ of $N$ channels to exchange data between nodes where

$$1 \leq M \leq N$$

which we denote as $M \times N$ channel selection.

Lost transmissions result in high network latency, increased retransmissions, energy inefficiency and decreased throughput [4], [5]. Performance of each data channel can be determined by defining the probability of successful transmission for channel $i$ as

$$\rho_i = \frac{S}{T}, \quad 0 \leq \rho_i \leq 1$$
where \( S \) is the number of successful transmissions and \( T \) is the total number of transmissions in a data channel. Thus, it is desirable for a channel to have a large value of \( \rho_i \).

Each node in a wireless network has a sequence of \( N \) probability of successful transmission values corresponding to \( N \) data channels. Nodes can select up to \( M \) data channels given a \( M \times N \) selection criteria during a session resulting in \( K \) possible combinations of channel selections equal to [20]

\[
K = \binom{N}{M} = \frac{N!}{M!(N-M)!}.
\]  

(3)

The probability of successful transmission for a wireless network \( \rho \) by a node given \( M \times N \) random channel selection is given by

\[
\rho = \frac{1}{K} \sum_{i=1}^{K} (\rho_1 \ldots \rho_M), \quad 0 \leq \rho \leq 1
\]  

(4)

where \((\rho_1 \ldots \rho_M)\) is a combination of \( M \) probabilities of transmission success for selected channels \( i \). For the \( 1 \times N \) selection case, Equation (4) simplifies to

\[
\rho = \frac{1}{N} \sum_{i=1}^{N} \rho_i.
\]  

(5)

The metric used to compare the performances of different multi-channel MAC channel selection schemes against each other in this thesis is defined by (4).

**B. RANDOM CHANNEL SELECTION**

Random channel selection is the process of selecting channels for communication between nodes at random without regard to performance. The motivation for a new scheme is the poor performance of random channel selection given a harsh network operational environment [8]. For the purposes of calculations in this thesis, when a channel is referred to as disadvantaged \( \rho_i = 0.001 \) and, in high performing channels, \( \rho_i = 0.999 \). To demonstrate the challenge of random channel selection, consider a \( M \times 8 \) wireless network that can have between one and eight disadvantaged channels. Using
Equations (4) and (5) while varying the number of disadvantaged channels and the number of channels selected $M$, we quantify the inefficiency of random selection in Figure 6.

Figure 6. $\rho$ for an eight channel ($N = 8$) wireless network while varying the number of disadvantaged channels and number of selected channels $M$.

The results demonstrate that as the number of disadvantaged channels increase using random channel selection, $\rho$ decreases due to an inability to identify and favor high performing channels. As the number of disadvantaged channels increases, $\rho$ decreases. When $M > 1$, the probability of successful transmission decreases rapidly as $M$ becomes larger. Clearly, a desirable attribute of a new scheme would be the ability to avoid selection of disadvantaged channels.

A proposed channel selection solution should provide a higher probability of successful transmission than the random selection scheme. The scheme should distinguish between disadvantaged and high performing channels, favoring selection of high performing channels. The new scheme should operate as well or better than random
channel selection when either all channels or none are performing well. When a subset of data channels is disadvantaged, the scheme should perform better than random channel selection, rapidly recognizing when a channel has become disadvantaged. Finally, a proposed scheme should not prematurely recognize a disadvantaged channel as high performing.

In the next section, state-based channel selection is introduced and the concept of Gilbert-Elliot channels discussed in Chapter II to multi-channel wireless networks is applied. This will allow for discrimination of channels based upon performance using metrics to make channel selection decisions.

C. STATE-BASED CHANNEL SELECTION

We now formally introduce the proposed scheme we call state-based channel selection. The main idea behind state-based channel selection, which is discrimination of channels based upon historical performance through the application of Gilbert-Elliot channels, is displayed in Figure 7. We assume each of $N$ channels in a multi-channel wireless network is an independent Gilbert-Elliot channel with $L = 2$ as discussed in Chapter II. Two vectors are created corresponding to the channel states good and bad. The good channel vector is $N_G$ in length where $N_G$ is the number of good channels. The bad channel vector is $N - N_G$ in length. Channels are monitored for performance and categorized as either disadvantaged or high performing. High performing channels are placed in the good channel vector, while disadvantaged channels are placed in the bad channel vector. Channel selection decisions in the scheme are based upon this categorization. Up to $M$ Channels from the good channel vector are randomly selected to initiate a transmission, while channels in the bad channel vector are not eligible for selection but are monitored for improvement.
Figure 7. State-based channel selection discriminates between good and bad channels placing them into their respective vectors.

State-based channel selection has two primary modes of operation, normal operation and the transition state as depicted in Figure 8. In normal operation the state-based channel selection scheme selects channels randomly from a vector of good channels while monitoring transmissions for errors. In the transition state, the scheme monitors channels in the bad channel vector for improvement placing channels which have improved into the good channel vector and then returns to normal operation.

Figure 8. State-based channel selection top level interaction of the normal operation state and transition state.

1. Parameters

A set of parameters are now introduced in order to describe the operation of the proposed state-based channel selection scheme. An $N$ valued integer sequence defined as the credit score $\psi$ with a value corresponding to each of the channels is initially set to its maximum value $\psi_{\text{max}}$. The credit score values have a range of

$$0 < \psi_i \leq \psi_{\text{max}}.$$  

The credit score provides an overall measure of performance for data channels. Next a parameter, the credit score threshold $\kappa$, which has the range

$$0 < \kappa \leq \psi_{\text{max}} - 1.$$  

17
is set to the desired value. The function of the credit score threshold is to indicate when to place disadvantaged channels into a bad state or when to transition an improving channel to a good state. Channel $i$ is considered in the good state if it satisfies the relationship

$$\psi_i \geq \kappa.$$  

(8)

Conversely, channel $i$ is considered to be in a bad state if

$$\psi_i < \kappa.$$  

(9)

The transition threshold $\beta$ is used to set the number of transmissions which occur before the scheme enters the transition state. The transition threshold is set to the range

$$2N \leq \beta \leq 10N.$$  

(10)

The transition threshold is established greater than $2N$ to ensure that the scheme operates long enough to identify disadvantaged channels and less than or equal to $10N$ to prevent the scheme from starving out improving channels. This range was established through experimentation. In conjunction with $\beta$, a parameter, the dynamic counter $C$, is initially set to zero. At the conclusion of each session, $C$ is incremented by an integer value of one until $\beta = C$, at which time the scheme enters the transition state where it can check for improvements in channels. Upon exiting the transition state, $C$ is set back to zero. These relationships imply that that the dynamic counter is in the range

$$0 \leq C \leq \beta.$$  

(11)

The improvement counter $\Phi$ is an $N$ member sequence which keeps track of the number of sessions for each channel since that channel’s credit score last improved by an integer value of one. The improvement counter for the $i^{th}$ channel $\Phi_i$ is incremented by one if the credit score $\psi_i$ does not improve for a session. If the credit score $\psi_i$ does improve, the improvement counter reset to zero. Given that the number of sessions is $Z$, the improvement counter for a channel $i$ takes values in the range

$$0 \leq \Phi_i \leq Z.$$  

(12)

An exponential back off timer $\Gamma_i$ is used to limit the number of test packets sent when monitoring disadvantaged channels for performance increases and takes the range

$$\beta \leq \Gamma_i \leq 2^n \beta.$$  

(13)
where \( n_i \) is the number of times the channel has entered the transition state without improvement in the channel’s credit score and is given by

\[
n_i = \frac{\Phi_i}{\beta}.
\]

(14)

The parameter \( n_i \) should be limited to a finite value because a channel can rapidly be starved out of use if it remains in a bad state for a long duration since the back off timer is exponential.

At the conclusion of the initialization of the scheme, nodes must synchronize using frequency hopping, TDMA or a multiple transceiver scheme discussed in Chapter II. If a dedicated control channel implementation is used, then synchronization between nodes occurs between each transmission session using the decentralized process outlined in Chapter II.

2. Normal Operation

Normal operation is the mode of operation where communication between nodes takes place and the credit score \( \psi_i \) is decremented when transmission errors occur. Once \( M \) selected available channels from the good channel vector are selected, transmission between nodes occurs. If the session fails to complete successfully, then the credit score for channel \( i, \psi_i \), is decremented by an integer value of one. If the session is successful, then the credit score stays at the same integer value it held prior to the session. If there are fewer channels in the good vector than the number of selected channels \( M \), then channels are randomly selected on the entire set of channels from the bad channel vector. The process of channel negotiation between nodes continues iteratively, consistent with the system synchronization scheme. When a channel has experienced enough failed transmissions and the credit score falls below the credit score threshold for channel \( i \), then channel \( i \) is added to the bad channel vector. At the conclusion of each session, the dynamic counter is incremented by an integer value of one, and the process iteratively continues beginning with checking for available channels in the good channel vector. Normal operation ends when the transition threshold and the dynamic counter are equal and the scheme enters the transition state, which is discussed in the next section.
3. State-Based Channel Selection Transition State

The transition state is the mode of operation where channels are tested for improvement. Once in the transition state, the dynamic counter is set back to zero. To limit overhead, channels currently in a good state have their credit score updated by an integer value of one rather than sending a test packet to check for improvement on a good channel. For these channels the values of $\psi_i$, $\Phi_i$ and $\Gamma_i$ are updated as follows:

$$
\psi_i \leftarrow \psi_i + 1, \quad \psi_i \leq \psi_{\text{max}} \\
\Gamma_i \leftarrow \beta \\
\Phi_i \leftarrow 0
$$

(15)

The $\psi$ should not be incremented above $\psi_{\text{max}}$ regardless of performance to protect a channel from accumulating large of a credit score. Channels that are in a bad state $(\psi_i < \psi_{\text{max}})$ and with

$$
\Phi_i < \Gamma_i
$$

(16)

keep their current credit score and are not checked for improvement. For these channels the values of $\psi_i$, $\Phi_i$ and $\Gamma_i$ are updated as follows:

$$
\psi_i \leftarrow \psi_i \\
\Gamma_i \leftarrow \Gamma_i \\
\Phi_i \leftarrow \Phi_i + \beta
$$

(17)

Channels that are in a bad state and with

$$
\Gamma_i \geq \Phi_i
$$

(18)

have a test packet sent to check for improvement through the successful transmission of the packet. Upon confirming a successful transmission in the channel values of $\psi_i$, $\Phi_i$ and $\Gamma_i$ for these channels are updated using Equation (15). If the test packet is unsuccessfully received, the values of $\psi_i$, $\Phi_i$ and $\Gamma_i$ for these channels are updated using the following relationships:

$$
\psi_i \leftarrow \psi_i \\
\Gamma_i \leftarrow 2\Gamma_i \\
\Phi_i \leftarrow \Phi_i + \beta
$$

(19)

The scheme then leaves the transition state and returns to normal operation. The process of iteratively fluctuating between normal operation and the transition state continues for
the duration of network operation. Next, we present flow charts that define the processes described in this chapter in a simplified format.

4. Flow Charts

The state-based channel selection scheme described in the preceding sections can be represented by flow charts. Displayed in Figure 9 is a general description of state-based channel selection in the form of a flow chart. How the general flow chart can be modified to accommodate the dedicated control channel node synchronization scheme as a frame of reference is illustrated in Figure 10. Similar modifications can occur for frequency hopping, TDMA and multi-transceiver approaches. The flow charts provide a concise understanding of the operation and assist with planning for implementation of the state-based channel selection scheme.
Figure 9. General state-based channel selection flow chart codifying the scheme into an easily comprehensible format.
In this chapter, we introduced a novel state-based channel selection scheme for multi-channel wireless networks. We examined the poor performance of random channel selection and presented an alternative by applying the concept of state-based channel selection. Flow charts were provided to aid in understanding the state-based channel selection operation and to facilitate its implementation. In the next chapter, we present a theoretical model to determine the performance of the proposed scheme.
IV. STATE-BASED CHANNEL SELECTION THEORETICAL ANALYSIS

In Chapter III, we formally introduced the novel scheme of state-based channel selection. A theoretical model of state-based channel selection to verify the scheme’s performance prior to simulation is described in this chapter.

Theoretically modeling state-based channel selection is achieved by applying a special case of the Markov chain. By finding limiting state probabilities associated with states in the Markov chain, one can model the performance of the scheme [20]. First, generalized forms of the model are presented. The model is then applied to an $M \times 8$ channel wireless network to demonstrate a performance analysis of the system. An expanded description of the Markov chain and MATLAB source code for theoretical results presented in this chapter is contained in Appendix A.

A. A MARKOV-CHAIN-BASED MODEL FOR STATE-BASED CHANNEL SELECTION

Using a special condition for a Markov chain, we model state-based channel selection. Assuming that one limits the change in time to a small interval, we can focus solely on the transitions of a Markov chain, specifically the transition rates of the system [20]. The goal of modeling the system as a Markov chain is to find the limiting state probabilities, which imply that a steady state is reached where one can associate a probability of being in a state at a given time [20].

An $N$ channel wireless network can be modeled as an $N + 1$ state Markov chain with a generalized form displayed in Figure 11, referred to as the transition rate diagram [20]. The Markov chain begins in state 0, corresponding to no channels in the good state in the system and transitions up to state $N$ representing $N$ channels in the good state in the system. We define $\mu_i$ as a transition rate to a state in the Markov chain with fewer channels in the good state or as the channel degradation rate. We define $\lambda_i$ as the transition rate to a state with more channels in the good state or as the channel improvement rate. The parameter $i$ in this figure equals $N - 1$. State-based channel
selection begins with the assumption that all channels are in good state by initializing the credit score to the maximum value $\psi_{\text{max}}$. To properly model the scheme, we modify Figure 11 by reversing the order of states assuming the scheme begins in state $N$ as illustrated in Figure 12.

