

**An Opportunistic Routing Protocol Design for Wireless Networks:
A Physical Layer Perspective**

By

Akinyemi Tolulope Aduwo

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Dr. Annamalai Annamalai, Chair

Dr. R. Michael Buehrer

Dr. William H. Tranter

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(Abstract)

Ad hoc networking research has received considerable attention in recent years as it represents the next phase of networking evolution. Efficient and reliable routing of data from the source to destination with minimal power consumption remains the crux of the research problem. Fading mechanisms inherent in wireless communications can impact the packet routing mechanisms in these types of networks. In this thesis, we develop a mathematical framework for evaluating several network diversity schemes that take advantage of the random nature of fading to provide/ enhance the network performance. The efficacy of these different network diversity mechanisms are examined in slow-fading, frequency non-selective Rice and Nakagami-m multipath fading channels. Performance metrics such as the end-to-end outage probability and the end-to-end average symbol error rate are studied in the analysis of these types of networks with the proposed network diversity schemes. Numerical results reveal that the proposed schemes can offer significant power efficiency improvement in a variety of operating scenarios of practical interest.

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*"But let your communication be,
yea, yea; nay, nay"
Matt 5:37*

Chapter 1

INTRODUCTION

The need to provide network systems that can connect various processor-controlled peripherals such as laptops, personal digital assistants (PDA), sensors etc. in locations without any fixed network infrastructure has led to the increased proliferation in research on ad hoc network technology. Wireless ad hoc networks are typically autonomous networks operating either in isolation or as "stub networks" connected to a fixed infrastructure. These types of networks have been proposed for use in scenarios where a rapid deployment of communication services are required such as physical or economical management/ recovery in disaster areas, where the deployment of fixed infrastructural networks is impractical or expensive e.g. military incursion on a foreign land, for data sharing at conferences or symposiums etc. Relative to the nodes' transceiver coverage areas, transmission power levels, co-channel interference levels and geographical location, ad hoc networks can be created and disbanded when necessary. Unlike its wired network counterpart, ad hoc networks require an improved and tailored communication protocol stack that can provide efficient networking capabilities in the face of its' continuously dynamic network topology. This occurs as a result of the non-restrictive movement of member nodes in an ad hoc network. Apart from the dynamic network topology, some of the features that uniquely characterize such networks are wireless medium bandwidth-constraint limitations, contention and channel scheduling, operational life limitation due to energy constraint, multi hop communications due to limited signal propagation characteristics and security vulnerability due to open air communication. To support data communications within this type of network

considering the afore-mentioned factors, an efficient ad hoc network routing protocol must be able to perform the following functions:

- Detect and adapt to changes in network topology when necessary
- Ensure proper contention and channel scheduling techniques to enable efficient utilization of bandwidth
- Combat susceptibility to fading mechanisms such as path loss, multipath and shadowing
- Route packet efficiently
- Enable fast converging route recovery techniques etc.

Extensive research has been done in some of the following areas cited above and many proposals have been submitted to the IETF (Internet Engineering Task Force) formed MANET (Mobile Ad hoc Networking) group which has been setup to develop and standardize routing support for mobile, wireless IP autonomous segments. Most of the routing protocols developed for this technology has been proposed and simulated based on ideal propagation characteristics only considering the transmission range of the transceiver been utilized thereby assuming optimistic situations such as bi-directional link support, free space propagation etc. Research done by [1], assumes the presence of fading mechanisms by considering propagation models such as the two ray model and the SCIRIM (Simulation of Mobile Radio Channel Impulse Response Models) model [2], which investigates path loss while considering shadowing effects and multipaths from empirical results such as those developed by [3][4]. Practical constraints limiting the ability of wireless mediums to perform at peak transmission levels such as inherent clutter in the transmission path, diverse weather conditions, shadowing effects of received local mean signal strength, diffusion of signals around obstacles and wave scattering should definitely be taken into consideration when designing protocols for communications in such networks, and mechanisms or algorithms for combating such effects should also be developed.

1.1 Diversity in Communication Systems

Cross-layer diversity improvements defined for the different layers in the communication protocol stack have been a widely increasing interest area in the academic and technological

research realm. Some established performance improvement measures have been implemented and utilized in specific layers and more research is being done on developing new algorithms to further improve the performance and effectiveness of communication systems based on enhancements derived from identifiable but random characteristics within the communication environment itself. We will go through a brief review of some of the optimization algorithms proposed and some that have already been implemented in the communication protocol stack in order to combat the time-varying nature of wireless channels. Applications and proposals for diversity mechanisms in the physical layer, media access control layer and network layer will be analyzed in the following section.

1.1.1 Physical Layer Diversity:

In general, the alleviation of the effects of such fading mechanisms on the physical layer of routing protocols based on wireless mediums have not been thoroughly investigated even though such mechanisms already exist in practice. Most existing and emerging wireless communication systems make use of diversity techniques to combat such fading mechanisms either at the receiver, transmitter or both. Diversity combination which involves the combining of two or more copies of the transmitted signal to increase the overall signal-to-noise ratio (SNR) has been the most efficient and well known concept for performance improvement of communication systems. Some of the well known methods of providing such diversity improvement to these types of communication systems are;

- Frequency Diversity

This is implemented by transmitting the information signal on more than one carrier frequency where the frequencies are assumed uncorrelated if they have a separation greater than the coherent bandwidth of the channel. This type of diversity is typically used in microwave line-of-site (LOS) which carries several channels in a frequency division multiplex mode (FDM) [3]. It is not an efficient technique due to its large bandwidth requirement

- Time Diversity

This type of diversity is achieved by transmitting information signals at spatial separations that exceed the coherent time of the channel to ensure the reception of uncorrelated multiple path copies of the transmitted signal at the receiver. This type of diversity technique is being implemented in the use of coding in fast fading channels.

- Space Diversity

This type of diversity entails the transmission or reception of the information signal through a number of antennas with separation distances of tens of wavelengths, in narrow angle spreads ($\lambda/2$ is sufficient enough for many other scenarios), to ensure uncorrelated multipaths arriving at the receiver. This type of diversity technique is being used in cellular mobile communications and is currently receiving implementation via the following techniques e.g. Maximal Ratio Combining (MRC), Equal Gain Combining (EGC), Selection Diversity Combining (SDC) etc.

- Code Diversity

This type of diversity involves the use of unique codes to multiplex transmitted data; so as to increase capacity and reduce the effect of interference by spreading the signal over large bandwidths thereby introducing the concept of low probability of intercept (LPI), since only the receiving node can decode the sent data. An example of this is Walsh codes used in CDMA technology to distinguish between multiple users in a given communication system. Another class of codes called error correction codes has also been utilized in communication systems to counter problems that may occur such as fading, pulse jamming etc. By encoding and interleaving the transmitted data, a block of affected data can be de-interleaved to produce an output with random bursts of errors rather than receiving a whole block of data in error.

1.1.2 Media Access Control (MAC) Layer Diversity:

Diversity schemes utilized in the MAC layer of communication systems have been in existence for a while now. Channel scheduling schemes that increase the probability of signal reception and reduce packet loss at the receivers use different types of algorithms to determine when to

allocate precious communication resources to the requesting communication node. Dynamic Smart Scheduling algorithms that exploit channel characteristics have been developed to allocate necessary channels and proper bandwidth needed for the communicating system based on feedback in the form of signals traversing the network that collects pertinent information about the channel. This can be implemented in a continuously adaptive or instantaneous manner.

Link adaptive algorithms also have been proposed in some communication systems where a system can utilize the bandwidth and energy efficiency of different modulation/ coding schemes e.g. GMSK (Gaussian Minimum shift Keying), 8-PSK (8-ary Phase Shift Keying), 16-QAM (16-ary Quadrature Amplitude Modulation) etc. inherent in the system to transmit symbols. This can be done based on feedback information, channel quality measurements and pre-defined adaptation thresholds. QoS (Quality of Service) for real time applications is one of the possible enhancements that can be achieved based on proper channel scheduling, bandwidth allocation and reduced data latency by introducing calculated delays in the transmission flow of packets when channel conditions deteriorate. Redundancy schemes such as ARQs are also used to alleviate the reception of erroneous data in a communication system. Automatic repeat request (ARQ) is a protocol for error control in data transmission. When the receiver detects an error in a packet above its correctional capabilities, it automatically requests the transmitter to resend the packet. This process is repeated until the packet is error free or the error continues beyond a predetermined number of transmissions. ARQ is sometimes used with Global System for Mobile (GSM) communications to guarantee data integrity [5].

Current research is being done in extracting information from packets involved in collisions within a specific transmission period. This form of diversity becomes useful if channel degradation is constant which makes mechanisms such as ARQ consistently redundant. Diversity is inherently achieved by combining collided packets with other collided packets that occur in future retransmissions, in order to perform separation techniques that will detect information from the individually collided packets. Selective retransmission algorithms are utilized in enabling only nodes whose packets have collided to retransmit their signals based on network resources. NDMA (Network-assisted Diversity Multiple Access), [6] is an example of this type of MAC layer diversity.

1.1.3 Network Layer Diversity:

The network layer basically determines the path to route the data packets based on information received from the MAC layer. Diversity techniques have been also utilized in this layer to reduce the probability of packet loss at the receiver. One of the more popular schemes used is Path Diversity. Path diversity involves the transmission of the same packet of data over different routes to the receiving node in such a manner as to minimize network congestion while increasing reliability of data delivery. Single/ Multiple copies of the packet can be made and relayed along these routes, depending on the routing algorithm, to reduce the probability of the next hop node not receiving the packet based on link failure or node failure of intermediary hops. The multiple path routes traversed can either be jointed or disjointed paths based on the type of algorithm used. Decisions carried out in the Network layer are made from cost metrics gathered in the system during route discovery methods. These cost metrics provide information such as power consumption levels, average end-to-end delays, battery discharge depth; alternate neighboring routes etc. and also determine broken links that help the network layer determine the appropriate path that will enable efficient routing.

Adaptive algorithms can also be implemented on Network layer routing protocols based on the present state of the network and its member nodes. In [7], a routing algorithm scheme is proposed where based on the remaining energy capacity of nodes in a given ad hoc network system, MTPR (Minimum Total Transmission Power Routing) or CMMBCR (Conditional Max-Min Battery Capacity Routing) algorithm can be used to provide considerable trade-offs between power savings (energy efficiency) and average end-to-end delay.

1.2 Overview of Physical Layer Diversity Combination Techniques

As stated above, diversity is a well known communication technique that provides increased performance in wireless links at relatively low cost with a wide range of implementations. Diversity exploits the random nature of transmitted radio signals by making use of highly uncorrelated or independent paths for communication. Diversity techniques are mainly employed at the receiver but have recently had proliferation in application at transmitters. Fading in communication systems can generally be categorized into two types, namely small-scale and

large-scale fading. Small-scale fades are basically deep amplitudinal fades and rapid fluctuations which occur as the receiving nodes move over distances of short wavelengths. Microscopic diversity techniques reduces the effect of instantaneous short term fading at the radio port by exploiting the rapidly changing signal for example using multiple antennas separated by a few wavelengths can ensure that while one antenna receives a null (deeply faded signal), the other antennas can receive a stronger signal. Large-scale fades are caused by the variations in local mean power received due to the nature of clutter or topology in the communication path. This phenomenon is called shadowing and can be combated by using groups of geographically distributed radio ports to improve system performance.

Some of the more common diversity schemes implemented in radio communications are classified based on their combination characteristics e.g. Maximal Ratio Combining (MRC), Equal Gain Combining (EGC), Selection Diversity Combining (SDC) and the more recent Generalized Selection Combining (GSC). In MRC, signals from ' L ' received branches are weighted according to their individual signal-to-noise ratios (SNR) and then summed. The individual signals are co-phased before they are summed to account for phase distortion due to channel noise. This technique provides the best performance of a signal subjected to a fading environment of any known linear diversity combiner [3]. Extensive research to analyze the performance of this scheme has been done for various types of propagation conditions [8][9][10]. Selection Diversity (SDC) is conceivably the simplest diversity technique that can be employed in communication systems where the branch with the highest SNR is selected form a set of ' L ' received branches to provide increased system performance against fading.

EGC combination is implemented by first co-phasing the outputs of different diversity branches and having them weighted equally before summing them up to provide the combined signal. Analysis of the performance of this type of diversity scheme has been done in [11][12]. Due to the complexity involved in receiver design to enable the capture of all the received signal branches, a hybrid combination technique known as GSC is considered. This has the advantage of selecting a set of strongly received signals from the signal branches received and summing the selected branch set after co-phasing and weighting. The analysis of the performance of this type of diversity scheme for different number of branches combined can be found in [13][14][15].

1.3 Overview of Routing Protocols

Routing can be basically defined as the determination of a reliable path within a network from a source node to a destination node. As mentioned above, many of the routing protocols that have been designed for ad hoc Network technology have been able to tackle most of the inherent problems that routing in an ad hoc wireless network environment presents. Examples of some of the protocols that have been developed can be found in [1][16][17][18] etc. Most of these protocols have been based on the existence of an efficient MAC protocol such as MACA [19], MACAW [20], PAMAS [21] etc., which have been designed to solve existing media contention problems (i.e. hidden node, exposed node and capture) and at the same time providing benefits such as efficient power conservation of nodes (PAMAS). Routing protocols can be grouped into three main categories which are described below;

- **Proactive (Active) Protocols**

These are routing protocols that maintain a global view of the network and are based on traditional distance-vector and link-state protocols. Each node in the network maintains information about every other network edge by using periodic or event-triggered routing update exchanges. This types of routing protocols generally have very high overhead due to the route updates exchanged periodically but very low latency for packet forwarding as the requested route path is already known. Examples are Destination Sequenced Distance Vector Routing Protocol (DSDV) [17], Wireless Routing Protocol (WRP) [23], Optimized Link State Routing Protocol (OLSR) [22] etc.

- **Reactive or On-Demand (Passive) protocols**

These types of routing protocols determine route paths when required by using data dissemination techniques such as flooding. Nodes operating with this type of protocol only maintain active routes in the network and these routes can be purged or retained in memory when no longer needed. On-demand protocols are generally associated with low overheads and have been known to have good scalability properties due to the transmission of control messages in the system only when necessary. They usually have a high latency for packet forwarding as the routing path discovery is initiated when there is data to be sent. Examples are Ad Hoc On-

Demand Distance Vector Routing Protocol (AODV) [16], Dynamic Source Routing Protocol (DSR) [18] etc.

- **Hybrid Protocols**

These types of protocol combine characteristics from active and passive routing protocols to achieve properties such as hierarchical routing. These types of protocol are generally implemented in clustered networks, where nodes are grouped into small clusters to form smaller networks within a large network. Intra-cluster routing among nodes are usually proactive, while Inter-cluster routing is done on-demand. Examples are Zone Routing Protocol (ZRP) [24].

Some of these protocols have been submitted for RFCs (Request for Comments) to the IETF while others are still being improved upon. Extensions to these protocols have also been developed that make use of redundant paths for the specialized case of multicast routing where a sender tries to transmit data to multiple receivers e.g. Ad hoc On-Demand Multiple Distance Vector Routing Protocol (AOMDV) [25], Multipath Dynamic Source Routing Protocol (MDSR) [26] etc. Current research is being done to propose energy efficient routing protocols that will conserve power and increase network operational lifetime.

1.4 Motivation for Research

Research on various ad hoc routing protocols have recognized the presence of fading mechanisms during packet transmissions [1][16][17], but none of these literature exploit the benefits of multiple path fading in the network layer. Multiple path routing is an interesting proposition to exploit distinct fading statistics on different paths to enhance the network performance or reliability. This is accomplished by creating multiple paths from a transmitter to the receiver, transmitting identical data simultaneously on these multiple paths and processing them at the receiver.

Reference [27] proposes and analyzes a network layer diversity scheme based on the selection of the path that provides the highest instantaneous and local mean SNR (similar in concept to the physical layer's macro and micro SDC scheme) from a set of monitored multiple routing paths.

It was also shown that the long term power consumption can be reduced by the fraction of nodes in the observed set. However, analysis carried out in [27] assumes optimistic scenarios such as assuming independent and identical fading statistics. Moreover, the number of nodes within the observed set is limited to two. Clearly, this performance can be improved by combining the signals from an increased number of multiple paths instead of limiting choices to choosing only the strongest path out of two monitored paths.

1.5 Contribution of Thesis

In this thesis, we extend the analysis presented in [27] in several ways:

First, we define several variants of the network diversity schemes namely Selection Route Path Combining Macro Network Diversity (SRPM), Maximal Ratio Route Path Micro Network Diversity (MRRP), Equal Gain Route Path Micro Network Diversity (EGRP) and Generalized Route Path Micro Network Diversity (GRP (N, L)) (similar in concept to the physical layer's MRC, EGC and GSC diversity schemes respectively for the latter schemes) to provide improved performance against fading mechanisms in ad hoc networks. The proposed schemes consider arbitrary L paths being monitored in each cluster instead of only two nodes in the observed set adopted in [27]. To model more practical scenarios, the restriction of independent and identical statistical distributions is shelved and analysis is carried out for various propagation fading models based on varying local mean strengths, varying fading severity indexes and mixed fading scenarios. The effects of correlation on this network diversity schemes are also considered. Previously developed analytical expressions are applied in these scenarios to determine the power consumption in the implementation of these diversity schemes and the inherent gain in power consumption is analyzed and compared to results provided in [27]. The performances of the various network diversity combination techniques defined will be determined using performance metrics such as end-to-end outage probability and end-to-end ASER (average symbol error rate).

1.6 Outline of Thesis

The remainder of this thesis is organized as follows:

A brief description of the factors that affect communication networks and various fading propagation models together with a framework for the implementation of the various network diversity schemes sited in our ad hoc network model are provided in Chapter 2.

Chapter 3 and 4 analyzes the performance of the proposed network diversity schemes in the presence of the Rice and the Nakagami-m fading scenarios with the Rayleigh fading scenario as a special case. Analytical expressions for the power consumption gains are developed, analyzed and compared for the various diversity schemes.

Finally, Chapter 5 summarizes the conclusions of this thesis and suggests further research work that can be carried out in this area.

*"Be who you are and say what you feel,
because those who mind don't matter and
those who matter don't mind".*

- Eleanor Roosevelt

Chapter 2

SYSTEM NETWORK MODEL:

2.1. PROPAGATION FADING MECHANISMS

In defining our system model to analyze the performance of diversity combining in ad hoc networks, the effect of the channel characteristics that serve as the medium of communication for wireless networks is taken into consideration. The independent effects that arise from the non-stability of the channel characteristics are namely; (i) path loss, (ii) Random Shadowing and (iii) Multipath Fading and are briefly described in the following section:

- **Path Loss**

This is the phenomenon that occurs as a result of the attenuation of the signal strength propagated relative to distance. This effect basically describes the decay of the mean signal strength between communicating mobile stations. Extensive research has been done in the past to correctly model the effects of path loss mathematically [3], and both theoretical and empirical propagation models have been developed. The results indicate that the mean signal strength decreases by a power law of the distance (or logarithmically in the dB scale). Mathematically, the path loss is expressed as

$$\mu(d)_{dB} = 10n \log_{10} \frac{d}{d_0} \quad (2.1)$$

where, n is the path loss exponent, with different values already defined for different propagation scenarios [3]. n is given as 2 for free space propagation, and 2-4 depending on the amount of clutter present in the propagation path. d_o is the close-in reference determined from measurements for different communication systems and d is the separation between the transmitting node and the receiving node.