![Figure 11](image)

**Figure 11.** The generalized form of a transition rate diagram for a Markov birth death process (From [20]).

![Figure 12](image)

**Figure 12.** The generalized form of a transition rate diagram for state-based channel selection. (After [20]).

In normal operation, the scheme decrements the number of channels in the good state as errors are detected, and there is no opportunity for the scheme to detect improving channels. The implication is that $\mu_i$ represents normal operation because it is the transition rate to a state in the Markov chain with fewer channels considered in the good state. The channel degradation rate is defined as

$$
\mu_i = \sum_{j=1}^{i-1} \prod_{k=1}^{N} \rho_k^{b_k} (1 - \rho_k)^{|i-b_k|}, \ i = N, N-1, \ldots, 2, 1
$$

(20)
where \( b_{jk} \) is an element of the \( \left( \frac{N}{i-1} \right) \times N \) array \( B_{i-1} \) of binary combinations of \( i \) in an \( N \)-bit word where a binary one represents a high performing channel and a zero represents a disadvantaged channel. When \( N = 4 \) and \( i = 3 \), the array is given by

\[
B_2 = \begin{bmatrix}
0 & 0 & 1 & 1 \\
0 & 1 & 0 & 1 \\
0 & 1 & 1 & 0 \\
1 & 0 & 0 & 1 \\
1 & 0 & 1 & 0 \\
1 & 1 & 0 & 0
\end{bmatrix}.
\] (21)

Consider that during the mode of operation referred to as the transition state, the scheme monitors for improvement in channels in the bad state. Therefore, \( \lambda \) represents the mode of operation called the transition state because \( \lambda \) is the transition rate to a state in the Markov chain with more channels considered in the good state. The channel improvement rate is defined as

\[
\lambda_i = \frac{1}{\beta} \sum_{j=1}^{N} \prod_{k=1}^{N} \rho_k^{b_{jk}} (1 - \rho_k)^{1-b_{jk}}, \quad i = 0, 1, \ldots, N-1
\] (22)

where \( b_{jk} \) is an element of the \( \left( \frac{N}{i+1} \right) \times N \) array \( B_{i+1} \) and \( \beta \) is the period at which the scheme checks for improvement in disadvantaged channels. When \( N = 4 \) and \( i = 2 \), the array is given by

\[
B_3 = \begin{bmatrix}
0 & 1 & 1 & 1 \\
1 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 \\
1 & 1 & 1 & 0
\end{bmatrix}.
\] (23)

Once steady state conditions are reached in a Markov chain, we have [20]

\[
\sum_{i=0}^{N} p_i = 1
\] (24)

where \( p_i \) is the limiting state probability of being in state \( i \). The limiting state probabilities for a Markov chain can be computed recursively using [20]
\[ p_{i+1} = \frac{\lambda_i}{\mu_{i+1}} p_i, \quad i = 0,1,\ldots,N \]  
and Equations (20), (22) and (24). From the limiting state probabilities and possible named states between 0 and \( N \), the expected number of good channels we define as \( N_G \) may be calculated using [20]

\[ N_G = E[N_S] = \sum_{i=0}^{N} ip_i \]  
(26)

where \( N_s \) is defined as the numbered state of the Markov chain.

Recall from Equation (3) that each node can select up to \( M \) data channels given an \( M \times N \) selection system during a session. This resulted in \( K \) possible combinations of channel selections for random selection. In state-based channel selection, we limit the channels that can be selected to \( N_G \), the number of good channels in a given state of the Markov chain. Therefore, we define the number of possible combinations of channel selections for a given state of the Markov chain in an \( M \times N \) wireless network as

\[ K_G = \binom{N_G}{M} = \frac{N_G^!}{M^!(N_G-M)!}. \]  
(27)

Each state of the Markov chain has number of channels it considers in the good state, so each state has its own mutually exclusive probability of successful transmission. Given an \( M \times N \) channel selection system for each state in the Markov chain there is a probability of successful transmission for a given state \( j \) in the Markov chain we refer to as \( \tau_j \) defined as

\[ \tau_j = \begin{cases} 
\frac{1}{K} \sum_{i=1}^{K} (\rho_1 \ldots \rho_M), & \text{for } j = 0, N \\
\frac{1}{K_G} \sum_{i=1}^{K_G} (\rho_1 \ldots \rho_M), & \text{for } j \neq 0, N 
\end{cases} \quad 0 \leq \tau_j \leq 1 \]  
(28)

where \( (\rho_1 \ldots \rho_M) \) is a random combination of \( M \) channel probability of successful transmission values corresponding to the set of good channels in a given state. For \( 1 \times N \) selection criteria, Equation (28) simplifies to
State-based channel selection incurs overhead we define as $\Omega$, resultant from checking if channels are improving when test packets are sent in the transition state. The parameter $N_B$ is defined as the number of bad channels, and the scheme enters the transition state at a frequency of $1/\beta$ with $N_B$ bad channels at that time. In the best case, no packets are sent because all channels are in a good state when $N_B = 0$. In the worst case, a test packet must be sent for every channel in the bad state assuming $N_B = N$. Due to these relationships, the range of overhead is defined as

$$0 \leq \Omega \leq \frac{N_B}{\beta}$$

where $N_B$ is the number of bad channels in a system. Combining Equations (25), (28) and (30) the probability of successful transmission for the system using state-based channel selection, may be defined as

$$\sum_{i=0}^{N} p_i \tau_i - \Omega \leq \rho \leq \sum_{i=0}^{N} p_i \tau_i \quad 0 \leq \rho \leq 1.$$ 

Equation (31) represents the sum the product of the limiting state probabilities with the performance of the scheme in the respective state with the overhead subtracted from the result. In the worst case, $\Omega = N_B / \beta$ is subtracted from $\rho$, and in the best case $\Omega = 0$ is subtracted from $\rho$.

In this section, a Markov chain was developed and equations presented that allowed performance analysis comparison of state-based to random channel selection given a $M \times N$ system. The remaining sections of this chapter present an $M \times 8$ numerical example to compare the performance of random to state-based channel selections.
B. AN EIGHT DATA CHANNEL SYSTEM EXAMPLE

In this section, the calculations for the Markov-chain-based model are obtained for a 1×8 channel selection case to demonstrate how the equations are applied. First, we calculate the probability of successful transmission for the 1×8 system where two data channels are disadvantaged for both random and state-based channel selection. Then, we calculate the respective probability of successful transmission for the 1×8 system where four channels are disadvantaged to show how the transition rates change in the Markov chain. Finally, we provide the graphical results of an $M \times 8$ wireless network while increasing the value of $M$.

1. 1×8 System With Two Disadvantaged Channels

Assume that a 1×8 wireless network exists and that two data channels are disadvantaged while the other six data channels are high performing. Disadvantaged channels are assumed to have $\rho_i = 0.001$, while the remaining high performing channels have a $\rho_i = 0.999$. Parameters for the scheme are $\psi_{\text{max}} = 10$, $\kappa = 5$, and $\beta = 40$, which are consistent with values outlined in Chapter III. The example physical layer with assumptions for this system is provided in Figure 13.

![Figure 13](image)

Figure 13. An eight channel system with two disadvantaged channels (red) and six high performing channels (green) for 1×8 selection.

The first step in analyzing this system is to evaluate how one would expect it to operate given random channel selection. For the system presented in Figure 13, applying Equation (5), we get $\rho = 0.749$. As expected, using random selection with two of eight channels disadvantaged and $M = 1$, approximately one-quarter of the transmissions are in
error. To begin the analysis of state-based channel selection, the first step is to draw the Markov chain from the generalized form presented in Figure 12. The transition rate diagram for an eight channel system with two disadvantaged channels is illustrated in Figure 14. Values of $\lambda_i$ and $\mu_i$ are obtained from Equation (22) and are listed in Table 1 and Table 2.

![Figure 14. Transition rate diagram for an eight channel system with two disadvantaged channels and six high performing channels.](image)

**Table 1.** The transition rates to higher numbered states in the Markov chain.

<table>
<thead>
<tr>
<th>Transition Rate to a Higher State ($\lambda_i$)</th>
<th>Numerical Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_7$</td>
<td>$5 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\lambda_6$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\lambda_5$</td>
<td>$0.05$</td>
</tr>
<tr>
<td>$\lambda_4$</td>
<td>$3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\lambda_3$</td>
<td>$7.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$\lambda_1$</td>
<td>$7.5 \times 10^{-14}$</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>$10^{-15}$</td>
</tr>
</tbody>
</table>

**Table 2.** The transition rates to lower numbered states in the Markov chain.

<table>
<thead>
<tr>
<th>Transition Rate to a Lower State ($\mu_i$)</th>
<th>Numerical Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_8$</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mu_7$</td>
<td>$0.992$</td>
</tr>
<tr>
<td>$\mu_6$</td>
<td>$6 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mu_5$</td>
<td>$1.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mu_4$</td>
<td>$2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\mu_3$</td>
<td>$1.5 \times 10^{-11}$</td>
</tr>
<tr>
<td>$\mu_2$</td>
<td>$6 \times 10^{-16}$</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>$10^{-17}$</td>
</tr>
</tbody>
</table>
Next, we used Equations (24) and (25) to find the limiting state probabilities of the Markov chain. We solved for the limiting state probabilities by taking values from the transition rate diagram and applying them to Equation (25). Listed in Table 3 are the algebraic expressions in terms of $p_0$ for the limiting state probabilities.

Table 3. Limiting state probabilities algebraic expressions in terms of $p_0$ obtained by solving Equations (24) and (25).

<table>
<thead>
<tr>
<th>Limiting State Probability ($p_i$)</th>
<th>Algebraic Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>299.7 $p_0$</td>
</tr>
<tr>
<td>$p_2$</td>
<td>37425 $p_0$</td>
</tr>
<tr>
<td>$p_3$</td>
<td>2.49×10^6 $p_0$</td>
</tr>
<tr>
<td>$p_4$</td>
<td>9.3×10^5 $p_0$</td>
</tr>
<tr>
<td>$p_5$</td>
<td>1.87×10^9 $p_0$</td>
</tr>
<tr>
<td>$p_6$</td>
<td>1.55×10^8 $p_0$</td>
</tr>
<tr>
<td>$p_7$</td>
<td>1.55×10^6 $p_0$</td>
</tr>
<tr>
<td>$p_8$</td>
<td>38.9 $p_0$</td>
</tr>
</tbody>
</table>

Recursively solving for the limiting state probabilities for states zero through eight, the results are summarized in column two of Table 4. Solving for the performance associated with each state in the Markov chain using Equation (29), we get column three of Table 4. As can be seen, since two channels are disadvantaged, state-based channel selection almost exclusively operates in states five or six, which is what one would expect.
Table 4. The limiting state probabilities and average performance in each state for a 1×8 system with two disadvantaged channels.

<table>
<thead>
<tr>
<th>State ( i )</th>
<th>Limiting State Probability ( (p_i) )</th>
<th>Probability of successful transmission ( (\tau_i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.7×10^{-11}</td>
<td>0.749</td>
</tr>
<tr>
<td>1</td>
<td>1.7×10^{-8}</td>
<td>0.999</td>
</tr>
<tr>
<td>2</td>
<td>2.1×10^{-6}</td>
<td>0.999</td>
</tr>
<tr>
<td>3</td>
<td>1.4×10^{-4}</td>
<td>0.999</td>
</tr>
<tr>
<td>4</td>
<td>5.3×10^{-3}</td>
<td>0.999</td>
</tr>
<tr>
<td>5</td>
<td>0.106</td>
<td>0.999</td>
</tr>
<tr>
<td>6</td>
<td>0.888</td>
<td>0.999</td>
</tr>
<tr>
<td>7</td>
<td>8.9×10^{-3}</td>
<td>0.714</td>
</tr>
<tr>
<td>8</td>
<td>2.2×10^{-9}</td>
<td>0.749</td>
</tr>
</tbody>
</table>

Solving Equation (26), we find the expected number of good channels in this system equals 5.882. Then solving Equation (31) using the values from Table 4, we obtain the overall probability of success of transmission in an eight data channel system with two disadvantaged channels using state-based channel selection to be between 0.898 ≤ \( \rho \) ≤ 0.998. Next, we consider an eight channel system with four disadvantaged channels.

2. \( 1 \times 8 \) System With Four Disadvantaged Channels

The channel frequency bands given a scenario where four of eight channels are disadvantaged is illustrated in Figure 15.

![Figure 15](image-url)
Using the process outlined in the previous section, we get the transition rate diagram shown in Figure 16. By inspection, transition rates into state four are larger than the others, demonstrating that increasing from two to four disadvantaged channels results in a shift from state six to state four as expected since there are four high performing channels for this scenario.

![Transition rate diagram](image)

Figure 16. Transition rate diagram for an eight channel system with four disadvantaged channels and four high performing channels.

The limiting state probabilities and probability of successful transmission for states zero through eight are summarized in Table 5. Since four channels are disadvantaged, state-based channel selection almost exclusively operates in states three or four as expected.

Table 5. The limiting state probabilities and average performance in each state for a $1 \times 8$ system with four disadvantaged channels.

<table>
<thead>
<tr>
<th>State $i$</th>
<th>Limiting State Probability ($p_i$)</th>
<th>Probability of successful transmission ($\tau_j$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$1.5 \times 10^{-7}$</td>
<td>0.500</td>
</tr>
<tr>
<td>1</td>
<td>$2.9 \times 10^{-3}$</td>
<td>0.999</td>
</tr>
<tr>
<td>2</td>
<td>$2.2 \times 10^{-1}$</td>
<td>0.999</td>
</tr>
<tr>
<td>3</td>
<td>0.074</td>
<td>0.999</td>
</tr>
<tr>
<td>4</td>
<td>0.923</td>
<td>0.999</td>
</tr>
<tr>
<td>5</td>
<td>$1.8 \times 10^{-4}$</td>
<td>0.799</td>
</tr>
<tr>
<td>6</td>
<td>$1.4 \times 10^{-8}$</td>
<td>0.666</td>
</tr>
<tr>
<td>7</td>
<td>$4.6 \times 10^{-13}$</td>
<td>0.571</td>
</tr>
<tr>
<td>8</td>
<td>$5.8 \times 10^{-18}$</td>
<td>0.500</td>
</tr>
</tbody>
</table>
We find the expected number of good channels in this system equals 3.922 by solving Equation (26). Using the values from Table 5 and applying them to Equation (31), we get the overall probability of success of transmission in an eight data channel system with four disadvantaged channels using state-based channel selection to be between $0.898 \leq \rho \leq 0.998$. The results for both the two and four disadvantaged channel scenarios for a $1 \times 8$ system verify that state-based channel selection performs better than random channel selection. Given random channel selection, the performance of the system when two and four channels were disadvantaged was $\rho = 0.749$ and $\rho = 0.5$, respectively. However, state-based channel selection results in a range of $0.898 \leq \rho \leq 0.998$ in both scenarios.

Examining all scenarios from zero to eight disadvantaged channels in a $1 \times 8$ system, we obtain the results illustrated in Figure 17. As the number of disadvantaged channels increases, $\rho$ decreases more rapidly for random selection than for state-based selection. As was discussed in Chapter III, the two schemes operate nearly the same when either zero channels are disadvantaged or all of the channels are disadvantaged. The sharp decline in performance from seven to eight disadvantaged channels occurs because, when there are no channels in the good state vector, the scheme randomly selects disadvantaged channels from the bad channel vector. This behavior is observed throughout the results in this thesis. These results demonstrate state-based channel selection performs better when a subset of the channels are disadvantaged.
Figure 17. A comparison on the effect of increasing the number of disadvantaged channels on $\rho$ between random and state-based channel selection for a $1 \times 8$ system.