- **Lognormal Shadowing**

Shadowing is the measured effect said to occur over a large number of measured locations which have the same separation distance but with different levels of clutter present in the propagation path. Empirical and theoretical data collected over the course of many experiments has shown that this phenomenon is closely modeled by the log normal distribution. In dB scale, the effect is defined by a Gaussian (normal) distribution around the distance dependent mean derived from the path loss model (2.1). The PDF (Probability density function) of the resulting signal power is as given below;

$$p(\bar{\gamma})_{dB} = \frac{1}{\sigma_{\gamma dB}^- \sqrt{2\pi}} \exp\left(-\frac{(\bar{y}_{dB} - \mu_{dB})^2}{2\sigma_{\gamma dB}^{-2}}\right) \quad (2.2)$$

$$p(\bar{\gamma}) = \frac{1}{\gamma\sigma_{\gamma}^- \sqrt{2\pi}} \exp\left(-\frac{\ln(\bar{\gamma} / \mu_{\gamma}^-)^2}{2\sigma_{\gamma}^{-2}}\right) \quad (2.3)$$

where, μ_{dB} is the mean power received (in dB) and σ_{dB} is the shadow standard deviation (in dB)

- **Multipath**

The phenomenon that occurs, whereby, delayed multiple copies of a transmitted signal is received at an intended (receiving) node is called multipath fading. These multiple copies result as an effect of the different channel characteristics encountered due to clutter in the propagation path that result in the reflection, scattering and diffraction of the transmitted signal. Due to the non-stability and randomness of the channel characteristics, short or long term fading of some reflected signals might result during propagation which can result in the constructive or destructive combination of the delayed signals at the receiver causing fluctuations in the envelope and phase of the received multipath signal.

2.2. Fading Channels

Based on the degree of variations between the transmitted signal and the fading channel, the effect of the channel characteristics on the transmitted signal can be classified into four categories that are described below;

- Flat Fading

Flat fading occurs as a result of the uniform effect of the channel on the spectral components of the transmitted signal. This occurs for narrowband systems in which the transmission signal bandwidth is much smaller relative to the channels' coherent bandwidth B_c , where B_c is defined as the frequency bandwidth for which two samples of the channel response are considered as correlated over a given frequency range

- Frequency Selective Fading

Frequency Selective Fading occurs as a result of the spectral components of the transmitted signal being affected by different characteristics of the same channel (i.e. different amplitudinal gains and phase shifts) resulting in a distortion of the received signal. This type of effect mostly applies to wide bandwidth systems in which the channels' coherence bandwidth is much smaller than the bandwidth of the transmitted signal

- Slow Fading

A signal is said to undergo slow fading if the symbols' time duration T_s is much smaller than the channels' coherence time T_c , where T_c is defined as the time period over which two samples of the channel response taken at the same frequency but at different time instances are considered correlated or in other words, the channel is assumed as changing much more slowly than the symbol duration.

- Fast Fading

A signal is considered to be undergoing fast fading if the symbols' time duration T_s is much larger than the coherent time of the channel T_c . This effect leads to frequency dispersion of

the transmitted signal due to a phenomenon called Doppler Spreading, which leads to the distortion of the signal (Doppler spreading also occurs in slow fading scenarios).

2.3. Propagation Channel Models

Depending on the nature of the propagation environment i.e. level of clutter, channel effects, degree of diffraction or scatter etc. the received envelopes of the multipath signals have been closely determined to follow one of the following fading distribution models;

2.3.1. Rayleigh Fading Model

This type of distribution model is used to define the fading of the received envelope for non line-of-sight (NLOS) components of multipath signals. This usually occurs in the presence of clutter between the transmitting and receiving nodes.

The signal received from the i th path in this case is mathematically defined as,

$$r(t) = \alpha_i x_i(t) + n(t) \quad (2.4)$$

where, α is the amplitudinal fading of the i th path signal by the channel and can be modeled by a Rayleigh distribution with a PDF which is given as,

$$p(\alpha) = \frac{2\alpha}{\Omega} \exp\left(-\frac{\alpha^2}{\Omega}\right), \alpha \geq 0 \quad (2.5)$$

where, $\Omega = E[\alpha^2]$ and $E[x]$ denotes the expectation of x . The instantaneous and mean SNR of the i th path is defined as γ and $\bar{\gamma}$, where the PDF of γ is defined as

$$p(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \quad (2.6)$$

The Cumulative Distribution Function (CDF) is defined as,

$$F(\gamma) = 1 - \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \quad (2.7)$$

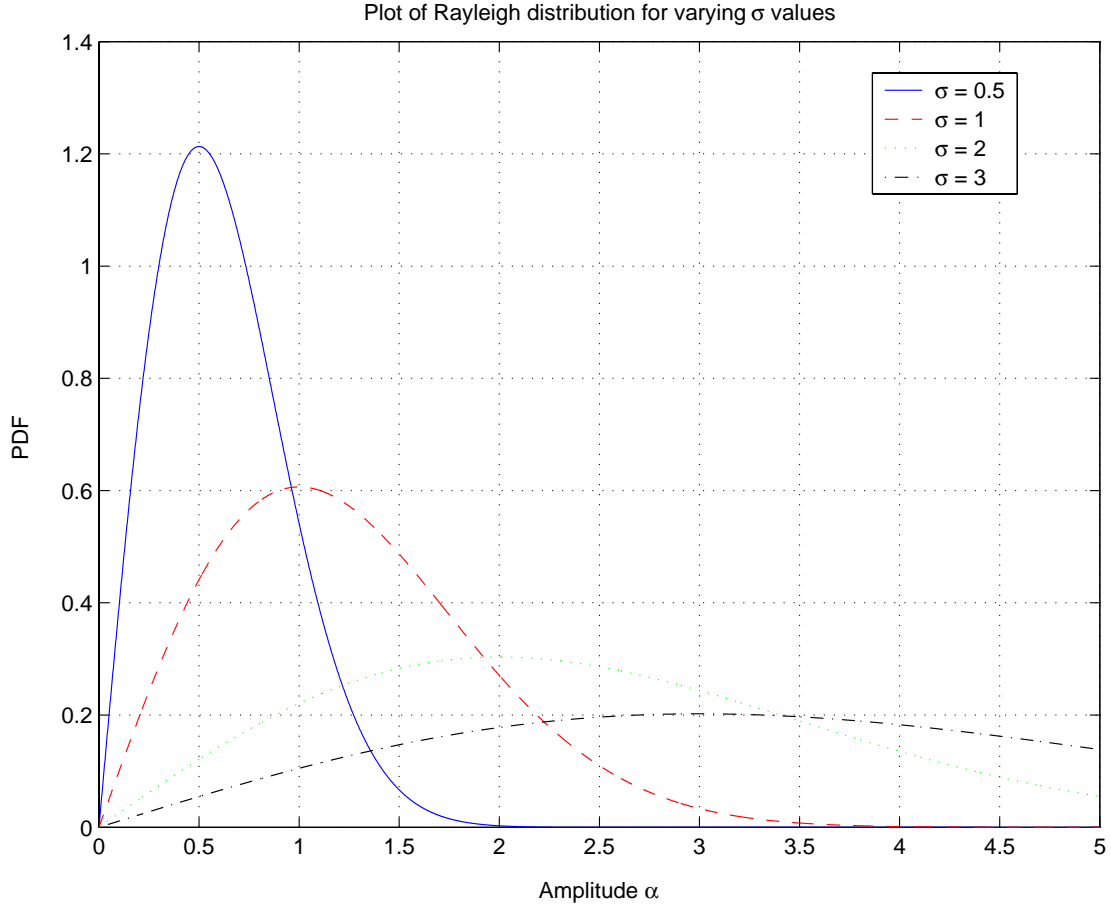


Fig 2.1: PDF of a Rayleigh distribution for different σ (standard deviation) values

2.3.2. Rice Fading Model

This distribution model is used to define the fading characteristics of the envelope of the received multipath components in the presence of a line-of-sight (LOS) component. The amplitude α of the received signal is defined by the non central chi distribution

$$p(\alpha) = \frac{2(1+K)\alpha}{\Omega} \exp(-K) \exp\left(-\frac{(1+K)\alpha^2}{\Omega}\right) I_0\left(2\alpha\sqrt{\frac{K(1+K)}{\Omega}}\right) \quad (2.8)$$

The PDF and CDF of the instantaneous SNR, γ are given as follows

$$p(\gamma) = \frac{K+1}{\gamma} \exp\left(-K-\frac{(K+1)\gamma}{\Omega}\right) I_0\left(2\sqrt{\frac{K(K+1)\gamma}{\Omega}}\right) \quad (2.9)$$

$$F(\gamma) = 1 - Q\left(\sqrt{2K}, \sqrt{\frac{2(K+1)\gamma}{\bar{\gamma}}}\right) \quad (2.10)$$

where K denotes the Rice fading factor which is defined mathematically as the ratio between the specular component and the variance of the multipath components, $I_0(x)$ is the zeroth-order modified Bessel function of the first kind and $Q(a,b)$ is the first order Marcum Q function which is defined as

$$Q(a,b) = \int_b^{\infty} x \exp\left(-\frac{x^2 + a^2}{2}\right) I_0(ax) dx \quad (2.11)$$

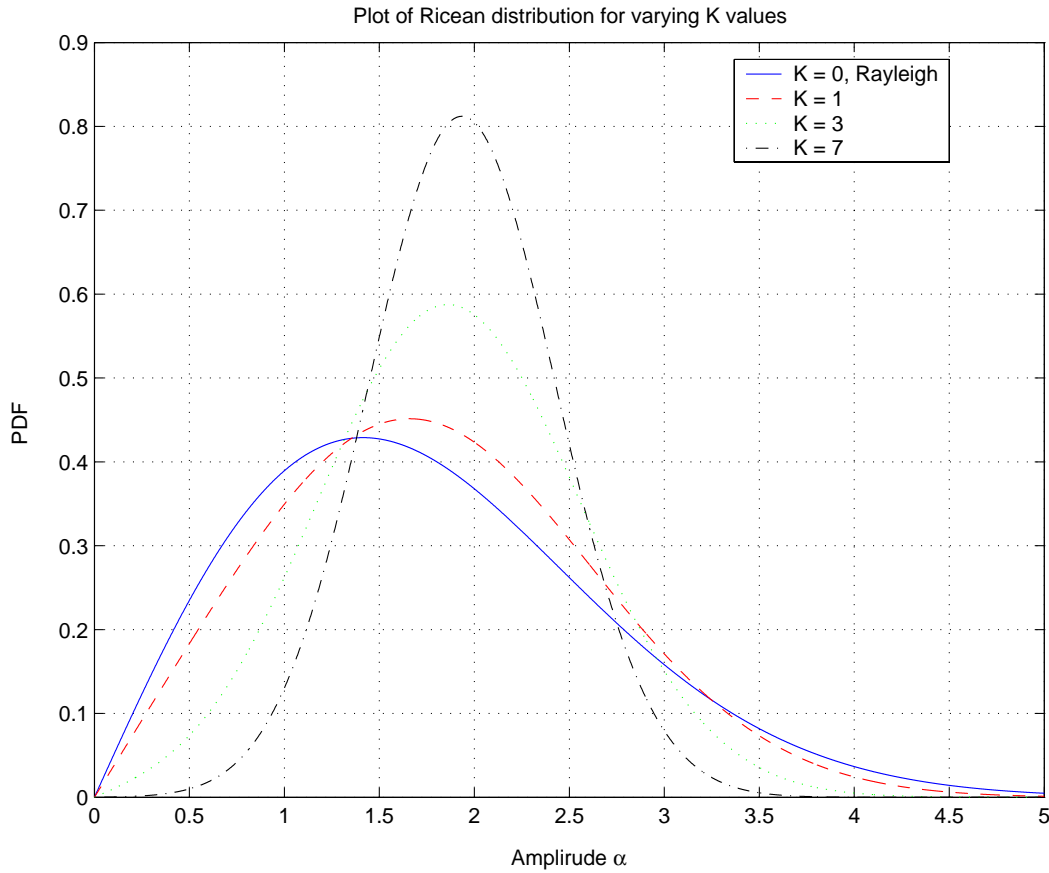


Fig 2.2: PDF of a Rice distribution for varying K values

2.3.3. Nakagami-m fading model

This distribution model has been known to closely define the statistical fading model of the received signals based on empirical results. The simple analytical form it possesses has made it very attractable for performance analysis and it is very flexible because it can easily

account for both severe and weak fading and can also model the classical Rayleigh fading distribution ($m = 1$) and the one sided Gaussian distribution ($m = 1/2$) as special cases. The Rice distribution can also be closely modeled by defining ($m = (K+1)^2 / (2K+1)$).

The PDF of the Nakagami-m distribution is defined as

$$p(\alpha) = \frac{2m^m \alpha^{2m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{m\alpha^2}{\Omega}\right), \alpha \geq 0 \quad (2.12)$$

The PDF and CDF of the instantaneous SNR, γ are defined as follows

$$p(\gamma) = \frac{1}{\Gamma(m)} \left(\frac{m}{\gamma}\right)^m \gamma^{m-1} \exp\left(-\frac{m\gamma}{\gamma}\right) \quad (2.13)$$

$$F(\gamma) = \frac{\Lambda\left(m, \frac{m\gamma}{\gamma}\right)}{\Gamma(m)} \quad (2.14)$$

where, $m = \Omega_i^2 / E[(\alpha_i^2 - \Omega_i^2)] \geq 0.5$ (fading parameter index of the i th path), $\Gamma(m)$ is the gamma function and $\Lambda(\cdot, \cdot)$ is the incomplete gamma function.

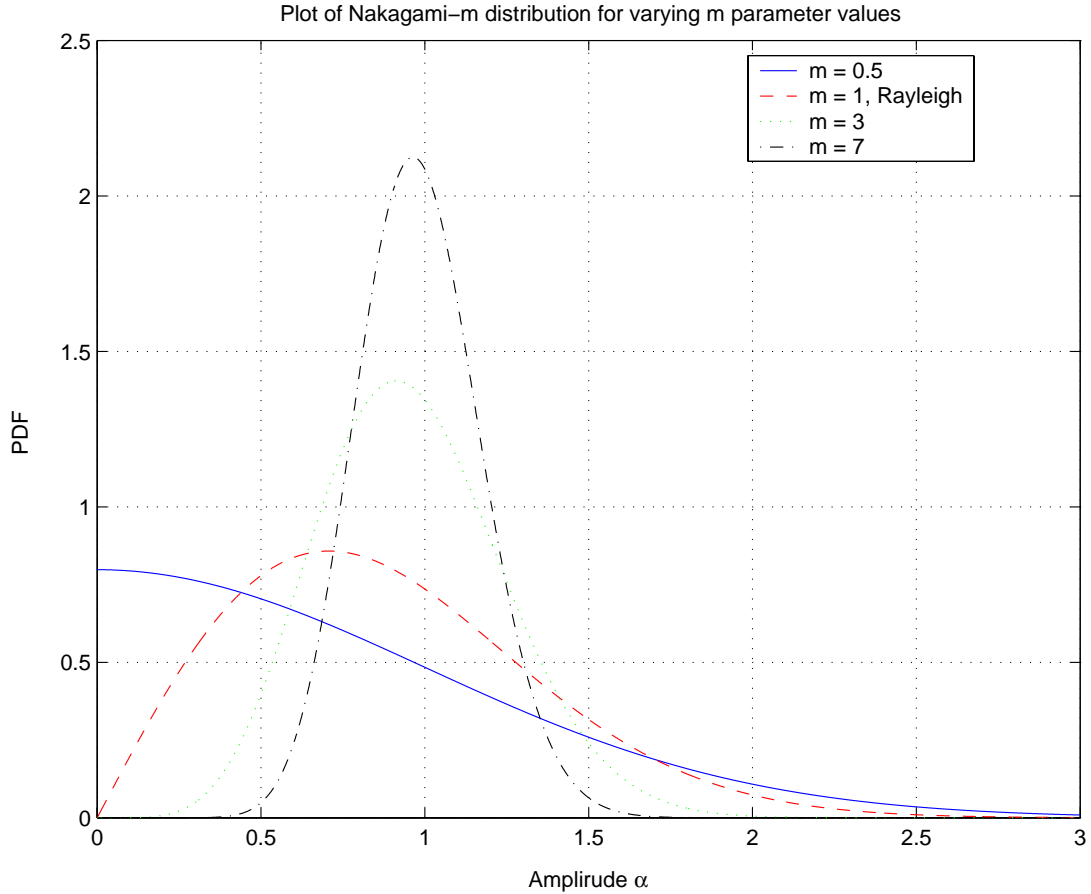


Fig 2.3: PDF of a Nakagami-m distribution for varying m (fading index) values with $\Omega = 1\text{dB}$

2.4. NETWORK LAYER DIVERSITY MECHANISMS

The ad hoc network defined for our model is based on the advantages provided by clustering technology. This clustering technique allows for small groups of nodes in the network to come together as a group or under the centralized administration of one of the nodes in the network in order to achieve a form of hierarchical routing. The small groups then intercommunicate with each other to form the network domain. Most clustering techniques employ the use of a cluster head that is selected based on some clustering algorithms such as the highest connectivity algorithm, the lowest ID algorithm, the least clusterhead change algorithm etc. to maintain the member nodes in the cluster and also to handle important issues such as media contention, channel scheduling etc. In our network model, the members of a cluster are assumed to be aware

of each other and can easily communicate with each other via a control channel or broadcast messages. The clustering algorithm is not the main issue here and extensive literature on it can be found in [1][28]. The main benefit proposed by clustering is to reduce traffic overhead incurred from control messages in the network by localizing these control messages within individual clusters.

In our system model, we assume that the network is defined by a certain number of cluster groups C_i , where $i = 0, 1, \dots, n$, which communicate with each other to define the network domain. Each cluster is defined by a certain number of individual nodes N_i where, $i = 0, 1, \dots, n$. Communication is achieved by either direct transmission from sender node to receiving node if they are within each others transmission ranges or by employing the use of other nodes as intermediate hops in the route path. Under normal operating conditions, the transmission ranges of each node will be limited by the random characteristics of the wireless medium, therefore we introduce the concept of diversity into our system whereby, multiple copies of the signal received by a set of nodes is analyzed to select the one that has the largest instantaneous/ local mean Signal-to-Noise Ratio (SNR), or is combined to increase the SNR of the signal received at that node. The Figure [2.4] below shows a model of our network

The network model assumes the following;

- Existing routing protocol present.
- Existing MAC layer that resolves contention situations such as the hidden and exposed node problem.
- Existence of a control channel (for control messages) and data channels (for transmitting packets).
- The path to the sending and receiving node is known using route discovery methods.
- Power levels of individual nodes in a cluster are monitored from control message exchanges among nodes.
- Allocation of a control channel for each cluster to allow for intra-cluster control message exchanges.

- Nodes in the receiving cluster can easily exchange data due to closeness in proximity (i.e. high SNRs of the signal will be received when data is exchanged among nodes in a cluster relative to their position, thereby fading is considered negligible).