C. AN $M \times 8$ SYSTEM EXAMPLE

The previous section provided an example of the application of theoretical equations to a $1 \times 8$ system. In this section, we vary the number of disadvantaged channels between zero and eight in an $M \times 8$ system while varying $M$ between one and four to explore the effect on system performance. The relative performances of an $M \times 8$ wireless network using random selection as $M$ is varied from one to four are compared in Figure 18. Initially, when $M = 1$ the probability of successful transmission decreases with a negative linear relationship. For $M > 1$ the relationship approaches a negative exponential decrease in the probability of successful transmission.
Figure 18. The theoretical effect of increasing the number of disadvantaged channels in $M \times 8$ system using random selection for $M = 1$ through $M = 4$.

The relative performances of a wireless network using state-based selection as $M$ is varied from one to four are compared in Figure 19. State-based channel selection is seen to have a higher value of probability of successful transmission than random selection given that a subset of $N$ channels is disadvantaged. For both state-based and random channel selection when $M > N_G$, the probability of successful transmission is near zero because there are not enough high performing channels to successfully transmit. The implication is that when

$$M \geq N_G$$

is satisfied, the performance of state-based channel selection is higher than random selection. When Equation (32) is satisfied and a subset of channels is disadvantaged, state-based channel selection performed comparably regardless of the value of $M$. 

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Figure 19. The theoretical effect of increasing the number of disadvantaged channels in $M \times 8$ system using state-based selection for $M = 1$ through $M = 4$.

A theoretical model for characterizing the behavior of state-based channel selection using a Markov chain was developed in this chapter. Next, a $M \times 8$ system was analyzed varying the number of disadvantaged channels while also varying the value of $M$ from one to four. We obtained a theoretical improvement by state-based channel selection over random selection. In the next chapter, we present simulation results to validate the theoretical model presented in this chapter.
V. SIMULATION

In this chapter, MATLAB and QualNet simulations are developed to validate the superior performance of state-based compared to random channel selection in multi-channel wireless networks. We begin with a brief discussion of the simulation model. We then simulate the $M \times 8$ system presented in Chapter IV to validate the theoretical results. We further explore the effect of parameters on system performance through simulation. The basic method for obtaining results in this chapter is based on a Monte Carlo simulation by repeating simulations over 1000 times. This method was applied for both random selection and state-based channel selection. Appendix B includes all source code for the simulations in this chapter.

A. SIMULATION MODEL

The basic scenario we simulate is presented in Figure 20. The simulation assumes there are between two and $N$ data channels in the system. Each of the transmission channels is a Rayleigh fading channel to be consistent with what is expected for mobile wireless networks with a harsh electromagnetic environment [1], [5]. The set of data channels in the system can either be high performing or disadvantaged.

![Figure 20. The simulation scenario which includes between two and $X$ nodes with between two and $N$ data channels between nodes.](image_url)
A schematic of the simulation model is provided in Figure 21 that is used for both random selection and state-based schemes. First, input is generated consisting of random bit streams of ones and zeros 1000 bits long for each packet sent and 1000 packets are sent for each session. Then the input is modulated using orthogonal quadrature phase-shift keying (OQPSK). Channels are selected using the respective channel selection function, either random or state-based. Next, we inject additive white Gaussian noise (AWGN) into Rayleigh transmission channels to change the signal-to-noise ratio (SNR) which in turn controls whether channels are high performing or disadvantaged. SNR is defined as [1]

\[ SNR = \frac{P_r}{P_i}. \]  

(33)

where \( P_r \) is the power transmitted and \( P_i \) is the sum of the noise and interference power present in the channel. The received signal is demodulated and checked for errors.

The channel bit error rate (BER) of the Rayleigh transmission channels a function of the SNR is illustrated in Figure 22. For OQPSK, theoretical (blue curve) and simulated (red discrete points) results are shown.
Figure 22. The BER for OQPSK of Rayleigh transmission channels used in simulations illustrating theoretical versus simulated results.

The behavior of a state-based channel in the model is displayed in Figure 23. Recall that state-based channels should rapidly identify declining channel performance while slowly improving to minimize transmission errors as discussed in Chapter III. The disadvantaged channel (red curve) rapidly decrements $\psi$ each time it is selected, resulting in a steep drop. The improving channel (blue curve) slowly increments $\psi$ at a rate established by $\beta$ represented by the horizontal sections of the curve. The simulation model and demonstrated the behavior a state-based channel were described in this section. A comparison of the simulated results of random versus state-based channel selection will be presented in the next section.
Figure 23. The state-based channel selection scheme results in a channel which rapidly transitions to a bad state when disadvantaged (red curve) while slowly returning to a good state when improving (blue curve).

B. \( M \times 8 \) SELECTION

In this section, we discuss the simulation of the \( M \times 8 \) channel selection system investigated in Chapter IV to validate the theoretical results. We first present the results of a \( 1 \times 8 \) system and then analyze the effect of increasing \( M \), on the system comparing simulated and theoretical results. For the \( M \times 8 \) system \( \psi_{\text{max}} = 10 \), \( \kappa = 5 \), and \( \beta = 40 \). We used an SNR of 0 dB for disadvantaged channels and an SNR of 25 dB for high performing channels. Nodes had a relative motion of 1 m/s.

1. \( 1 \times 8 \) Performance

The effect on the probability of successful transmission in a \( 1 \times 8 \) channel selection system of increasing the number of disadvantaged channels from zero to eight is displayed in Figure 24. The simulated and theoretical results closely match. As the number of disadvantaged channels increases, the probability of successful transmission decreases more rapidly for random selection than for state-based selection. The two schemes operate nearly the same when either none of the channels are disadvantaged, or
all of the channels are disadvantaged. State-based channel selection performs better when a subset of the channels are disadvantaged which agrees with the design objectives from Chapter III.

Figure 24. Simulation (discrete black points on plot) and theoretical (solid lines on plot) results of a $1 \times 8$ selection system illustrating that state-based performance has increased over random selection when a subset of channels are disadvantaged.

2. $M \times 8$ Performance

In this section, we simulate the effect on the probability of successful transmission of varying $M$ in a $M \times 8$ selection system while increasing the number of disadvantaged channels. The relative performances of a system using random selection as $M$ is varied from one to four are compared in Figure 25. For $M = 1$, the probability of successful transmission decreases linearly. For $M > 1$ the probability of successful transmission approaches an exponential decrease as $M$ increases. These results demonstrate that the performance of random selection degrades rapidly when a subset of channels is disadvantaged.
Figure 25. Simulation (discrete red points on plot) compared to theoretical (solid lines on plot) results of $M \times 8$ selection system using random channel selection while varying $M$ from one to four.

The performance as $M$ is varied from one to four when state-based selection is displayed in Figure 26. The simulation results agree with theoretical results and demonstrate that state-based channel selection has a higher value of probability of successful transmission than random selection given that a subset of channels is disadvantaged. When Equation (32) is satisfied and a subset of channels is disadvantaged state-based channel selection performed comparably regardless of the value of $M$. 
Figure 26. Simulation (discrete red points on plot) compared to theoretical (solid lines on plot) results of $M \times 8$ selection system using state-based selection while varying $M$ from one to four.

In this section, we presented the results of simulating a $M \times 8$ channel selection system comparing simulations to theoretical results presented in Chapter IV. We simulated the case of a $1 \times 8$ system and an $M \times 8$ wireless network. Simulations validated theoretical results and demonstrated that state-based channel selection performed better than random selection when a subset of the channels is disadvantaged for both cases. In the next section, we will explore the effect of changing parameters in state-based channel selection for both random and state-based channel selection on performance.
C. PARAMETERS AND SCHEME PERFORMANCE

In this section, we simulate an $M \times 50$ system to explore the effects of changing parameters in state-based channel selection and compare the results to random channel selection. We chose an $M \times 50$ system to stress the ability of the state-based channel selection scheme to maintain high performance and to allow for various ratios of good channels ($N_G/N$) to be explored. We first explore the effect of varying $M$ on the probability of successful transmission. We then investigate the effect of varying the transition threshold $\beta$ on the probability of successful transmission and overhead. For the $M \times 50$ system we used $\psi_{\max} = 10$, $\kappa = 5$, and $\beta = 250$, which are consistent with guidelines described in Chapter III. We set an SNR of 0 dB for disadvantaged channels and a SNR of 25 dB for high performing channels. Nodes were simulated with a relative motion of 1 m/s.

1. $M$ Effects

The number of channels selected is controlled by the parameter $M$. Recall from Chapter IV and the previous section that Equation (32) must be satisfied in order for state-based selection to operate with higher performance than random selection in an $M \times N$ system. To simulate the effect of varying $M$ on state-based channel selection, we established three scenarios for simulating the 50 channel system by setting the ratio $N_G/N$ equal to 0.25, 0.5 and 0.75, respectively, and varying the value of $M$ between one and six. The results of the simulation for varying $M$ are illustrated in Figure 27. State-based selection (solid curves) consistently performs higher than random selection (dotted curves) regardless of $M$ and $N_G/N$. An observation from Figure 27 is that the probability of successful transmission is lower than it has been in previous cases. Since there are 50 channels in the system, the effect of $\Omega$, which increases proportionally to the number of bad channels, slightly decreases the probability of successful transmission due to the effects of overhead which were defined in Equations (30) and (31).
2. Transition Threshold ($\beta$) Effects

The value of $\beta$ controls how often state-based selection enters the transition state and ultimately how often the scheme checks for improving channels. To simulate the effect of varying $\beta$ on state-based channel selection, we established three scenarios for the 50 channel system by setting $\frac{N_G}{N}$ equal to 0.25, 0.5 and 0.75, respectively. We then measured probability of successful transmission by varying $\beta$ between zero and six hundred for both state-based and random channel selection. Simulation results are presented for a $1 \times 50$ system for the base case. Next, results are presented for a $2 \times 50$, system representing the $M \times 50$ case where $M > 1$.

The results of varying $\beta$ for a $1 \times 50$ system are displayed in Figure 28, and the results of varying $\beta$ for a $2 \times 50$ system are shown in Figure 29. We use the $2 \times 50$ system to represent the effect on systems with $M > 1$. The $x$-axis has been normalized by
dividing $\beta$ by $N$. For low values of $\beta/N$, the probability of successful transmission is about the same for both state-based (solid curve) and random (dotted line) selection. The probability of successful transmission approaches its maximum value at around $\beta/N \geq 2$. These results agree with Equation (10) that $\beta/N$ should be set to greater than two. Further, the results show that for $1 \leq M \leq N$, $\rho$ stays consistent for state-based selection.

Figure 28. Effect of varying $\beta$ on $\rho$ for a 1×50 channel system with respective $N_{c}/N$ values of 0.25, 0.5, and 0.75 for state-based selection (solid curve) and random selection (dotted line).
Figure 29. Effect of varying $\beta$ on $\rho$ for a $2 \times 50$ channel system with respective $N_G/N$ values of 0.25, 0.5, and 0.75 for state-based selection (solid curve) and random selection (dotted line).

The probability of channel transmission success in Figure 28 and Figure 29 is lower than it has been in previous examples. Since there are 50 channels in the system, there is an increased effect from overhead in the wireless network, which increases proportionally to $N_B$ resulting in a lower probability of successful transmission.

3. **Transition Threshold ($\beta$) Effects on Overhead ($\Omega$)**

Overhead was defined in Equation (30) and results from test packets being sent to check for improvements in channels in the bad state. In this section, we explore the effect of varying $\beta$ on overhead for an $M \times 50$ system. We use the $2 \times 50$ system to represent the effect on systems with $M > 1$.

Simulation results of varying $\beta$ on overhead are displayed in Figure 30 and Figure 31. At low values of $\beta/N$, overhead is larger, and for $\beta/N > 5$, overhead decreases. As
$N_c/N$ increases, overhead decreases because as there are more good channels in the wireless network and fewer test packets are sent to check for improvements in bad channels.

![Figure 30](image_url)

**Figure 30.** Effect of varying $\beta$ on $\Omega$ for a $1 \times 50$ channel system with respective $N_c/N$ values of 0.25, 0.5, and 0.75 for state-based selection.

![Figure 31](image_url)

**Figure 31.** Effect of varying $\beta$ on $\Omega$ for a $2 \times 50$ channel system with respective $N_c/N$ values of 0.25, 0.5, and 0.75 for state-based selection.

In this section, we simulated an $M \times 50$ system to explore the effects of changing parameters in state-based channel selection and compared results to random channel
We first explored the effect of $M$ on the probability of successful transmission, demonstrating that as $M$ increases state-based channel selection maintains performance as long as Equation (32) is satisfied. On the other hand, random selection approaches an exponential decrease in performance as $M$ increases. We explored the effect of varying $\beta$ on the probability of successful transmission, finding that $\beta$ must be larger than $2N$ for state-based channel selection to improve performance over random selection. Finally, we explored the effect of varying $\beta$ on overhead, demonstrating that to reduce the amount of overhead $\beta$ should be more than $5N$. In the next section we explore the ability of state-based channel selection to respond to jamming.

D. JAMMING EFFECTS

In this section, we explore the effect of jamming on a $1 \times 3$ system as a jammer rotates through a subset of channels that are jammed. This situation is consistent with either mobile environments where the availability of channels may change over time or in scenarios where a reactive multiple tone jammer may selectively choose jamming patterns [1], [5]. We used an SNR of 0 dB for jammed channels and an SNR of 25 dB for channels not jammed. Nodes were simulated with a relative motion of 1 m/s.

Simulation results over six intervals of 2000 sessions each are displayed in Figure 32. For each interval, the slope of the respective curve compares the relative performance of each scheme. For intervals where jamming is off, the random (blue curve) performs comparably to state-based selection (red curve), which is in agreement with the design objectives established in Chapter III. Beginning at sessions 2001, 6001 and 8001, we see that the subset of jammed channels are rotated, and state-based selection has a slight increase in accumulated bit errors but rapidly returns to nearly a slope of zero. Random selection begins accumulating errors at a larger rate (larger positive slope) when channels are jammed.

The derivative of the results in Figure 32 resulting in a plot of the instantaneous bit errors per session is shown in Figure 33. We applied a first-order filter to obtain the moving average over the previous 100 data points, resulting in the blue (random selection) and red (state-based selection) curves. When one or more channels are
jammed, state-based selection has fewer instantaneous bit errors per session. At sessions 2001, 6001 and 8001, the subset of jammed channels is rotated. State-based selection has a slight jump in the instantaneous bit errors per sessions but then returns to nearly zero. State-based selection performs better in the presence of jamming because it has the ability to favor selection of channels that are not jammed.

Figure 32. The cumulative bit errors as jamming rotates between channels comparing random (blue curve) to state-based (red curve) channel selection.
Figure 33. The instantaneous bit errors per session as jamming rotates between channels comparing random (blue curve) to state-based (red curve) channel selection.