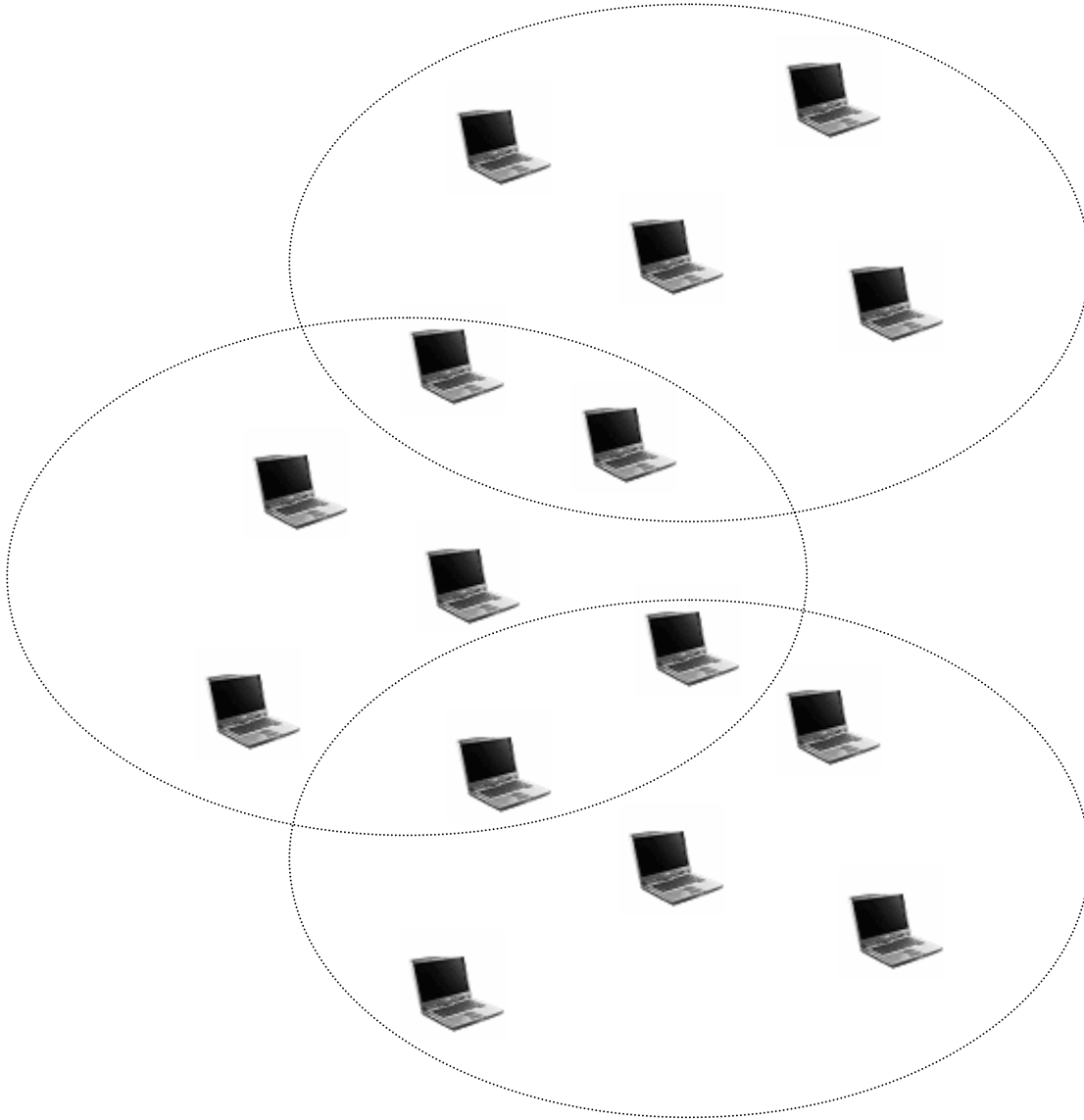


Figure 2.4: System network model for network diversity algorithms

The MAC layer contention system considered in the implementation of these network diversity schemes allows a node from one cluster to communicate with a node or group of nodes in another cluster. Many schemes already exist that provide the desired operation and some of them are CDMA, FDMA/ TDMA and Space Time Coding with orthogonal code design. To effectively study the improvements introduced by network diversity, the use of some of these

contention/ access techniques will involve a division of transmission power among the nodes in the observed set while transmitting multiple copies of the data to be sent so as not to exceed the amount of power needed during the operation of conventional routing protocols. This inherently provides improved system performance in terms of system capacity and channel/ frequency re-use for these types of access schemes.

2.5. NETWORK DIVERSITY PROTOCOL SCHEMATICS FOR SYSTEM NETWORK MODEL

Improved performance such as increased SNR levels and reduced transmission powers can be gained in the defined network model by the application of diversity combination techniques at the network layer of ad hoc network routing protocols which will inherently provide diversity improvements at the physical layer that will transcend back to the network layer. The framework for the application of such models is as described below

2.5.1. Selection Route Path Combining Network Macro Diversity (SRPM):

As mentioned in the introduction, existing and newly developing protocols use various metrics to determine the path route without taking into consideration the effects of multipath fading and shadowing in the wireless medium. Increased improvement can be gained in terms of system performance by basing the routing decisions, on the route path to the destination with the highest local mean power, thereby accounting for shadowing in the system. To this effect, we introduce the SRPM scheme, whereby based on location information, a sending node monitors L nodes with the highest local mean SNRs from the receiving cluster of N nodes. The node with the highest local mean power is then selected a priori to be the next hop by the sender when data is to be relayed to the intended receiver. The local mean power levels of the surrounding neighbors of all nodes in the network can be monitored by measuring the strength of broadcast/ HELLO messages received in the network system at intermittent periods. This information is updated and stored within a look-up table in the receiving node. The mathematical representation for this selection operation is as given below.

$$\gamma_{out} = \max(\bar{\gamma}_1, \bar{\gamma}_2, \dots, \bar{\gamma}_L) \quad (2.15)$$

From the Figure [2.5] below, the operation that transpires in the routing of packets from a node ‘S’ to a node ‘R’ is labeled 1-3 in its sequence of occurrence. In stage 1, the $L = 3$ nearest neighbors are monitored with respect to their received local mean power levels. When a packet arrives at the buffer of node S, it selects the node with the largest local mean level determined from various route maintenance mechanisms and transmits the packet with the necessary routing information attached. The node checks its internal route tables and discovers that it has a direct path to the receiving node R. In stage 3, the message is then transmitted to the intended receiving node.

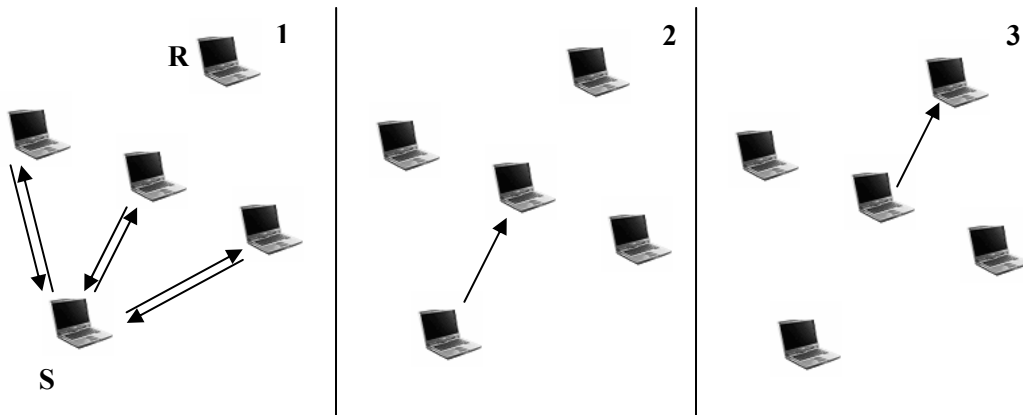


Figure 2.5: Routing operation from sender node ‘S’ to receiving node ‘R’ using the network based macro diversity selection scheme.

2.5.2. Selection Based Route Path Combining Network Micro Diversity (SRP):

More diversity can be introduced into the system by taking into account the effects of multipath fading in the system. This can be included by choosing the node in the receiving cluster with the largest local mean and instantaneous SNR as the next hop node.

In [27], the network system is analyzed based on the concept of pre-selecting two nodes with the highest local mean SNR in the receiving cluster. The data to be sent is then transmitted to the 2 selected nodes. The selected nodes, upon processing a portion of the packet header, communicate with each other to determine the node that received the transmitted data with the highest instantaneous SNR. This node then continues to process the data and the whole process is repeated until the data reaches the intended receiver. In this thesis, we introduce more

diversity into the network system by removing the restriction of pre-selecting 2 nodes and monitor L nodes instead. The data destined for the receiver is then transmitted to the L nodes which process the packet header to determine the instantaneous SNR value of the signal received. The L nodes in the receiving cluster communicate among themselves using short burst messages via a control channel to determine which node received the highest instantaneous SNR. The selected node processes the message and sends it to the next receiving cluster. This process is repeated until the data gets to the intended receiver. The signal received at the next hop in the receiving cluster is defined by;

$$\gamma_{out} = \max(\gamma_1, \gamma_2, \dots, \gamma_L) \quad (2.16)$$

This diversity scheme introduced in the network layer will bring about improvements in terms of increase in the SNR of the transmitted signal at the receiver. Inherently, to achieve the same performance in terms of outage probability and average symbol error rates in conventional routing protocols, the power needed by this scheme will be a fraction of the power used in these types of routing protocols, this is due to the fact that conventional route protocols try to use shortest hop algorithms in determining their route path. Generally, this reduced power consumption will bring about improvements in terms of system capacity (improved frequency re-use in terms of multiple access technologies such as FDMA) based on the limited channels provided for communication in the network system and also introduce more hops in the route path (since closer nodes will be more likely to have higher local mean SNRs). The increased number of hops in the network system will allow for increased reliability in terms of transmission and reception of signals and will also reduce the number of possible interferers for contention mediums such as CDMA. The assumption of slow fading is made in this system; thereby a receiver can determine the instantaneous SNR of the signal being received by processing a portion of the packet header. Control channels are assumed to be unique among clusters in the network and only used to transmit such inter-cluster information. This network diversity scheme is based on the SRPM and can be integrated into already existing unicast and multicast routing protocols. An illustration of the Selection based micro diversity scheme is shown in Figure [2.6] below.

From the Figure [2.6] below, the 4 stage operation for this routing scheme is shown. Stage 1, shows the $L = 3$ nearest neighbors being monitored with respect to their received local mean

power via broadcast messages. The second stage shows data being transmitted to the L monitored nodes and also shows the exchange of messages via the control channel containing information on the instantaneous SNR for the signals received by each node. The node with the highest instantaneous SNR continues processing of the data being received while the other nodes stop processing as depicted in stage 3. Stage 4 shows the final transmission to the intended receiver.

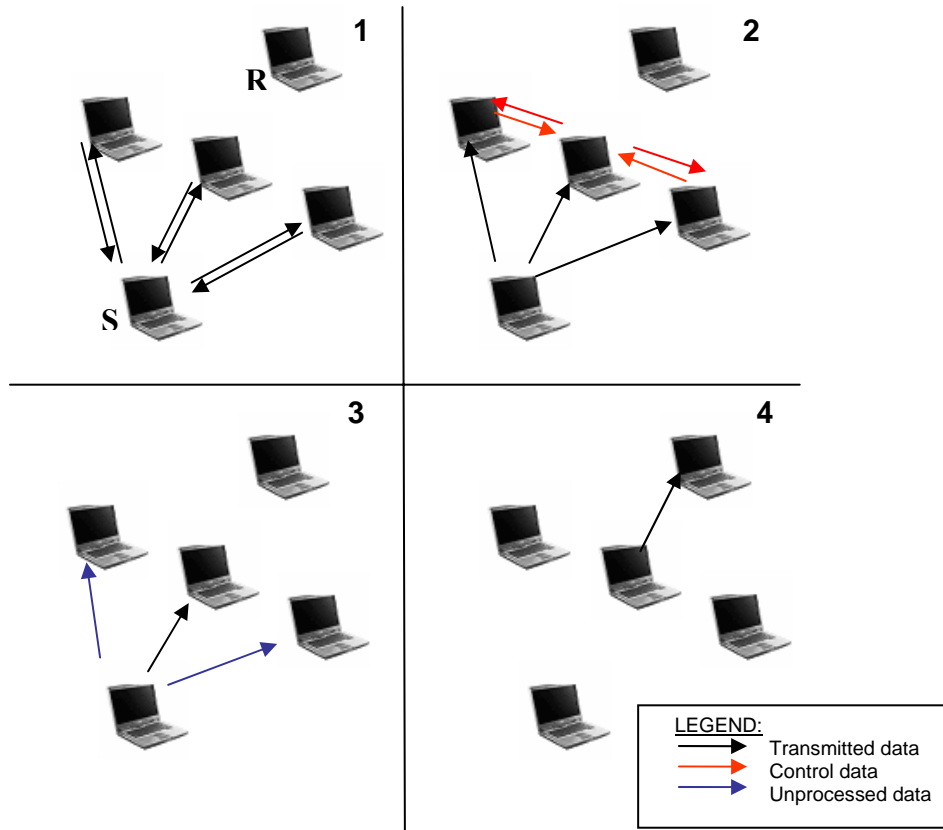


Figure 2.6: Routing operation from sender node ‘S’ to receiving node ‘R’ using the network based selection micro diversity scheme.

2.5.3 Maximal Ratio Route Path Network Micro Diversity (MRRP):

A unique variance of the SRP scheme is the MRRP. This network diversity scheme also involves monitoring the local mean powers of L neighbor nodes based on location information relative to the position of the receiver. In this scheme, the nodes in the receiving cluster, receive and process the transmitted data. Control messages containing the instantaneous SNRs received

by the various nodes are exchanged, and this information is used in weighting the signals at each node according to the received signal strength. The received signal is then transmitted to the node that has been selected to be the next intermediary hop. Upon receipt of the weighted signals, the node combines the signal and then proceeds to forward it to the next intermediary hop or the intended receiver. To simplify the complexity of determining the node that will be the next intermediary hop, the sending node predetermines the node based on its own location information and includes the nodes ID in the packet header of the data transmitted to the receiving cluster. The received instantaneous SNR at the determined intermediary node will be

$$\gamma_{out} = \sum_{i=1}^L \gamma_i, \quad (2.17)$$

where, $\gamma_1, \gamma_2 \dots \gamma_n$ are the weighted instantaneous power levels of the signals received from the remaining monitored nodes in the receiving cluster. An illustration showing the routing operation for this diversity technique is as shown in Figure [2.7] below. Note that delay introduced in receiving and combining the signals will be in the order of microseconds and therefore can be considered as not introducing significant latency relative to the average end-to-end delay of transmission in the network model. The signals transmitted within the receiving cluster are assumed to have very high SNRs, which allows the assumption of negligible fading of the received signals due to transmission within the cluster.

In Figure [2.7] below, stage 1 shows the monitoring of the power levels of the neighboring nodes by the sender 'S'. When a packet arrives, it is broadcast to the L monitored nodes (stage 2) with necessary route information attached determining the next hop node. Information concerning the instantaneous SNR of the received signals is also exchanged at this stage to determine the weights of the individually received signals. In stage 3, the selected node waits for the weighted signals to be received from all other nodes in the observed set before the combining operation. At the final stage, the node is transmitted to the next receiving cluster or the intended receiver

2.5.4 Equal Gain Route Path Network Micro Diversity (EGRP):

The EGRP scheme is implemented in a similar fashion to the MRRP diversity scheme described above. The signals received by each node in the observed set of the receiving cluster are forwarded to the selected next hop node. The selected node weights the received signal equally

before combining them to form the signal to be transmitted to the next cluster or intended receiver. The output SNR for the EGRP scheme at the pre-selected node is given as

$$\gamma_{out} = \frac{1}{L} \left(\sum_1^L \alpha \right)^2 \quad (2.18)$$

This network diversity technique is proposed to provide performance that is comparable to the MRRP scheme but with greater simplicity in implementation since the nodes in the receiving cluster do not have to share information based on the instantaneous SNR levels of their received signals. A graphical model of this diversity scheme can also be depicted by Fig [2.7] without the inclusion of the control message exchange process in the second stage.

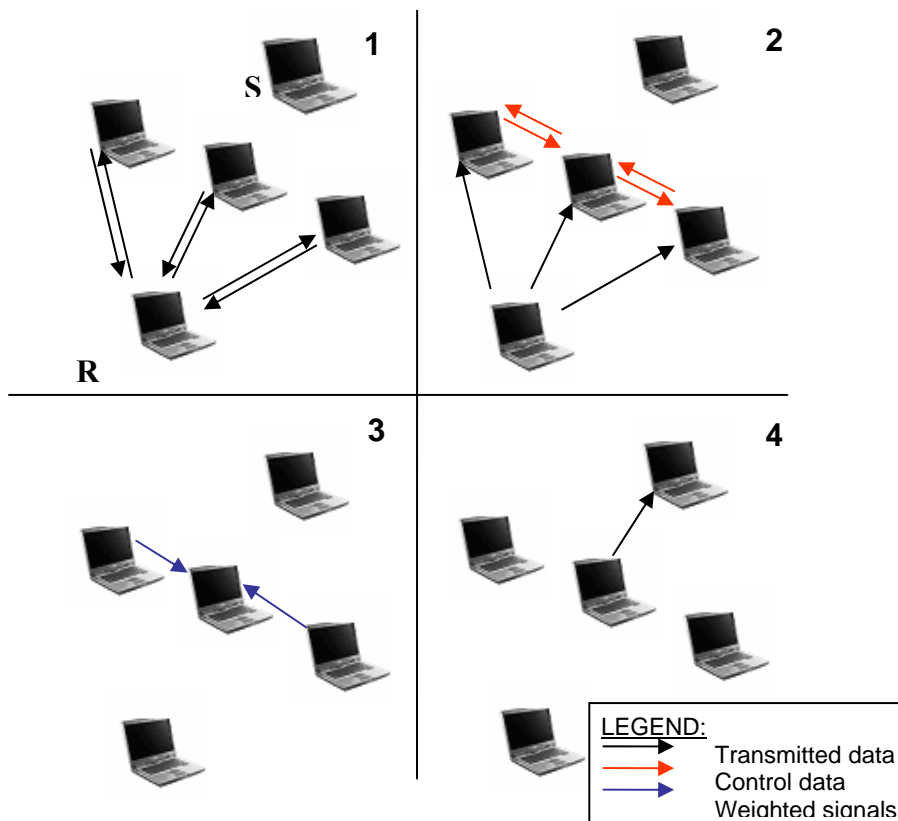


Figure 2.7: Routing operation from sender node ‘S’ to receiving node ‘R’ using the network based MRRP and EGRP micro diversity schemes.

2.5.5 Generalized Route Path Network Micro Diversity (GRP (N, L)):

Relative improvement in performance can be derived from combining a sub set of the observed nodes in the receiving cluster, thereby reducing the computational complexity and processes

involved in introducing diversity in the network system. This is a more practical structure where a fraction of the monitored route paths i.e. ($N \leq L$) with the highest instantaneous SNRs are combined out of the L largest local mean selected paths by the pre-determined next hop node. This combination technique is implemented in a similar fashion to the MRRP scheme (MRRP is a generalization of the GRP scheme, when $N = L$). Weighting of the received signals is done via short burst control messages before combination at the selected node. Figure [2.8] illustrates the operation of the GRP (N, L) scheme.