In presence of jamming, in which the jammer rotates among channels, state-based channel selection performed better than random channel selection. State-based channel selection has the ability to dynamically change which channels it favors for selection as it takes feedback from the environment, selecting only high-performing channels. Initially, there is an increase in the instantaneous error rate for state-based channel selection, but the error rate decreased to nearly zero once the scheme adjusts its good channel selection vector.

E. QUALNET

To further validate the scheme and ensure that bias was removed from the MATLAB simulation, we simulated state-based channel selection in QualNet, a network evaluation software package. We implemented a $1 \times 3$ system while varying the number of disadvantaged channels from one to three for the simulation. The effect on the probability of successful transmission in a $1 \times 3$ channel selection system, while
increasing the number of disadvantaged channels from zero to three, is displayed in Figure 34. The simulated and theoretical results closely match. As the number of disadvantaged channels increases, the probability of successful transmission decreases more rapidly for random selection than for state-based selection. The two schemes operate nearly the same when either none of the channels are disadvantaged or all of the channels are disadvantaged. The QualNet simulation validates the results presented in the MATLAB simulations.

Figure 34. QualNet Simulated (discrete black points on plot) and theoretical (solid lines on plot) results of a 1×3 selection system.

In this chapter, MATLAB and QualNet simulations were developed to validate the increased performance of state-based compared to random channel selection in multi-channel wireless networks. We first validated the theoretical calculations of the $M \times 8$ system presented in Chapter IV. Next, we presented a series of simulations for $M \times N$ selection systems demonstrating the effects of scheme parameters on both random and state-based channel selection performance. We then explored the ability of state-based
channel selection to respond to jamming assuming a crowded electromagnetic mobile environment or a reactive multiple tone jammer rotating which channels are jammed [1], [2]. Finally, we presented results from a QualNet simulation as a second simulation to validate the MATLAB simulation model. The results demonstrated an improvement for state-based over random channel selection.
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VI. CONCLUSIONS

In this thesis, we explored state-based channel selection, a novel scheme for use in multi-channel wireless networks to favor selection of high performing channels. A review of related work revealed that other schemes exist for addressing this problem including a random selection scheme that we used as a baseline to compare against the performance of state-based channel selection. Then, a state-based channel selection scheme that favors high performance channels was proposed and developed. A theoretical model and a simulation model were developed, which validated that the state-based channel selection scheme significantly improves performance in $M \times N$ wireless networks.

A. SIGNIFICANT CONTRIBUTIONS

Four main contributions were presented in this thesis. A novel state-based channel selection scheme for multi-channel wireless networks was presented. State-based channel selection demonstrated that channel selection could be based upon historical channel performance to improve system performance. Previous work had not established metrics or the ability to discriminate between disadvantaged channels and high performing channels. Channel selection schemes in previous work defaulted to the suboptimal performance of random selection in environments where one or more channels were disadvantaged.

We introduced the challenge of $M \times N$ channel selection, where previous work had only considered $1 \times N$ channel selection. We explored the challenge of $M \times N$ selection, quantifying the performance of both random channel selection and state-based channel selection. As $M$ was increased in wireless networks, state-based channel selection performance was shown to be consistently high when a subset of channels was disadvantaged.

A theoretical model was created to analyze the performance of state-based channel selection using a Markov chain. Reducing the periods of interest to only those at
the transitions in the model, we demonstrated that the performance of state-based channel selection could be successfully analyzed with this model.

Finally, we validated that state-based channel selection performed significantly better than random selection through simulation. State-based channel selection successfully favors selection of high performing channels resulting in an overall performance that approaches the average probability of successful transmission of the high performing channels in system.

B. RECOMMENDED FUTURE WORK

In this thesis, we explored channel selection for multi-channel wireless networks. Simulation verified the validity of the scheme; however, there were a few limitations. We assumed perfect synchronization between nodes in frequency-hopping and TDMA systems for the application and simulation of the scheme. Research could be expanded to explore the true effect of synchronization on system performance and the feasibility of implementation in these types of systems. A future effort may investigate more complex tactical or emergency response environments and mobility models as applied to state-based channel selection. These results could be used to develop optimization models for state-based channel selection dependent upon the environment or mobility characteristics while dynamically changing system parameters. Further, the effect of network size on the performance of state-based channel selection could be explored in these environments.

Additional work could be undertaken on how to overcome reactive multiple tone jammers that have the ability to hop faster than state-based channel selection can react to them. Strategies or heuristics could be explored for how to modify the scheme to overcome these challenges.
This appendix provides source code for theoretical calculations from Chapter IV of this thesis.

A. MATLAB THEORETICAL RANDOM SELECTION FILE

The MATLAB source code presented in this section can be used to test the random selection theoretical calculations presented in Chapter III and Chapter IV of this thesis. The code is run by changing the number of values in the alpha vector to reflect the desired number of channels in a system. Assign $M$ to desired value in a $M \times N$ system. Assign $\alpha$ value which corresponds to the desired performance of a channel with values zero through one.

```matlab
%% Random Channel Selection Source Code

clear
ChannelReliability = [.999,.999,.001,.001];

%M = Size of Permutations
M = 2;

AllPerms = perms([1:length(ChannelReliability)]);
Selections = AllPerms(:,1:M);

for i = 1:length(Selections)
    Selections(i,:) = ChannelReliability(Selections(i,:));
end

ColumnProduct = prod(Selections,2)*(1/length(AllPerms));

sum(ColumnProduct)
```
B. MATLAB THEORETICAL STATE-BASED FILE

The MATLAB source code presented in this section can be used to test state-based theoretical calculations presented in Chapter IV of this thesis. The code is run by changing the number of values in the alpha vector to reflect the desired number of channels in a system. Assign $M$ to desired value in a $M \times N$ system. Assign $\alpha$ value which corresponds to the desired performance of a channel with values zero through one.

```matlab
clear
format long eng
%Establish Variables for Math Modify the number of alpha values to effect %the number of channels
length(alpha)= number of channels
alpha= [.001,.999,.001,.999,.001,.999,.001,.999]
M = 1;
gamma = 1-alpha;
num_channels=length(alpha);
sessions = 2000;

%Establish how often to check if getting better and calculate the number of %checks over time and the percent time if transition state
kappa = 20;
num_checks = sessions/20;

%This is better known as $P[T]$ percent_time_transition = num_checks/sessions;

%First we need to create the total number of possible states transposed in %order to make processing easier
states=transpose(0:1:2^num_channels-1);

%Now changes the states vector into a table. Need to set the binary output %equal
for i=1:length(states)
    states_bin_table(i,:) = fliplr(dec2binvec(states(i),num_channels));
end

%Now sum the rows of ones and zeros to capture the number of good states %given
```
num_good_in_state=sum(states_bin_table,2)

% Create a table that substitutes values from alpha and gamma into
% corresponding ones and zeros of the states_bin_table

[rows cols]=size(states_bin_table);
state_prob_table = ones(rows,cols);

% Use a for loop to cycle through the state table and place values in the
% probability table

for j=1:cols
    for k=1:rows
        % if the logic table has a zero in it put in the pf for that channel
        % else put in the ps value for that channel
        if (states_bin_table(k,j)==0)
            state_prob_table(k,j)=gamma(j);
        else
            state_prob_table(k,j)=alpha(j);
        end
    end
end

prob_state=prod(state_prob_table,2)

% Now it is necessary to sum up the probabilities for all the cases of 0 through N good states

prob_state_consol=zeros(1,max(num_good_in_state)+1);
for l=1:(max(num_good_in_state)+1)
    % Capture the index and consolidate into state probabilities for each state corresponding
    % to various states
    index=find(num_good_in_state ==(l-1));
    prob_state_consol(l)=sum(prob_state(index));
end

% This is the probability associated with being in a state for the Markov
prob_state_consol;

% Now we must transition these values into transition rates for the Markov

Lambda = prob_state_consol.*percent_time_transition;
Mu=prob_state_consol;
Lambda(1)=[]
Mu(end)=[]

% To solve for the coefficients in the relation cumprod is necessary to
% find the p0_coeffs

p0_coeffs=cumprod(Lambda./Mu)
p0 = 1/(sum(p0_coeffs))

% Now calculate the limiting state probabilities

limiiting_state_probs= [p0,p0_coeffs.*p0]

% Average state

markov_chain_states=0:1:num_channels;
average_state=sum(markov_chain_states.*limiting_state_probs)

% Now we need to find tau for each state so that we can calculate pn

N=num_channels;

% Middle values of tau established

tau_holders = ones(1,num_channels-1).*max(alpha)

% The first and last correspond to the mean of all channels while the other
% states rely on selecting only channels in good states. This constructs
% tau

tau = [mean(alpha),tau_holders,mean(alpha)]

% Overall system performance is defined as pn for the scheme

pn=sum(limiiting_state_probs.*tau)
APPENDIX B—SIMULATION SOURCE CODE

The appendix provides the source code for both the MATLAB Rayleigh fading channel and QualNet models. MATLAB simulations require the “Communications Toolbox” due to the use of Rayleigh fading channels and modulation schemes.

A. MATLAB MAIN RAYLEIGH FADING CHANNEL SIMULATION FILE

% Create Rayleigh fading channel object.
clear

%Constants

c=3e8; %Speed of Light
SNRGood = 25; %Will be used to set channel quality in simulation
SNRBad = 0;
GoodChannels = [1,2,3,4,5,6];
BadChannels = [7,8];
NumChannels = length(GoodChannels) + length(BadChannels);
PacketLength = 1000;
Sessions = 2000;
Trials=1000;
SchemeTitle = ‘Random Channel Selection’;

% Number of Channels to be selected in an MxN system

M=2;

%Simulation Variables
%signaling frequency

fs=2.4e9;
ts=1/fs;

%Speed of node moving (m/s)

v=1;

%Doppler Shift fd=(v*fs)/c

fd=(v*fs)/c;
%Generate Rayleigh Channels

Channels = GenerateRayleighChannels(NumChannels,ts,fd);

%Create the Noise In Channels depending on whether it is a good or bad channel. %SNR in dB in a vector

ChannelSNR = zeros(1, NumChannels); ChannelSNR(GoodChannels) = SNRGood; ChannelSNR(BadChannels) = SNRBad;

%Initialized Variables for Speed in the loops

Error = zeros(1,Sessions); nErrors = zeros(1,Sessions); BER = zeros(1,Sessions); SelectedChannelsHistoryRandom = zeros(Sessions,M); ErrorHistoryRandom = zeros(Trials,Sessions); pnRandom = zeros(1,Trials); ErrorTest = zeros(1,M); nErrorsTest = zeros(1,M); BERTest = zeros(1,M);

%Monte Carlo For loop

for i = 1:Trials

%For loop which runs the sessions

for j = 1:Sessions

%Select the channel

SelectedChannels=RandomRayleighChannelSelect(NumChannels, M); SelectedChannelsHistoryRandom(j,:)=SelectedChannels;

%Now transmit the data using the selected channels. Pass the channels, SNR %and Packet Length

for l = 1:length(SelectedChannels)
    [ErrorTest(l) nErrorsTest(l) BERTest(l)] = TransmitData(Channels(SelectedChannels(l)),ChannelSNR(SelectedChannels(l)),PacketLength);
end
if sum(ErrorTest) >= 1
    Error(j) = 1;
else
    Error(j) = 0;
end

end

ErrorHistoryRandom(i,:) = Error;
pnRandom(i) = 1 - (sum(Error)/Sessions);
end

RunsHistoryRandom = [SelectedChannelsHistoryRandom, reshape(Error, Sessions, 1)];

% Gather Simulation Statistics
CumulativeRandomErrors = mean(cumsum(ErrorHistoryRandom, 2), 1);
pnRandomMean = mean(pnRandom)

% Plots for Random Selection Simulation
figure()
hold on
plot(CumulativeRandomErrors, ’b’, ’linewidth’, 2);
title([’Number of Errors as Packets are Transmitted Averaged Over ‘, num2str(Trials), ’ Trials in Random Selection’], ’fontsize’, 10, ’fontweight’, ’b’);
xlabel(’Number of Packets Transmitted’, ’fontsize’, 14, ’fontweight’, ’b’);
ylabel(’Cumulative Number of Errors’, ’fontsize’, 14, ’fontweight’, ’b’)
legend(’Random Selection’, ’location’, ’Southeast’)
grid on
hold off

figure()
hold on
hist(reshape(SelectedChannelsHistoryRandom, 1, M*Sessions))
title([’Histogram for ‘, SchemeTitle, ’ Scheme’], ’fontsize’, 10, ’fontweight’, ’b’);
xlabel(’Channel Selected’, ’fontsize’, 14, ’fontweight’, ’b’);
ylabel(’Number of times selected’, ’fontsize’, 14, ’fontweight’, ’b’)
grid on
hold off

figure()
hold on
hist(pnRandom)
title(’Histogram for’, SchemeTitle,’ Scheme’),’fontsize’,10,’fontweight’,’b’);
xlabel(’Probability of Transmission Success’,’fontsize’,14,’fontweight’,’b’);
ylabel(’Number of times selected’,’fontsize’,14,’fontweight’,’b’)
grid on
hold off

%% State-based Selection Simulation with Rayleigh Channels

SchemeTitle = ‘State Based Channel Selection’;

%Generate Rayleigh Channels

Channels = GenerateRayleighChannels(NumChannels,ts,fd);

%Create the Noise In Channels depending on whether it is a good or bad channel.
%SNR in dB in a vector

ChannelSNR = zeros(1, NumChannels);
ChannelSNR(GoodChannels) = SNRGood;
ChannelSNR(BadChannels) = SNRBad;

% State Based Scheme Variables

CreditScoreMax = 10;
CreditScoreThreshold = 5;
TransitionThreshold = 20;
DynamicCounter = 0;
OverheadHistory = zeros(Trials, Sessions);
ExponBackOffTimer = TransitionThreshold.*zeros(1,NumChannels);
SessionsSinceSuccess = zeros(1,NumChannels);

% Initialized Variables for Speed in the loops

Error = zeros(1,Sessions);
nErrors = zeros(1,Sessions);
BER = zeros(1,Sessions);
ErrorTest = zeros(1,M);
nErrorsTest = zeros(1,M);
BERTest = zeros(1,M);
SelectedChannelsHistoryStateBased = zeros(Sessions,M);
ErrorHistoryStateBased = zeros(Trials,Sessions);
CreditScoreHistory = zeros(Sessions,NumChannels);
pnStateBased = zeros(1,Trials);
pnStateBasedWithOverhead = zeros(1,Trials);

%Monte Carlo For loop

for i = 1:Trials

    %Set Credit Score to Max at Initialization and set up the Good and Bad
    %Channel Vectors for easy indexing of good Channels. Initialize other
    %variables that must be established for each simulation run.
    CreditScores = CreditScoreMax*ones(1, NumChannels);
    GoodChannelVector = find(CreditScores >= CreditScoreThreshold);
    BadChannelVector = find(CreditScores < CreditScoreThreshold);
    ExponBackOffTimer = TransitionThreshold.*ones(1,NumChannels);
    SessionsSinceSuccess = zeros(1,NumChannels);
    Overhead = 0;

    %For loop which runs the sessions

    for j = 1:Sessions

        %Select the channel pass good channels when they are available
        %otherwise choose one of the bad channels

        if(~isempty(GoodChannelVector))
            SelectedChannels = StateBasedRayleighChannelSelect(GoodChannelVector,BadChannelVector,M);
        else
            display(‘Stuck In All Bad Channels’)
            SelectedChannels = StateBasedRayleighChannelSelect(BadChannelVector,GoodChannelVector,M);
        end

        SelectedChannelsHistoryStateBased(j,:) = SelectedChannels;

        %Now transmit the data using the selected channel. Pass the channel, SNR
        %and Packet Length

        for l = 1:length(SelectedChannels)
            [ErrorTest(l) nErrorsTest(l) BERTest(l)] = TransmitData(Channels(SelectedChannels(l)),ChannelSNR(SelectedChannels(l)),PacketLength);
        end

        if sum(ErrorTest)>=1
            Error(j)=1;
        end

    end

end
else
    Error(j)=0;
end

%If there is an Error Update Credit Score Else Do Nothing and
%process the next session
if (Error(j) == 1)
    %Now we update the credit scores and the good and bad channels
    CreditScores=UpdateCreditScore(SelectedChannels,CreditScores,CreditScoreThreshold, ErrorTest);
    GoodChannelVector = find(CreditScores>=CreditScoreThreshold);
    BadChannelVector = find(CreditScores<CreditScoreThreshold);
else
    %Update the Good and Bad Channel Vector after each run
    GoodChannelVector = find(CreditScores>=CreditScoreThreshold);
    BadChannelVector = find(CreditScores<CreditScoreThreshold);
end

%Update the Dynamic Counter once the session is complete
DynamicCounter=DynamicCounter+1;

%The state based scheme must enter the transition state to see if conditions are
%improving when Dynamic Counter and Transition Threshold are Equal
if(DynamicCounter==TransitionThreshold)
    SessionsSinceSuccess=SessionsSinceSuccess + TransitionThreshold;
    [CreditScores Overhead ExponBackOffTimer SessionsSinceSuccess] = TransitionState(Channels,ChannelSNR,CreditScores,PacketLength,CreditScoreMax,CreditScoreThreshold,ExponBackOffTimer,SessionsSinceSuccess,TransitionThreshold,Overhead);
    DynamicCounter = 0;  %Reset the DynamicCounter back to zero after exiting the transition state
    GoodChannelVector = find(CreditScores>=CreditScoreThreshold);
    BadChannelVector = find(CreditScores<CreditScoreThreshold);
end
%Collect the Credit Score History

CreditScoreHistory(j,:) = CreditScores;
OverheadHistory(i,j) = Overhead;
end

%Collect Statistics based upon the simulations

ErrorHistoryStateBased(i,:) = Error;
pnStateBased(i) = 1-(sum(Error)/Sessions);
pnStateBasedWithOverhead(i) = 1-((sum(Error)+Overhead)/Sessions);
end

RunsHistoryStateBased = [SelectedChannelsHistoryStateBased, reshape(Error, Sessions, 1)];

%Process Simulation Statistics

OverheadMean = mean(OverheadHistory(:, Sessions))/Sessions;
CumulativeStateBasedErrors = mean(cumsum(ErrorHistoryStateBased, 2), 1);
pnStateBasedMean = mean(pnStateBased);
pnStateBasedWithOverheadMean = mean(pnStateBasedWithOverhead);
PercentIncreaseWithoutOverhead = mean((pnStateBased-pnRandom)./pnRandom);
PercentIncreaseWithOverhead = mean((pnStateBasedWithOverhead-pnRandom)./pnRandom);

%Plots for Random Selection Simulation

figure()
hold on
plot(CumulativeStateBasedErrors,'b','linewidth', 2);
title(['Number of Errors as Packets are Transmitted Averaged Over ', num2str(Trials), ' Trials in Random Selection'],'fontsize',10,'fontweight','b');
xlabel('Number of Packets Transmitted','fontsize',14,'fontweight','b');
ylabel('Cumulative Number of Errors','fontsize',14,'fontweight','b');
legend('Random Selection','location','Southeast')
grid on
hold off

figure()
hold on
hist(reshape(SelectedChannelsHistoryStateBased, 1, M*Sessions))
B. MATLAB GENERATE RAYLEIGH CHANNELS FUNCTION

%% Function to generate N Channels

function r = GenerateRayleighChannels(NumChannels,ts,fd)

% Create the Channel with values
for i=1:NumChannels
    Channels(i) = rayleighchan(ts,fd);
end

% Return the channel vector
r = Channels;
end
C. MATLAB RANDOM CHANNEL SELECT FUNCTION

%%% Function to randomly select $M$ of $N$ channels

function r = RandomRayleighChannelSelect(NumChannels,M)

%function call for rand selection of a channel from a uniform %distribution

SelectedChannels=randperm(NumChannels);
SelectedChannels=SelectedChannels(1:M);

r = SelectedChannels;

end

D. MATLAB STATE-BASED CHANNEL SELECTION FUNCTION

%%% Function to select one of $M$ of $N$ channels in state based channel selection

function r = StateBasedRayleighChannelSelect(GoodChannels, BadChannels, M)

MChannelsSelected = 0;
NumChannels=length(GoodChannels)+length(BadChannels);
Errors = 0;

if(length(GoodChannels)>=M)

  % Make sure no bad channels are in the selected channels

  while MChannelsSelected == 0

    SelectedChannels=randperm(NumChannels);
    SelectedChannels=SelectedChannels(1:M);

    for i=1:length(BadChannels)

      Errors=Errors+sum(SelectedChannels==BadChannels(i));

    end

    %Check if there was an error in selecting channels
    if Errors > 0
      MChannelsSelected == 0;
    end

end
else %If no errors then leave the loop and select the channels

    MChannelsSelected = 1;

end

%Set Errors back to zero

Errors = 0;

end

else %If M channels unavailable then just randomly select channels.

    SelectedChannels=randperm(NumChannels);
    SelectedChannels=SelectedChannels(1:M);

end

r = SelectedChannels;

end

E. MATLAB TRANSITION STATE FUNCTION

%%% Function that controls the scheme in the transition state which increases the credit score where necessary sending test packets

function [UpdatedCreditScores UpdatedOverhead UpdatedExponBackOffTimer UpdatedSessionsSinceSuccess] = TransitionState(Channels,ChannelSNR,CreditScores,PacketLength,CreditScoreMax,CreditScoreThreshold,ExponBackOffTimer,SessionsSinceSuccess,TransitionThreshold,Overhead)

%Cycle through the channels to see if conditions have improved

    Error=ones(1,length(Channels));
    nErrors=ones(1,length(Channels));
    BER=ones(1,length(Channels));

    for i = 1:length(Channels)

        if(CreditScores(i)>=CreditScoreThreshold)  %If in a good state don’t transmit set back off timer back to 2^0*TransitionThreshold

            %

        end

    end

end
Error(i) = 0;
ExponBackOffTimer(i) = TransitionThreshold;
Overhead = Overhead + 0;
SessionsSinceSuccess(i) = 0;

elseif(SessionsSinceSuccess(i)>=ExponBackOffTimer(i)) %The case that it is time to check if the channel is good or bad

[Error(i) nErrors(i)
BER(i)] = TransmitData(Channels(i),ChannelSNR(i),PacketLength);

if(Error(i)==1) %If there is another error in an already bad channel

ExponBackOffTimer(i) = ExponBackOffTimer(i).*2;
Overhead = Overhead + 1;
else %If the channel is improving and there was no error then do this

ExponBackOffTimer(i) = TransitionThreshold;
Overhead = Overhead + 1;
SessionsSinceSuccess(i) = 0;
end

else %Don’t check the bad channel if it is not time yet

Error(i) = 1; %Need to set the Error of i to one so that the Credit Score doesn’t update but add 0 for the overhead

Overhead = Overhead + 0;

end

end

%When there is not an error we add an integer value of 1 to the credit score
CreditScores(Error==0) = CreditScores(Error==0) + 1;

%For Credit Scores which are too large set them back to the Max
CreditScores(CreditScores>=CreditScoreMax) = CreditScoreMax;
UpdatedCreditScores = CreditScores;
UpdatedOverhead = Overhead;
UpdatedExponBackOffTimer = ExponBackOffTimer;
UpdatedSessionsSinceSuccess = SessionsSinceSuccess;

end

F. MATLAB UPDATE CREDIT SCORES FUNCTION

%%% Function to update the credit score in the case of an error

function UpdatedCreditScores = UpdateCreditScore(SelectedChannels, CreditScores, CreditScoreThreshold,MErrorVector)

% Since this function is only called if a channel is selected and there is an error we 
% subtract an integer value of one when there is an error

for i = 1:length(MErrorVector)

% Need to check which channel had the error and update

if MErrorVector(i)==1

if (CreditScores(SelectedChannels(i))>=CreditScoreThreshold)

    CreditScores(SelectedChannels(i)) = CreditScores(SelectedChannels(i)) - 1;

else

    CreditScores(SelectedChannels(i)) = CreditScores(SelectedChannels(i));

end

else

    CreditScores(SelectedChannels(i)) = CreditScores(SelectedChannels(i));

end

end

UpdatedCreditScores=CreditScores;
end
G. MATLAB MODULATION AND TRANSMISSION FUNCTION

%%% Function that generates a random message, modulates it and transmits it returning errors and BER

function [Error nErrors BER] = TransmitData(Channel,SNR,PacketLength)

% Generate data and apply fading channel.
M = 2; % QPSK modulation order
hMod = modem.oqpskmod(M, M); % Create a OQPSK modulator
hDemod = modem.oqpskdemod(hMod); % Create a OQPSK demodulator

% using the modulator

tx = randi([0 M-1],PacketLength,1); % Generate a random bit stream
oqpskSig = modulate(hMod, tx); % OQPSK modulate the signal

fadedSig = filter(Channel,oqpskSig);
rxSig = awgn(fadedSig,SNR); % Add Gaussian noise

%rxSig=fadedSig;
rx = demodulate(hDemod, rxSig); % Demodulate
reset(hDemod);

% Compute error rate.
[nErrors, BER] = biterr(tx,rx);

Error=Error;
nErrors=nErrors;
BER=BER;

end

H. QUALNET SIMULATION DESCRIPTION

Simulation was achieved using the method displayed in Figure 35. First a test plan was created using MATLAB, varying which channels were high performing and which channels were disadvantaged. Dependent on the scenario in the test plan and using a Monte Carlo approach, a group of batch files were run and results aggregated. At the simulation level, nodes with three data channels were initialized. Each channel could be placed into a disadvantaged state or high performing state by manipulating a parameter called Propagation Limit, affecting how well each channel performed given distance, affects from fading, affects from shadowing and other multi-path losses. Two types of
files were created and batched together in order to create simulation scenarios one referred to as a normal operation file and the other as a transition state file.

Figure 35. QualNet simulation architecture highlighting that $N$ batch files run together for each scenario.

I. QUALNET RANDOM SELECTION BATCH FILE

```
# ***** QualNet Configuration File *****
#******************************************General Settings******************************************
VERSION 5.0
EXPERIMENT-NAME QualNet
EXPERIMENT-COMMENT None
SEED 1
#******************************************Parallel Settings******************************************
PARTITION-SCHME AUTO
#******************************************ATM Configuration******************************************
DUMMY-ATM-LOGICAL-SUBNET-CONFIGURED NO
ATM-STATIC-ROUTE NO
#******************************************Dynamic Parameters******************************************
DYNAMIC-ENABLED NO
#******************************************Terrain******************************************
COORDINATE-SYSTEM CARTESIAN
```
**TERRAIN-DIMENSIONS (1500, 1500)**
**DUMMY-ALTITUDES (1500, 0)**
**DUMMY-ENABLE-URBAN-TERRAIN-FEATURE NO**
**WEATHER-MOBILITY-INTERVAL 100MS**

#******************Channel Properties***********************************

**PROPAGATION-CHANNEL-FREQUENCY[0] 1400000000**
**PROPAGATION-MODEL[0] STATISTICAL**
**PROPAGATION-PATHLOSS-MODEL[0] TWO-RAY**
**PROPAGATION-SHADOWING-MODEL[0] CONSTANT**
**PROPAGATION-SHADOWING-MEAN[0] 4.0**
**PROPAGATION-FADING-MODEL[0] NONE**
**PROPAGATION-LIMIT[0] -25.0**
**PROPAGATION-MAX-DISTANCE[0] 0**
**PROPAGATION-COMMUNICATION-PROXIMITY[0] 400**
**PROPAGATION-PROFILE-UPDATE-RATIO[0] 0.0**
**PROPAGATION-CHANNEL-FREQUENCY[1] 1700000000**
**PROPAGATION-MODEL[1] STATISTICAL**
**PROPAGATION-PATHLOSS-MODEL[1] TWO-RAY**
**PROPAGATION-SHADOWING-MODEL[1] CONSTANT**
**PROPAGATION-SHADOWING-MEAN[1] 4.0**
**PROPAGATION-FADING-MODEL[1] NONE**
**PROPAGATION-LIMIT[1] -111.0**
**PROPAGATION-MAX-DISTANCE[1] 0**
**PROPAGATION-COMMUNICATION-PROXIMITY[1] 400**
**PROPAGATION-PROFILE-UPDATE-RATIO[1] 0.0**
**PROPAGATION-CHANNEL-FREQUENCY[2] 1900000000**
**PROPAGATION-MODEL[2] STATISTICAL**
**PROPAGATION-PATHLOSS-MODEL[2] TWO-RAY**
**PROPAGATION-SHADOWING-MODEL[2] CONSTANT**
**PROPAGATION-SHADOWING-MEAN[2] 4.0**
**PROPAGATION-FADING-MODEL[2] NONE**
**PROPAGATION-LIMIT[2] -111.0**
**PROPAGATION-MAX-DISTANCE[2] 0**
**PROPAGATION-COMMUNICATION-PROXIMITY[2] 400**
**PROPAGATION-PROFILE-UPDATE-RATIO[2] 0.0**