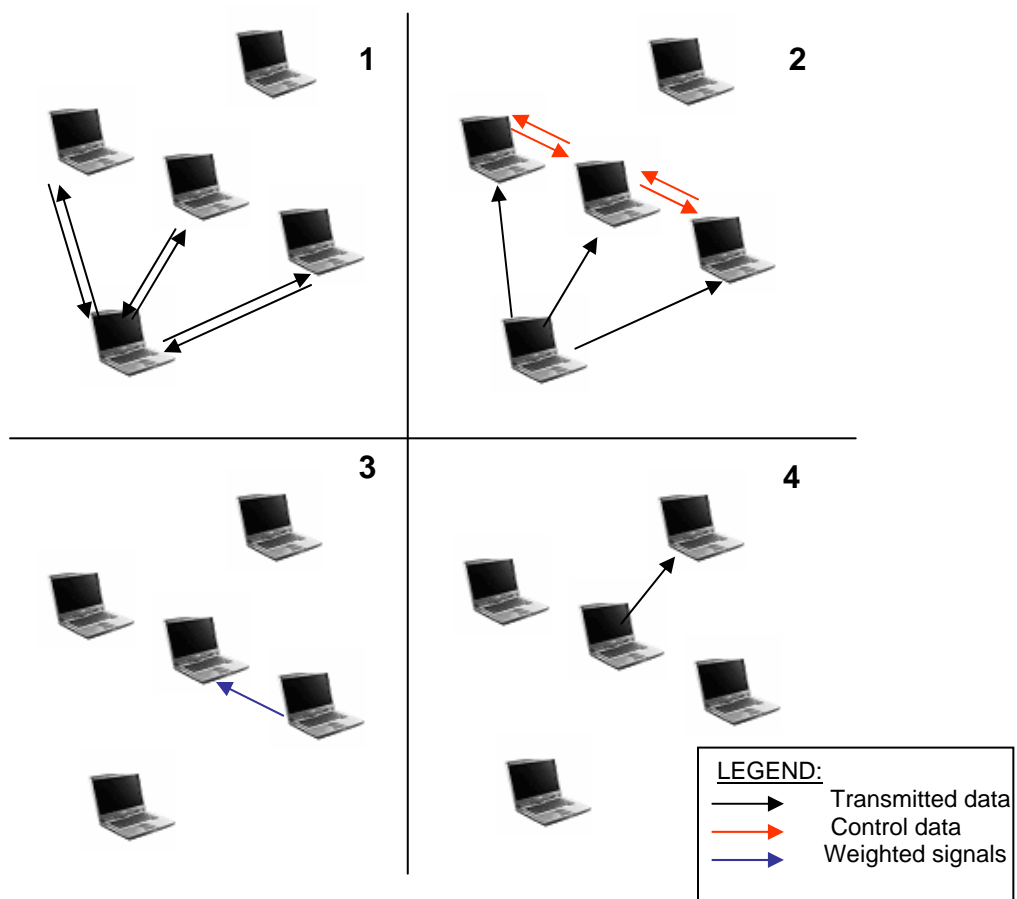


Figure 2.8: Routing operation from sender node 'S' to receiving node 'R' using the Enhanced selection based diversity scheme for $N = 2$.

Note that after the subset of nodes have been determined in the receiving cluster, the nodes not included in the routing process simply stops processing the packets received and discards portions of the packet that have been previously processed.

The figure above depicts a system that has been designed to combine 2 paths with the highest instantaneous power levels to form the transmission signal for the next hop. The power levels are monitored in stage 1 and the L nodes with the highest local mean power levels are selected. The intermediary next hop node is also determined at this stage from the 2 selected nodes in the observed set. Stage 2 shows the transmission of packets to the L selected nodes with control messages exchanged to select the 2 strongest instantaneous power levels and also determine the weights for the individually received signals of the 2 selected nodes. The third stage involves the transmission of the weighted signal to the selected node which then combines all received signals to form the resultant message.

*"The heights that great men reached and kept
were not attained by sudden flight
but they, while their companions slept
kept toiling upwards in the night"*

Chapter 3

NETWORK LAYER DIVERSITY IN THE RICE CHANNEL MODEL

In this chapter, we analyze the performance of our network system with the Rice propagation fading model for the various diversity combination schemes mentioned in the previous chapter. The Rice fading model is of interest because it considers a specular (LOS) component as being present in the system. In a more practical scenario, consider a conference or seminar where individuals come together to set up a network. Movement in this type of scenario can be considered as correlated, therefore the probability that the sending node is within the transmission range of the receiving node is very high and will most likely give rise to the presence of an LOS component.

To analyze our network model, performance metrics such as the end-to-end outage probability and the end-to-end ASER (average Symbol Error Rate) are considered. Both independent, identically distributed (i.i.d.) and independent, non-identically distributed (i.n.d.) channels and mixed fading scenarios are considered.

3.1. Outage Probability Analysis

- Single Hop

The outage probability of a system is defined as the probability that the output SNR of the signal received in a system falls below a certain threshold level. This is defined mathematically as

$$P_{out} = P[0 \leq \gamma \leq \gamma_{th}] = \int_0^{\gamma_{th}} p_{\gamma}(\gamma) d\gamma \quad (3.1)$$

where, γ is the instantaneous SNR received

and γ_{th} is the defined threshold level

Due to the complexity of defining the PDF in closed form expressions, for the received signal at the output of a system for various combination schemes that combine L multipath signals, to obtain the outage probability expressions, a simple and more generic method is employed. The Laplacian conversion of CDFs [29] is a generic formula that determines the outage probability of a given system using a defined network diversity combination scheme by making use of the Moment Generating Function (MGF) of the signal received at the output of the system instead. This algorithm is non-restrictive and is also computationally tractable for the evaluation of i.n.d. and correlated paths. The PDF, CDF and MGF for different distribution models can be expressed in closed forms and some of them are given in Table [3.2] at the end of this chapter.

The outage probability from the Laplacian conversion of CDFs is mathematically defined as given below

$$P_{out} = P_{\gamma}(\gamma_{th}; A, N, Q)$$

$$P_{out} = \frac{2^{-Q} \exp(A/2)}{\gamma_{th}} \sum_{q=0}^Q \binom{Q}{q} \sum_{n=0}^{N+q} \frac{(-1)^n}{\beta^n} \Re \left\{ \frac{M_{\gamma} \left(-\frac{A + 2\pi j n}{2\gamma_{th}} \right)}{\frac{A + 2\pi j n}{2\gamma_{th}}} \right\} + E(A, N, Q) \quad (3.2a)$$

With the overall truncation error term $E(A, Q, N)$ being estimated by

$$|E(A, N, Q)| \approx \frac{e^{-A}}{1 - e^{-A}} + \left| \frac{2^{-Q} \exp(A/2)}{\gamma_{th}} \sum_{q=0}^Q (-1)^{N+1+q} \binom{Q}{q} \Re \left\{ \frac{M_{\gamma} \left(-\frac{A + 2\pi j(N+q+1)}{2\gamma_{th}} \right)}{\frac{A + 2\pi j(N+q+1)}{2\gamma_{th}}} \right\} \right| \quad (3.2b)$$

where, A is the discretization error term

N is the truncation error term

Q is a partial series of length N

γ_{th} is the defined threshold level

while, β_n is defined as, $\beta_n = \begin{cases} 2, & n = 0 \\ 1, & n = 1, 2, \dots, N \end{cases}$

and, $M_{\gamma}(s) = E_{\gamma} [e^{s\gamma}]$ is the moment generating function (MGF) for a given instantaneous SNR value γ .

- Multiple hop

The end-to end outage error probability for a complete transmission route path from sender to receiver can be defined as

$$P_{out} = 1 - \prod_{i=1}^n [1 - P_{out}^i] \quad (3.3)$$

where, P_{out}^i is the outage probability for hop i,

Selection Route Path Combining Macro Network Diversity (SRPM):

The outage probability for this network diversity scheme can be calculated based on the derivation for the MGF of the Lognormal Rice distribution given in [40]. The PDF of the SRPM scheme for L received multiple paths is defined as

$$f(\gamma) = \int_{-\infty}^{\infty} \sum_{i=1}^L \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left(-\frac{(\ln \bar{\gamma} - \ln \mu_i)^2}{2\sigma_i^2}\right) \prod_{\substack{j=1 \\ j \neq i}}^L Q\left(\frac{\ln \bar{\gamma} - \ln \mu_j}{\sigma_j}\right) \frac{K+1}{\gamma} \exp\left(-K - \frac{(K+1)\gamma}{\gamma}\right) I_0\left(2\sqrt{\frac{K(K+1)\gamma}{\gamma}}\right) d\bar{\gamma} \quad (3.4)$$

The PDF of the output combiner can be evaluated numerically using Hermite integration, i.e.,

$$\sum_{i=1}^L \frac{1}{\sqrt{\pi}} \sum_{k=1}^n w_k q(\gamma_k) \quad (3.5)$$

where, $w = \frac{\ln(\gamma / \mu)}{\sigma\sqrt{2}}$

$$\text{and } q(\gamma_k) = \prod_{\substack{j=1 \\ j \neq i}}^L Q\left(\frac{x\sigma_i\sqrt{2} + \ln(\mu_i / \mu_j)}{\sigma_j}\right) \frac{K+1}{\mu_i \exp(x\sigma_i\sqrt{2})} \exp\left(-K - \frac{(K+1)}{\mu_i \exp(x\sigma_i\sqrt{2})} \gamma\right) I_0\left(2\sqrt{\frac{K(K+1)\gamma}{\mu_i \exp(x\sigma_i\sqrt{2})}}\right)$$

The outage probability can then be computed using the MGF in equation (3.2) which results as the Laplacian transform of (3.5) above.