#**************************STATISTICS*********************************

**PHY-LAYER-STATISTICS YES**
**MAC-LAYER-STATISTICS YES**
**ACCESS-LIST-STATISTICS NO**
**ARP-STATISTICS YES**
ROUTING-STATISTICS YES
POLICY-ROUTING-STATISTICS NO
QOSPF-STATISTICS NO
ROUTE-REDISTRIBUTION-STATISTICS NO
EXTERIOR-GATEWAY-PROTOCOL-STATISTICS YES
NETWORK-LAYER-STATISTICS YES
INPUT-QUEUE-STATISTICS NO
INPUT-SCHEDULER-STATISTICS NO
QUEUE-STATISTICS YES
SCHEDULER-STATISTICS NO
SCHEDULER-GROUP-STATISTICS NO
DIFFSERV-EDGE-ROUTER-STATISTICS NO
ICMP-STATISTICS NO
IGMP-STATISTICS NO
NDP-STATISTICS NO
MOBILE-IP-STATISTICS NO
TCP-STATISTICS YES
UDP-STATISTICS YES
RSVP-STATISTICS NO
SRM-STATISTICS NO
RTP-STATISTICS NO
APPLICATION-STATISTICS YES
BATTERY-MODEL-STATISTICS NO
ENERGY-MODEL-STATISTICS YES
MOBILITY-STATISTICS NO
CELLULAR-STATISTICS YES
GSM-STATISTICS NO
VOIP-SIGNALLING-STATISTICS NO
SWITCH-PORT-STATISTICS NO
SWITCH-SCHEDULER-STATISTICS NO
SWITCH-QUEUE-STATISTICS NO
MPLS-STATISTICS NO
MPLS-LDP-STATISTICS NO
HOST-STATISTICS NO

#**********************PACKET TRACING***********************************
PACKET-TRACE NO
ACCESS-LIST-TRACE NO

#**********************Supplemental Files***********************************
DUMMY-USER-PROFILE-FILE-NUMBER 0
DUMMY-TRAFFIC-PATTERN-FILE-NUMBER 0
DUMMY-ARBTRARY-DISTRIBUTION-FILE-NUMBER 0

#***********************HLA Interface***********************************
HLA NO

#***********************DIS Interface***********************************
DIS NO

#***********************STK Interface*********************************************
STK-ENABLED NO

#**********************Physical Layer***********************************************
PHY-LISTENABLE-CHANNEL-MASK 111
PHY-LISTENING-CHANNEL-MASK 111
PHY-MODEL PHY802.11b
PHY802.11-AUTO-RATE-FALLBACK NO
PHY802.11-DATA-RATE 2000000
PHY802.11b-TX-POWER--1MBPS 15.0
PHY802.11b-TX-POWER--2MBPS 15.0
PHY802.11b-TX-POWER--6MBPS 15.0
PHY802.11b-TX-POWER-11MBPS 15.0
PHY802.11b-RX-SENSITIVITY--1MBPS -94.0
PHY802.11b-RX-SENSITIVITY--2MBPS -91.0
PHY802.11b-RX-SENSITIVITY--6MBPS -87.0
PHY802.11b-RX-SENSITIVITY-11MBPS -83.0
PHY802.11-ESTIMATED-DIRECTIONAL-ANTENNA-GAIN 15.0
PHY-RX-MODEL PHY802.11b
ANTENNA-GAIN 0.0
ANTENNA-HEIGHT 1.5
ANTENNA-EFFICIENCY 0.8
ANTENNA-MISMATCH-LOSS 0.3
ANTENNA-CABLE-LOSS 0.0
ANTENNA-CONNECTION-LOSS 0.2
ANTENNA-MODEL OMNIDIRECTIONAL
PHY-TEMPERATURE 290.0
PHY-NOISE-FACTOR 10.0
ENERGY-MODEL-SPECIFICATION NONE

#***********************MAC Layer#################################################
LINK-MAC-PROTOCOL ABSTRACT
LINK-PROPAGATION-DELAY 1MS
LINK-BANDWIDTH 10000000
LINK-HEADER-SIZE-IN-BITS 224
LINK-TX-FREQUENCY 13170000000
LINK-RX-FREQUENCY 13170000000
LINK-TX-ANTENNA-HEIGHT 30
LINK-RX-ANTENNA-HEIGHT 30
LINK-TX-ANTENNA-DISH-DIAMETER 0.8
LINK-RX-ANTENNA-DISH-DIAMETER 0.8
LINK-TX-ANTENNA-CABLE-LOSS 1.5
LINK-RX-ANTENNA-CABLE-LOSS 1.5
LINK-TX-POWER 30
LINK-RX-SENSITIVITY -80
LINK-NOISE-TEMPERATURE 290
LINK-NOISE-FACTOR 4
LINK-TERRAIN-TYPE PLAINS
LINK-PROPAGATION-RAIN-INTENSITY 0
LINK-PROPAGATION-TEMPERATURE 25
LINK-PROPAGATION-SAMPLING-DISTANCE 100
LINK-PROPAGATION-CLIMATE 1
LINK-PROPAGATION-REFRACTIVITY 360
LINK-PROPAGATION-PERMITTIVITY 15
LINK-PROPAGATION-CONDUCTIVITY 0.005
LINK-PROPAGATION-HUMIDITY 50
LINK-PERCENTAGE-TIME-REFRACTIVITY-GRADIENT-LESS-STANDARD 15
MAC-PROTOCOL MACDOT11
MAC-DOT11-SHORT-PACKET-TRANSMIT-LIMIT 7
MAC-DOT11-LONG-PACKET-TRANSMIT-LIMIT 4
MAC-DOT11-RTS-THRESHOLD 0
MAC-DOT11-STOP-RECEIVING-AFTER-HEADER-MODE NO
MAC-DOT11-ASSOCIATION NONE
MAC-DOT11-IBSS-SUPPORT-PS-MODE NO
MAC-DOT11-DIRECTIONAL-ANTENNA-MODE NO
MAC-SECURITY-PROTOCOL NO
WORMHOLE-VICTIM-COUNT-TURNAROUND-TIME NO
MAC-PROPAGATION-DELAY 1US

#********************Schedulers and Queues************************************
IP-QUEUE-PRIORITY-INPUT-QUEUE-SIZE 150000
IP-QUEUE-SCHEDULER STRICT-PRIORITY
IP-QUEUE-NUM-PRIORITIES 3
IP-QUEUE-PRIORITY-QUEUE-SIZE 150000
QUEUE-WEIGHT 0
IP-QUEUE-TYPE FIFO

#************************QoS Configuration***********************************
#********************Network Security****************************************
IPSEC-ENABLED NO
ISAKMP-SERVER NO
CERTIFICATE-ENABLED NO
EAVESDROP-ENABLED NO
AUDIT-ENABLED NO

#**************************ROUTER******************************************
MODEL
DUMMY-ROUTER-TYPE USER-SPECIFIED
DUMMY-PARAM NO

#**************************NETWORK*****************************************
LAYER
NETWORK-PROTOCOL IP
IP-ENABLE-LOOPBACK YES
IP-LOOPBACK-ADDRESS 127.0.0.1
IP-FRAGMENT-HOLD-TIME 15S
IP-FRAGMENTATION-UNIT 2048
ECN NO
ICMP NO
IPv6-ENABLE-6to4-TUNNELING NO
#**********************ROUTING
ROUTING-PROTOCOL BELLMANFORD
STATIC-ROUTE NO
DEFAULT-ROUTE NO
HSRP-PROTOCOL NO
#**************************TRANSPORT*******************************
***
TRANSPORT-PROTOCOL-RSVP YES
GUI_DUMMY_CONFIG_TCP YES
TCP LITE
TCP-USE-RFC1323 NO
TCP-DELAY-SHORT-PACKETS-ACKS NO
TCP-USE-NAGLE-ALGORITHM YES
TCP-USE-KEEPALIVE-PROBES YES
TCP-USE-OPTIONS YES
TCP-DELAY-ACKS YES
TCP-MSS 512
TCP-SEND-ACKS 16384
TCP-RECEIVE-ACKS 16384
#**********************MPLS Spec**************************
MPLS-PROTOCOL NO
#*******************Application Layer***************************
DUMMY-VOIP-APPLICATION-EXISTS NO
RTP-ENABLED NO
#******************USER BEHAVIOR***************************
DUMMY-UBEE-ENABLED NO
#**********************Battery Models**************************
BATTERY-MODEL NONE
#***********************Adaptation Protocol**************************
ADAPTATION-PROTOCOL AAL5
ATM-CONNECTION-REFRESH-TIME 5M
ATM-CONNECTION-RETRIEVAL-TIME 1M
#********** [Default Wireless Subnet] ******************
SUBNET N8-169.0.0.0 {1 thru 6} Default
#***********************Physical Layer**************************
[ N8-169.0.0.0 ] PHY-LISTENABLE-CHANNEL-MASK[0] 111
[ N8-169.0.0.0 ] PHY-LISTENING-CHANNEL-MASK[0] 111
[ N8-169.0.0.0 ] PHY-MODEL PHY802.11b
[ N8-169.0.0.0 ] PHY802.11-AUTO-RATE-FALLBACK NO
[ N8-169.0.0.0 ] PHY802.11-DATA-RATE 2000000
[ N8-169.0.0.0 ] PHY802.11b-TX-POWER--1MBPS 15.0
[ N8-169.0.0.0 ] PHY802.11b-TX-POWER--2MBPS 15.0
[ N8-169.0.0.0 ] PHY802.11b-TX-POWER--6MBPS 15.0
[ N8-169.0.0.0 ] PHY802.11b-TX-POWER--11MBPS 15.0
[ N8-169.0.0.0 ] PHY802.11b-RX-SENSITIVITY--1MBPS -94.0
[ N8-169.0.0.0 ] PHY802.11b-RX-SENSITIVITY--2MBPS -91.0
[ N8-169.0.0.0 ] PHY802.11b-RX-SENSITIVITY--6MBPS -87.0
[ N8-169.0.0.0 ] PHY802.11b-RX-SENSITIVITY--11MBPS -83.0
[ N8-169.0.0.0 ] PHY802.11-ESTIMATED-DIRECTIONAL-ANTENNA-GAIN 15.0
[ N8-169.0.0.0 ] PHY-RX-MODEL PHY802.11b
[ N8-169.0.0.0 ] ANTENNA-GAIN 0.0
[ N8-169.0.0.0 ] ANTENNA-HEIGHT 1.5
[ N8-169.0.0.0 ] ANTENNA-EFFICIENCY 0.8
[ N8-169.0.0.0 ] ANTENNA-MISMATCH-LOSS 0.3
[ N8-169.0.0.0 ] ANTENNA-CABLE-LOSS 0.0
[ N8-169.0.0.0 ] ANTENNA-CONNECTION-LOSS 0.2
[ N8-169.0.0.0 ] ANTENNA-MODEL OMNIDIRECTIONAL
#***********************NETWORK LAYER**************************************************************************
[ N8-169.0.0.0 ] NETWORK-PROTOCOL IP
#**************************Interface Configuration**************************************************************************
[1] NETWORK-PROTOCOL[0] IP
[1] IP-SUBNET-MASK[0] 255.255.255.0
[1] IP-ADDRESS[0] 169.0.0.1
[2] NETWORK-PROTOCOL[0] IP
[2] IP-SUBNET-MASK[0] 255.255.255.0
[2] IP-ADDRESS[0] 169.0.0.2
[3] NETWORK-PROTOCOL[0] IP
[3] IP-SUBNET-MASK[0] 255.255.255.0
[3] IP-ADDRESS[0] 169.0.0.3
[4] IP-SUBNET-MASK[0] 255.255.255.0
[4] IP-ADDRESS[0] 169.0.0.4
[5] NETWORK-PROTOCOL[0] IP
[5] IP-SUBNET-MASK[0] 255.255.255.0
[5] IP-ADDRESS[0] 169.0.0.5
[6] NETWORK-PROTOCOL[0] IP
[6] IP-SUBNET-MASK[0] 255.255.255.0
[6] IP-ADDRESS[0] 169.0.0.6
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[0] 150000
83

[169.0.0.1 169.0.0.2] PHY-LISTENABLE-CHANNEL-MASK 100
[169.0.0.5 169.0.0.6] PHY-LISTENING-CHANNEL-MASK 001
[169.0.0.3 169.0.0.4] PHY-LISTENING-CHANNEL-MASK 010
[169.0.0.3 169.0.0.4] PHY-LISTENABLE-CHANNEL-MASK 010
[169.0.0.1 169.0.0.2] PHY-LISTENING-CHANNEL-MASK 100
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[0] FIFO
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[2] 150000
[169.0.0.5 169.0.0.6] PHY-LISTENABLE-CHANNEL-MASK 001
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[1] FIFO
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[1] 150000
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[2] FIFO

#********************Hierarchy Configuration***********************************
#******************Node Configuration***********************************
[1 thru 6] NETWORK-PROTOCOL IP
[1 thru 6] IP-LOOPBACK-ADDRESS 127.0.0.1
[1] HOSTNAME host1
[2] HOSTNAME host2
[3] HOSTNAME host3
[4] HOSTNAME host4
[5] HOSTNAME host5
[6] HOSTNAME host6
[1 thru 6] IP-FRAGMENT-HOLD-TIME 15S
[1 thru 6] GUI-NODE-2D-ICON C:/snt/qualnet/5.0/gui/icons/BLACKSQUARE.png
[1 thru 6] NODE-PLACEMENT FILE
[1 thru 6] IP-ENABLE-LOOPBACK YES

J.qualnet normal operation batch file

# ***** QualNet Configuration File *****
#**************************General Settings**********************************
VERSION 5.0
EXPERIMENT-NAME QualNet
EXPERIMENT-COMMENT None
SEED 1

#**************************Parallel Settings***********************************
PARTITION-SCHEME AUTO

#**************************ATM Configuration***********************************
DUMMY-ATM-LOGICAL-SUBNET-CONFIGURED NO
ATM-STATIC-ROUTE NO

#**************************Dynamic Parameters***********************************
DYNAMIC-ENABLED NO

#**************************Terrain***********************************
COORDINATE-SYSTEM CARTESIAN
TERRAIN-DIMENSIONS (1500, 1500)
DUDDY-ALTITUDES (1500, 0)
DUMMY-ENABLE-URBAN-TERRAIN-FEATURE NO
WEATHER-MOBILITY-INTERVAL 100MS

#**************************Channel Properties**************************************************************************
PROPAGATION-CHANNEL-FREQUENCY[0] 1400000000
PROPAGATION-MODEL[0] STATISTICAL
PROPAGATION-PATHLOSS-MODEL[0] TWO-RAY
PROPAGATION-SHADOWING-MODEL[0] CONSTANT
PROPAGATION-SHADOWING-MEAN[0] 4.0
PROPAGATION-FADING-MODEL[0] NONE
PROPAGATION-LIMIT[0] -25.0
PROPAGATION-MAX-DISTANCE[0] 0
PROPAGATION-COMMUNICATION-PROXIMITY[0] 400
PROPAGATION-PROFILE-UPDATE-RATIO[0] 0.0
PROPAGATION-CHANNEL-FREQUENCY[1] 1700000000
PROPAGATION-MODEL[1] STATISTICAL
PROPAGATION-PATHLOSS-MODEL[1] TWO-RAY
PROPAGATION-SHADOWING-MODEL[1] CONSTANT
PROPAGATION-SHADOWING-MEAN[1] 4.0
PROPAGATION-FADING-MODEL[1] NONE
PROPAGATION-LIMIT[1] -111.0
PROPAGATION-MAX-DISTANCE[1] 0
PROPAGATION-COMMUNICATION-PROXIMITY[1] 400
PROPAGATION-PROFILE-UPDATE-RATIO[1] 0.0
PROPAGATION-CHANNEL-FREQUENCY[2] 1900000000
PROPAGATION-MODEL[2] STATISTICAL
PROPAGATION-PATHLOSS-MODEL[2] TWO-RAY
PROPAGATION-SHADOWING-MODEL[2] CONSTANT
PROPAGATION-SHADOWING-MEAN[2] 4.0
PROPAGATION-FADING-MODEL[2] NONE
PROPAGATION-LIMIT[2] -111.0
PROPAGATION-MAX-DISTANCE[2] 0
PROPAGATION-COMMUNICATION-PROXIMITY[2] 400
PROPAGATION-PROFILE-UPDATE-RATIO[2] 0.0

#**************************Mobility and Placement**************************************************************************
NODE-PLACEMENT FILE
NODE-POSITION-FILE Thesis_Simulation.nodes
MOBILITY NONE

#**************************STATISTICS**************************************************************************
**
PHY-LAYER-STATISTICS YES
MAC-LAYER-STATISTICS YES
ACCESS-LIST-STATISTICS NO
ARP-STATISTICS YES
ROUTING-STATISTICS YES
POLICY-ROUTING-STATISTICS NO
QOSPF-STATISTICS NO
ROUTE-REDISTRIBUTION-STATISTICS NO
EXTERIOR-GATEWAY-PROTOCOL-STATISTICS YES
NETWORK-LAYER-STATISTICS YES
INPUT-QUEUE-STATISTICS NO
INPUT-SCHEDULER-STATISTICS NO
QUEUE-STATISTICS YES
SCHEDULER-STATISTICS NO
SCHEDULER-GRAPH-STATISTICS NO
DIFFSERV-EDGE-ROUTER-STATISTICS NO
ICMP-STATISTICS NO
IGMP-STATISTICS NO
NDP-STATISTICS NO
MOBILE-IP-STATISTICS NO
TCP-STATISTICS YES
UDP-STATISTICS YES
RSVP-STATISTICS NO
SRM-STATISTICS NO
RTP-STATISTICS NO
APPLICATION-STATISTICS YES
BATTERY-MODEL-STATISTICS NO
ENERGY-MODEL-STATISTICS YES
MOBILITY-STATISTICS NO
CELLULAR-STATISTICS YES
GSM-STATISTICS NO
VOIP-SIGNALLING-STATISTICS NO
SWITCH-PORT-STATISTICS NO
SWITCH-SCHEDULER-STATISTICS NO
SWITCH-QUEUE-STATISTICS NO
MPLS-STATISTICS NO
MPLS-LDP-STATISTICS NO
HOST-STATISTICS NO
#**************************PACKET TRACING***********************************
PACKET-TRACE NO
ACCESS-LIST-TRACE NO
#**************************Supplemental Files**************************************************************************
DUMMY-USER-PROFILE-FILE-NUMBER 0
DUMMY-TRAFFIC-PATTERN-FILE-NUMBER 0
DUMMY-ARBITRARY-DISTRIBUTION-FILE-NUMBER 0
#**************************HLA Interface**************************************************************************
HLA NO
#**************************DIS Interface**************************************************************************
DIS NO
#***********************STK Interface***********************************
STK-ENABLED NO
#**********************Physical Layer***********************************
PHY-LISTENABLE-CHANNEL-MASK 111
PHY-LISTENING-CHANNEL-MASK 111
PHY-MODEL PHY802.11b
PHY802.11-AUTO-RATE-FALLBACK NO
PHY802.11-DATA-RATE 2000000
PHY802.11b-TX-POWER--1MBPS 15.0
PHY802.11b-TX-POWER--2MBPS 15.0
PHY802.11b-TX-POWER--6MBPS 15.0
PHY802.11b-TX-POWER--11MBPS 15.0
PHY802.11b-RX-SENSITIVITY--1MBPS -94.0
PHY802.11b-RX-SENSITIVITY--2MBPS -91.0
PHY802.11b-RX-SENSITIVITY--6MBPS -87.0
PHY802.11b-RX-SENSITIVITY--11MBPS -83.0
PHY802.11-ESTIMATED-DIRECTIONAL-ANTENNA-GAIN 15.0
PHY-RX-MODEL PHY802.11b
ANTENNA-GAIN 0.0
ANTENNA-HEIGHT 1.5
ANTENNA-EFFICIENCY 0.8
ANTENNA-MISMATCH-LOSS 0.3
ANTENNA-CABLE-LOSS 0.0
ANTENNA-CONNECTION-LOSS 0.2
ANTENNA-MODEL OMNIDIRECTIONAL
PHY-TEMPERATURE 290.0
PHY-NOISE-FACTOR 10.0
ENERGY-MODEL SPECIFICATION NONE
#***************************MAC Layer*******************************
LINK-MAC-PROTOCOL ABSTRACT
LINK-PROPAGATION-DELAY 1MS
LINK-BANDWIDTH 10000000
LINK-HEADER-SIZE-IN-BITS 224
LINK-TX-FREQUENCY 1317000000
LINK-RX-FREQUENCY 1317000000
LINK-TX-ANTENNA-HEIGHT 30
LINK-RX-ANTENNA-HEIGHT 30
LINK-TX-ANTENNA-DISH-DIAMETER 0.8
LINK-RX-ANTENNA-DISH-DIAMETER 0.8
LINK-TX-ANTENNA-CABLE-LOSS 1.5
LINK-RX-ANTENNA-CABLE-LOSS 1.5
LINK-TX-POWER 30
LINK-RX-SENSITIVITY -80
LINK-NOISE-TEMPERATURE 290
LINK-NOISE-FACTOR 4
LINK-TERRAIN-TYPE PLAINS
LINK-PROPAGATION-RAIN-INTENSITY 0
LINK-PROPAGATION-TEMPERATURE 25
LINK-PROPAGATION-SAMPLING-DISTANCE 100
LINK-PROPAGATION-CLIMATE 1
LINK-PROPAGATION-REFRACTIVITY 360
LINK-PROPAGATION-PERMITTIVITY 15
LINK-PROPAGATION-CONDUCTIVITY 0.005
LINK-PROPAGATION-HUMIDITY 50
LINK-PERCENTAGE-TIME-REFRACTIVITY-GRADIENT-LESS-STANDARD 15
MAC-PROTOCOL MACDOT11
MAC-DOT11-SHORT-PACKET-TRANSMIT-LIMIT 7
MAC-DOT11-LONG-PACKET-TRANSMIT-LIMIT 4
MAC-DOT11-RTS-THRESHOLD 0
MAC-DOT11-STOP-RECEIVING-AFTER-HEADER-MODE NO
MAC-DOT11-ASSOCIATION NONE
MAC-DOT11-IBSS-SUPPORT-PS-MODE NO
MAC-DOT11-DIRECTIONAL-ANTENNA-MODE NO
MAC-SECURITY-PROTOCOL NO
WORMHOLE-VICTIM-COUNT-TURNAROUND-TIME NO
MAC-PROPAGATION-DELAY 1US
#**************************Schedulers and Queues****************************************
IP-QUEUE-PRIORITY-INPUT-QUEUE-SIZE 150000
IP-QUEUE-SCHEDULER STRICT-PRIORITY
IP-QUEUE-NUM-PRIORITIES 3
IP-QUEUE-PRIORITY-QUEUE-SIZE 150000
QUEUE-WEIGHT 0
IP-QUEUE-TYPE FIFO
#**************************QoS Configuration*********************************************
#**************************Network Security*********************************************
IPSEC-ENABLED NO
ISAKMP-SERVER NO
CERTIFICATE-ENABLED NO
EAVESDROP-ENABLED NO
AUDIT-ENABLED NO
#**************************ROUTER*****************************************************
MODEL******************************************************************************
DUMMY-ROUTER-TYPE USER-SPECIFIED
DUMMY-PARAM NO
#**************************NETWORK*****************************************************
LAYER******************************************************************************
NETWORK-PROTOCOL IP
IP-ENABLE-LOOPBACK YES
IP-LOOPBACK-ADDRESS 127.0.0.1
IP-fragment-hold-time 15s
IP-fragmentation-unit 2048
ecn no
icmp no
IPv6-enable-6to4-tunneling no

#**********************************Routing
Routing-protocol bellmanford
static-route no
default-route no
hsrp-protocol no

#**********************************Transport
Transport-protocol-rsvp yes
Gui_dummy_config_TCP yes
tcp lite
tcp-use-rfc1323 no
tcp-delay-short-packets-acks no
tcp-use-nagle-algorithm yes
tcp-use-keepalive-probes yes
tcp-use-options yes
tcp-delay-acks yes
tcp-mss 512
tcp-send-buffer 16384
tcp-receive-buffer 16384

#**********************************Mpls
Specs
Mpls-protocol no

#**********************************Application Layer
Dummy-voip-application-exists no
rtp-enabled no

#**********************************User
Behavior
Dummy-Ubee-enabled no

#**********************************Battery Models
Battery-model none

#**********************************Adaptation Protocol
Adaptation-protocol aal5
atm-connection-refresh-time 5m
atm-connection-timeout-time 1m

#********* [Default Wireless Subnet] 
Subnet n8-169.0.0.0 {1 thru 6} Default

#**********Physical Layer

[ n8-169.0.0.0 ] Phy-listenable-channel-mask[0] 111
[ n8-169.0.0.0 ] Phy-listening-channel-mask[0] 111
<table>
<thead>
<tr>
<th>Network Layer Configuration</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Network Protocol</strong></td>
<td>IP</td>
</tr>
<tr>
<td>1 IP-Protocol</td>
<td>IP</td>
</tr>
<tr>
<td>IP-Address [0]</td>
<td>169.0.0.1</td>
</tr>
<tr>
<td>2 IP-Protocol</td>
<td>IP</td>
</tr>
<tr>
<td>IP-Address [0]</td>
<td>169.0.0.2</td>
</tr>
<tr>
<td>3 IP-Protocol</td>
<td>IP</td>
</tr>
<tr>
<td>IP-Address [0]</td>
<td>169.0.0.3</td>
</tr>
<tr>
<td>4 IP-Protocol</td>
<td>IP</td>
</tr>
<tr>
<td>IP-Address [0]</td>
<td>169.0.0.4</td>
</tr>
<tr>
<td>5 IP-Protocol</td>
<td>IP</td>
</tr>
<tr>
<td>IP-Address [0]</td>
<td>169.0.0.5</td>
</tr>
<tr>
<td>6 IP-Protocol</td>
<td>IP</td>
</tr>
<tr>
<td>IP-Address [0]</td>
<td>169.0.0.6</td>
</tr>
<tr>
<td>[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-Queue-Priority</td>
<td>Queue-Size [0] 150000</td>
</tr>
<tr>
<td>[169.0.0.5 169.0.0.6] PHY-Listening-Channel-Mask 001</td>
<td></td>
</tr>
</tbody>
</table>
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4] PHY-LISTENING-CHANNEL-MASK 010
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4] PHY-LISTENABLE-CHANNEL-MASK 010
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[0] FIFO
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[2] 150000
[169.0.0.5 169.0.0.6] PHY-LISTENABLE-CHANNEL-MASK 001
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[1] FIFO
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[1] 150000
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[2] FIFO

#*************************Hierarchy Configuration***********************************
#**************************Node Configuration******************************************

[1 thru 6] NETWORK-PROTOCOL IP
[1 thru 6] IP-LOOPBACK-ADDRESS 127.0.0.1
[1] HOSTNAME host1
[2] HOSTNAME host2
[3] HOSTNAME host3
[4] HOSTNAME host4
[5] HOSTNAME host5
[6] HOSTNAME host6

[1 thru 6] IP-FRAGMENT-HOLD-TIME 15S
[1 thru 6] GUI-NODE-2D-ICON C:/snt/qualnet/5.0/gui/icons/BLACKSQUARE.png
[1 thru 6] NODE-PLACEMENT FILE
[1 thru 6] IP-ENABLE-LOOPBACK YES

K. QUALNET TRANSITION STATE BATCH FILE

# ***** QualNet Configuration File *****
#***************************************General Settings**************************************
VERSION 5.0
EXPERIMENT-NAME Check if Getting Better
EXPERIMENT-COMMENT None
SEED 1

#****************************************Parallel Settings*****************************************
PARTITION-SCHEME AUTO

#************************ATM Configuration*****************************************
DUMMY-ATM-LOGICAL-SUBNET-CONFIGURED NO
ATM-STATIC-ROUTE NO

#************************Dynamic Parameters*****************************************
DYNAMIC-ENABLED NO

#**************************Terrain*****************************************************
COORDINATE-SYSTEM CARTESIAN
TERRAIN-DIMENSIONS (1500, 1500)
DUMMY-ALTITUDES (1500, 0)
DUMMY-ENABLE-URBAN-TERRAIN-FEATURE NO
WEATHER-MOBILITY-INTERVAL 100MS
#************ Channel Properties ************************************
PROPAGATION-CHANNEL-FREQUENCY[0] 1400000000
PROPAGATION-MODEL[0] STATISTICAL
PROPAGATION-PATHLOSS-MODEL[0] TWO-RAY
PROPAGATION-SHADOWING-MODEL[0] CONSTANT
PROPAGATION-SHADOWING-MEAN[0] 4.0
PROPAGATION-FADING-MODEL[0] NONE
PROPAGATION-LIMIT[0] -25.0
PROPAGATION-MAX-DISTANCE[0] 0
PROPAGATION-COMMUNICATION-PROXIMITY[0] 400
PROPAGATIONPROFILE-UPDATE-RATIO[0] 0.0
PROPAGATION-CHANNEL-FREQUENCY[1] 1700000000
PROPAGATION-MODEL[1] STATISTICAL
PROPAGATION-PATHLOSS-MODEL[1] TWO-RAY
PROPAGATION-SHADOWING-MODEL[1] CONSTANT
PROPAGATION-SHADOWING-MEAN[1] 4.0
PROPAGATION-FADING-MODEL[1] NONE
PROPAGATION-LIMIT[1] -111.0
PROPAGATION-MAX-DISTANCE[1] 0
PROPAGATION-COMMUNICATION-PROXIMITY[1] 400
PROPAGATIONPROFILE-UPDATE-RATIO[1] 0.0
PROPAGATION-CHANNEL-FREQUENCY[2] 1900000000
PROPAGATION-MODEL[2] STATISTICAL
PROPAGATION-PATHLOSS-MODEL[2] TWO-RAY
PROPAGATION-SHADOWING-MODEL[2] CONSTANT
PROPAGATION-SHADOWING-MEAN[2] 4.0
PROPAGATION-FADING-MODEL[2] NONE
PROPAGATION-LIMIT[2] -111.0
PROPAGATION-MAX-DISTANCE[2] 0
PROPAGATION-COMMUNICATION-PROXIMITY[2] 400
PROPAGATIONPROFILE-UPDATE-RATIO[2] 0.0

#************ Mobility and Placement **************************
NODE-PLACEMENT FILE
NODE-POSITION-FILE Experiment-1.nodes
MOBILITY NONE

#******STATISTICS**********
**
PHY-LAYER-STATISTICS YES
MAC-LAYER-STATISTICS YES
ACCESS-LIST-STATISTICS NO
ARP-STATISTICS YES
ROUTING-STATISTICS YES
POLICY-ROUTING-STATISTICS NO
QOSPF-STATISTICS NO
ROUTE-REDISTRIBUTION-STATISTICS NO
EXTERIOR-GATEWAY-PROTOCOL-STATISTICS YES
NETWORK-LAYER-STATISTICS YES
INPUT-QUEUE-STATISTICS NO
INPUT-SCHEDULER-STATISTICS NO
QUEUE-STATISTICS YES
SCHEDULER-STATISTICS NO
SCHEDULER-GRAPH-STATISTICS NO
DIFFSERV-EDGE-ROUTER-STATISTICS NO
ICMP-STATISTICS NO
IGMP-STATISTICS NO
NDP-STATISTICS NO
MOBILE-IP-STATISTICS NO
TCP-STATISTICS YES
UDP-STATISTICS YES
RSVP-STATISTICS NO
SRM-STATISTICS NO
RTP-STATISTICS NO
APPLICATION-STATISTICS YES
BATTERY-MODEL-STATISTICS NO
ENERGY-MODEL-STATISTICS YES
MOBILITY-STATISTICS NO
CELLULAR-STATISTICS YES
GSM-STATISTICS NO
VOIP-SIGNALLING-STATISTICS NO
SWITCH-PORT-STATISTICS NO
SWITCH-SCHEDULER-STATISTICS NO
SWITCH-QUEUE-STATISTICS NO
MPLS-STATISTICS NO
MPLS-LDP-STATISTICS NO
HOST-STATISTICS NO
#**************************************************PACKET
TRACING****************************************************************************
PACKET-TRACE NO
ACCESS-LIST-TRACE NO
#******************************************************************************Supplemental Files******************************************************************************
DUMMY-USER-PROFILE-FILE-NUMBER 0
DUMMY-TRAFFIC-PATTERN-FILE-NUMBER 0
DUMMY-ARBITRARY-DISTRIBUTION-FILE-NUMBER 0
#******************************************************************************HLA Interface******************************************************************************
HLA NO
#******************************************************************************DIS Interface******************************************************************************
DIS NO
#******************************************************************************STK Interface******************************************************************************
STK-ENABLED NO
#******************************************************************************Physical Layer******************************************************************************

PHY-LISTENABLE-CHANNEL-MASK 111
PHY-LISTENING-CHANNEL-MASK 111
PHY-MODEL PHY802.11b
PHY802.11-AUTO-RATE-FALLBACK NO
PHY802.11-DATA-RATE 2000000
PHY802.11b-TX-POWER--1MBPS 15.0
PHY802.11b-TX-POWER--2MBPS 15.0
PHY802.11b-TX-POWER--6MBPS 15.0
PHY802.11b-TX-POWER--11MBPS 15.0
PHY802.11b-RX-SENSITIVITY--1MBPS -94.0
PHY802.11b-RX-SENSITIVITY--2MBPS -91.0
PHY802.11b-RX-SENSITIVITY--6MBPS -87.0
PHY802.11b-RX-SENSITIVITY--11MBPS -83.0
PHY802.11-ESTIMATED-DIRECTIONAL-ANTENNA-GAIN 15.0
PHY-RX-MODEL PHY802.11b
ANTENNA-GAIN 0.0
ANTENNA-HEIGHT 1.5
ANTENNA-EFFICIENCY 0.8
ANTENNA-MISMATCH-LOSS 0.3
ANTENNA-CABLE-LOSS 0.0
ANTENNA-CONNECTION-LOSS 0.2
ANTENNA-MODEL OMNIDIRECTIONAL
PHY-TEMPERATURE 290.0
PHY-NOISE-FACTOR 10.0
ENERGY-MODEL-SPECIFICATION NONE
MAC
Layer
LINK-MAC-PROTOCOL ABSTRACT
LINK-PROPAGATION-DELAY 1MS
LINK-BANDWIDTH 10000000
LINK-HEADER-SIZE-IN-BITS 224
LINK-TX-FREQUENCY 13170000000
LINK-RX-FREQUENCY 13170000000
LINK-TX-ANTENNA-HEIGHT 30
LINK-RX-ANTENNA-HEIGHT 30
LINK-TX-ANTENNA-DISH-DIAMETER 0.8
LINK-RX-ANTENNA-DISH-DIAMETER 0.8
LINK-TX-ANTENNA-CABLE-LOSS 1.5
LINK-RX-ANTENNA-CABLE-LOSS 1.5
LINK-TX-POWER 30
LINK-RX-SENSITIVITY -80
LINK-NOISE-TEMPERATURE 290
LINK-NOISE-FACTOR 4
LINK-TERRAIN-TYPE PLAINS
LINK-PROPAGATION-RAIN-INTENSITY 0
LINK-PROPAGATION-TEMPERATURE 25
LINK-PROPAGATION-SAMPLING-DISTANCE 100
LINK-PROPAGATION-CLIMATE 1
LINK-PROPAGATION-REFRACTIVITY 360
LINK-PROPAGATION-PERMITTIVITY 15
LINK-PROPAGATION-CONDUCTIVITY 0.005
LINK-PROPAGATION-HUMIDITY 50
LINK-PERCENTAGE-TIME-REFRACTIVITY-GRADIENT-LESS-STANDARD 15
MAC-PROTOCOL MACDOT11
MAC-DOT11-SHORT-PACKET-TRANSMIT-LIMIT 7
MAC-DOT11-LONG-PACKET-TRANSMIT-LIMIT 4
MAC-DOT11-RTS-THRESHOLD 0
MAC-DOT11-STOP-RECEIVING-AFTER-HEADER-MODE NO
MAC-DOT11-ASSOCIATION NONE
MAC-DOT11-IBSS-SUPPORT-PS-MODE NO
MAC-DOT11-DIRECTIONAL-ANTENNA-MODE NO
MAC-SECURITY-PROTOCOL NO
WORMHOLE-VICTIM-COUNT-TURNAROUND-TIME NO
MAC-PROPAGATION-DELAY 1US
#************************Schedulers and Queues**********************************************************
IP-QUEUE-PRIORITY-INPUT-QUEUE-SIZE 150000
IP-QUEUE-SCHEDULER STRICT-PRIORITY
IP-QUEUE-NUM-PRIORITIES 3
IP-QUEUE-PRIORITY-QUEUE-SIZE 150000
QUEUE-WEIGHT 0
IP-QUEUE-TYPE FIFO
#**************************QoS Configuration**********************************************************
#**************************Network Security**********************************************************
IPSEC-ENABLED NO
ISAKMP-SERVER NO
CERTIFICATE-ENABLED NO
EAVESDROP-ENABLED NO
AUDIT-ENABLED NO
#**************************ROUTER**********************************************************
DUMMY-ROUTER-TYPE USER-SPECIFIED
DUMMY-PARAM NO
#**************************NETWORK**********************************************************
NETWORK-PROTOCOL IP
IP-ENABLE-LOOPBACK YES
IP-LOOPBACK-ADDRESS 127.0.0.1
IP-FRAGMENT-HOLD-TIME 15S
IP-FRAGMENTATION-UNIT 2048
ecn NO
ICMP NO
IPv6-ENABLE-6to4-TUNNELING NO

#**************************ROUTING PROTOCOL********************************************
ROUTING-PROTOCOL BELLMANFORD
STATIC-ROUTE NO
DEFAULT-ROUTE NO
HSRP-PROTOCOL NO

#**************************************************************************TRANSPORT***********************************************
TRANSPORT-PROTOCOL-RSVP YES
GUI_DUMMY_CONFIG_TCP YES
TCP LITE
TCP-USE-RFC1323 NO
TCP-DELAY-SHORT-PACKETS-ACKS NO
TCP-USE-NAGLE-ALGORITHM YES
TCP-USE-KEEPALIVE-PROBES YES
TCP-USE-OPTIONS YES
TCP-DELAY-ACKS YES
TCP-MSS 512
TCP-SEND-BUFFER 16384
TCP-RECEIVE-BUFFER 16384

#**************************************************************************MPLS Specs**********************************************
MPLS-PROTOCOL NO

#*******************Application Layer********************************************
DUMMY-VOIP-APPLICATION-EXISTS NO
RTP-ENABLED NO

#***********************USER BEHAVIOR********************************************
DUMMY-UBEE-ENABLED NO

#**********************Battery Models********************************************
BATTERY-MODEL NONE

#**********************Adaptation Protocol********************************************
ADAPTATION-PROTOCOL AAL5
ATM-CONNECTION-REFRESH-TIME 5M
ATM-CONNECTION-TIMEOUT-TIME 1M

#******** [Default Wireless Subnet] ********************************************
SUBNET N8-169.0.0.0 {1 thru 6} Default

#**************************************************************************Physical Layer********************************************
[ N8-169.0.0.0 ] PHY-LISTENABLE-CHANNEL-MASK[0] 111
[ N8-169.0.0.0 ] PHY-LISTENING-CHANNEL-MASK[0] 111
[ N8-169.0.0.0 ] PHY-MODEL PHY802.11b
[ N8-169.0.0.0 ] PHY802.11-AUTO-RATE-FALLBACK NO
[ N8-169.0.0.0 ] PHY802.11-DATA-RATE 2000000
[N8-169.0.0.0] PHY802.11b-TX-POWER--1MBPS 15.0
[N8-169.0.0.0] PHY802.11b-TX-POWER--2MBPS 15.0
[N8-169.0.0.0] PHY802.11b-TX-POWER--6MBPS 15.0
[N8-169.0.0.0] PHY802.11b-TX-POWER--11MBPS 15.0
[N8-169.0.0.0] PHY802.11b-RX-SENSITIVITY--1MBPS -94.0
[N8-169.0.0.0] PHY802.11b-RX-SENSITIVITY--2MBPS -91.0
[N8-169.0.0.0] PHY802.11b-RX-SENSITIVITY--6MBPS -87.0
[N8-169.0.0.0] PHY802.11b-RX-SENSITIVITY--11MBPS -83.0
[N8-169.0.0.0] PHY802.11-ESTIMATED-DIRECTIONAL-ANTENNA-GAIN 15.0
[N8-169.0.0.0] PHY-RX-MODEL PHY802.11b
[N8-169.0.0.0] ANTENNA-GAIN 0.0
[N8-169.0.0.0] ANTENNA-HEIGHT 1.5
[N8-169.0.0.0] ANTENNA-EFFICIENCY 0.8
[N8-169.0.0.0] ANTENNA-MISMATCH-LOSS 0.3
[N8-169.0.0.0] ANTENNA-CABLE-LOSS 0.0
[N8-169.0.0.0] ANTENNA-CONNECTION-LOSS 0.2
[N8-169.0.0.0] ANTENNA-MODEL OMNIDIRECTIONAL

#*********************************************************NETWORK

LAYER**************************************************************

[N8-169.0.0.0] NETWORK-PROTOCOL IP

#******************************************************************Interface Configuration*******************************************************************************

[1] NETWORK-PROTOCOL[0] IP
[1] IP-SUBNET-MASK[0] 255.255.255.0
[1] IP-ADDRESS[0] 169.0.0.1
[2] NETWORK-PROTOCOL[0] IP
[2] IP-SUBNET-MASK[0] 255.255.255.0
[2] IP-ADDRESS[0] 169.0.0.2
[3] NETWORK-PROTOCOL[0] IP
[3] IP-SUBNET-MASK[0] 255.255.255.0
[3] IP-ADDRESS[0] 169.0.0.3
[4] IP-SUBNET-MASK[0] 255.255.255.0
[4] IP-ADDRESS[0] 169.0.0.4
[5] NETWORK-PROTOCOL[0] IP
[5] IP-SUBNET-MASK[0] 255.255.255.0
[5] IP-ADDRESS[0] 169.0.0.5
[6] NETWORK-PROTOCOL[0] IP
[6] IP-SUBNET-MASK[0] 255.255.255.0
[6] IP-ADDRESS[0] 169.0.0.6

[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[0] 150000
[169.0.0.1 169.0.0.2] PHY-LISTENABLE-CHANNEL-MASK 100
[169.0.0.5 169.0.0.6] PHY-LISTENING-CHANNEL-MASK 001
[169.0.0.3 169.0.0.4] PHY-LISTENING-CHANNEL-MASK 010
[169.0.0.3 169.0.0.4] PHY-LISTENABLE-CHANNEL-MASK 010

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[169.0.0.1 169.0.0.2] PHY-LISTENING-CHANNEL-MASK 100
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[0] FIFO
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[2] 150000
[169.0.0.5 169.0.0.6] PHY-LISTENABLE-CHANNEL-MASK 001
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[1] FIFO
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-PRIORITY-QUEUE-SIZE[1] 150000
[169.0.0.1 169.0.0.2 169.0.0.3 169.0.0.4 169.0.0.5 169.0.0.6] IP-QUEUE-TYPE[2] FIFO

#****************Hierarchy Configuration***********************************
#******************Node Configuration***********************************

[1 thru 6] NETWORK-PROTOCOL IP
[1 thru 6] IP-LOOPBACK-ADDRESS 127.0.0.1
[1] HOSTNAME host1
[2] HOSTNAME host2
[3] HOSTNAME host3
[4] HOSTNAME host4
[5] HOSTNAME host5
[6] HOSTNAME host6
[1 thru 6] IP-FRAGMENT-HOLD-TIME 15S
[1 thru 6] GUI-NODE-2D-ICON C:/snt/qualnet/5.0/gui/icons/BLACKSQUARE.png
[1 thru 6] NODE-PLACEMENT FILE
[1 thru 6] IP-ENABLE-LOOPBACK YES
LIST OF REFERENCES


INITIAL DISTRIBUTION LIST

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   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Dr. R. Clark Robertson
   Naval Postgraduate School
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