Selection Based Route Path Combining Micro Network Diversity (SRP):

This diversity technique is similar in concept to the physical layer's SDC combination technique; therefore analysis for this system is going to be based on the latter. Mathematically, the outage probability of a system is the CDF of the received output signal of the propagation model evaluated at γ_{th} . Therefore, for L independently received paths, the outage probability for the Rice propagation model will be a result of the product of the CDFs of each individual path i.e.

$$P_{out} = P[0 \leq \gamma_{1\dots L} \leq \gamma_{th}] = \prod_{i=1}^L \int_0^{\gamma_{th}} p_{\gamma_i}(\gamma_i) d\gamma_i$$

$$P_{out} = P[0 \leq \gamma_{1\dots L} \leq \gamma_{th}] = \prod_{i=1}^L 1 - Q\left(\sqrt{2K_i}, \sqrt{\frac{2(K_i+1)\gamma_i}{\gamma_i}}\right) \quad (3.6)$$

The overall outage probability from the sending node to the receiving node is then determined by averaging P_{out} over the PDF of the received signals based on the selection of nodes with the highest local mean SNRs by the sender as given in the equation below.

$$\overline{P_{out}} = \underbrace{\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty}}_{L\text{-fold int gral}} P_{out} f(\gamma_1) \dots f(\gamma_L) d\gamma_1 \dots d\gamma_L \quad (3.7)$$

where, $f(\gamma_i)$ is the PDF of the macro diversity selected path to the receiving node in the observed set as given in equation (3.4).

Maximal Ratio Route Path Micro Network Diversity (MRRP):

This diversity technique is similar to the MRC combination scheme in the physical layer and

will be analyzed as such. In the case of uncorrelated fading, the MGF of the output signal for the MRRP combination scheme for L order of diversity is defined as the product of the MGF of the individually received multiple paths in the network i.e.

$$M_{\gamma}(s) = \prod_{l=1}^L M_{\gamma_l}(s) \quad (3.8)$$

The overall outage probability for this scheme is as described in the SRP scheme above.

Equal Gain Route Path Micro Network Diversity (EGRP):

Similar in concept to the EGC combination scheme of the physical layer, the inherent performance gains derived in the application of this diversity scheme will be analyzed as follows. In [11], Abu Dayya *et al* derives the CDF of an EGC combining scheme for arbitrary L paths using the infinite but convergent Beaulieu series that can be truncated to give the desired accuracy. The formulation of the Beaulieu series used in deriving the CDF is given as below

$$F(\alpha) \approx \frac{1}{2} + \frac{2}{\pi} \sum_{\substack{n=1 \\ \text{nodd}}}^{\infty} \frac{A_n \sin(\theta_n)}{n} \quad (3.9)$$

with, $A_n = \prod_{i=1}^L A_{in}$ and $\theta_n = \sum_{i=1}^L \theta_{in}$

$$A_{in} = \sqrt{E^2[\cos(nwX_i)] + E^2[\sin(nwX_i)]}, \quad \theta_{in} = \tan^{-1}\left(\frac{E[\sin(nw(X_i - \varepsilon))]}{E[\cos(nw(X_i - \varepsilon))]} \right)$$

where, $\varepsilon = \frac{x}{L}$ and $w = \frac{2\pi}{T}$

The MGF of this signal can be shown in closed form expression to be,

$$M_{cd}(s) = \exp(-K) \sum_{j=0}^K \frac{K^j}{j!} {}_1F_1\left[j+1, \frac{1}{2}; \frac{\Omega_l s^2}{4(1+K)}\right] + \dots$$

$$\frac{s \exp(-K) \sqrt{\Omega_l}}{\sqrt{1+K}} \sum_{j=0}^K \frac{\Gamma(j+3/2)}{(j!)^2} K^j {}_1F_1\left[m_l + \frac{1}{2}, \frac{3}{2}; \frac{\Omega_l s^2}{4(1+K)}\right] \quad (3.10)$$

The overall outage probability for this scheme is also obtained as described in the SRP scheme above.

Generalized Route Path Micro Network Diversity (GRP (N, L)):

The complexity involved in obtaining the MGF of a GRP (N, L) receiver lies in obtaining the joint PDF of the ordered individual received paths, where $\gamma_{1:L} \leq \gamma_{2:L} \leq \dots \gamma_{L:L}$ represents the ordered statistic obtained by arranging the instantaneous SNRs $\gamma_1, \gamma_2, \dots, \gamma_L$ in increasing order. It is shown in [15] that the joint PDF is given by

$$p_{\gamma_{1:L}, \gamma_{2:L}, \dots, \gamma_{L:L}}(\gamma_1, \dots, \gamma_L) = \begin{vmatrix} + & p_1(\gamma_1) & p_2(\gamma_1) & \dots & p_L(\gamma_1) \\ & p_1(\gamma_2) & p_2(\gamma_2) & \dots & p_L(\gamma_2) \\ & \vdots & \vdots & \vdots & \vdots \\ & p_1(\gamma_L) & p_2(\gamma_L) & \dots & p_L(\gamma_L) \end{vmatrix} \quad (3.11)$$

where, $|^+ A^+|$ is defined as the permanent of a square matrix A

The MGF is then defined as,

$$M_\gamma(s) = E \left[\exp \left(-s \sum_{i=L-N+1}^L \gamma_{i:L} \right) \right], s \geq 0 \quad (3.12)$$

Simplifying further for the i.i.d. case, we have

$$M_\gamma(s) = N \binom{L}{N} \int_0^\infty \exp(-s\gamma) f(\gamma) [F(\gamma)]^{L-N} [M(s, \gamma)]^{N-1} d\gamma, \quad 1 \leq N \leq L/2 \quad (3.13)$$

where, $MGF_\gamma(s, \gamma)$ is defined as the marginal MGF given by $\int_\gamma^\infty \exp(-st) f(t) dt$.

3.2. ASER Analysis:

- Single hop

The average SER is computed by taking the Conditional Error Probability (CEP) for a given modulation scheme in an Additive White Gaussian Noise (AWGN) channel and averaging it over the PDF of the output SNR ($p_\gamma(\gamma)$). Mathematically, this is defined as given below.

$$P_s(E) = \int_0^\infty p_\gamma(\gamma) P_s(E/\gamma) d\gamma \quad (3.14)$$

- End-to-End SER

From one hop to the next hop, the probability of a symbol error occurring arises if an error

occurs in the previous hop and there is no error in the present hop or if there was no error in the previous hop and an error occurs in the present hop. This is described mathematically by [27] as,

$$P_s^{m+1}(E) = P_s^{m+1}(E)(1 - P_{m+1}) + (1 - P_s^{m+1}(E))P_{m+1} \quad (3.15)$$

Therefore for n hops, the end-to-end average SER is given by

$$\begin{aligned} P_s(E) &= S_n^1 - 2S_n^2 + 4S_n^3 - \dots + (-2)^{n-1} S_n^n \\ &= \sum_{k=1}^n (-2)^{k-1} S_n^k \end{aligned}$$

where, S_n^k denotes the sum of the product of all k distinctive terms selected from P_1, P_2, \dots, P_n i.e.

$$S_n^k = \sum_{\substack{\alpha_1 \dots \alpha_k = 1 \\ \alpha_i \neq \alpha_j}}^n P_{\alpha_1} P_{\alpha_2} \dots P_{\alpha_k} \quad (3.16)$$

The derivation for this expression is given in Appendix A.

To facilitate the easy computation of the ASER in a computationally tractable closed form expression, the technique described by [14] is used below:

$$P_b(E) = -\int_0^{\infty} P_{\gamma}(\gamma) \left[\frac{d}{d\gamma} P_s(E/\gamma) \right] d\gamma \quad (3.17)$$

The above expression is derived as a result of evaluating (3.14) above using integration by parts. The expression developed involves using the CDF of the output SNR signals for the fading channel defined and the negative derivatives of the SER expression for the modulation scheme employed in the system, both of which are obtainable in closed form expressions. Table [3.3] shows the already computed expressions for the negative derivative of the conditional SER for various modulation techniques.

For binary signals using the BPSK modulation technique, the ASER expression derived from using the different combination schemes can be given as follows;

Selection Route Path Combining Macro Network Diversity (SRPM):

The SRPM case can be computed using (3.20) below with the MGF defined from (3.5).

Selection Based Route Path Combining Micro Network Diversity (SRP):

$$P_s(E) = -\int_0^{\infty} \prod_{i=1}^L 1 - Q\left(\sqrt{2K_i}, \sqrt{\frac{2(K_i+1)\gamma_i}{\gamma_i}}\right) \left[\frac{0.5e^{-\gamma}}{\sqrt{\pi}\sqrt{\gamma}} \right] d\gamma \quad (3.18)$$

where, $P_\gamma(\gamma)$ is $\prod_{i=1}^L 1 - Q\left(\sqrt{2K_i}, \sqrt{\frac{2(K_i+1)\gamma_i}{\gamma_i}}\right)$ for a Rice fading channel and

$$-\frac{d}{d\gamma} P_s(E/\gamma) \text{ is } \frac{0.5ae^{-a\gamma}}{\sqrt{\pi}\sqrt{a\gamma}} \text{ with } a = 1$$

The overall average SER is obtained by averaging over the PDFs of the received highest local mean power selected signals. The mathematical formulation can be defined as

$$\overline{P_{ov}(E)} = \underbrace{\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty}}_{L\text{-fold integral}} \overline{P_s(E)} f(\gamma_1) \cdots f(\gamma_L) d\gamma_1 \cdots d\gamma_L \quad (3.19)$$

where, γ_i is the PDF of the macro diversity selected path to the receiver in the observed set as given in equation (3.4), $\overline{P_{ov}(E)}$ is the overall ASER and $\overline{P_s(E)}$ is the ASER due to the combination of the weighted signals.

Maximal Ratio Route Path Micro Network Diversity (MRRP):

For the MRRP case, an expression involving the derivation of the ASER from the MGF is employed as described in [33] for a single hop

$$P_s(E) = \frac{1}{\pi} \int_0^{\pi/2} \prod_{i=1}^L M_{\gamma_i} \left(\frac{1}{\sin^2 \theta} \right) d\theta \quad (3.20)$$

where, $M(\cdot)$ is the MGF of the individual paths to be combined.

Therefore,

$$P_s(E) = \frac{1}{\pi} \int_0^{\pi/2} \prod_{i=1}^L \frac{1 + K_i}{1 + K_i + \left(\frac{1}{\sin^2 \theta} \right)^{\overline{\gamma}}} e^{-\left(\frac{\left(\frac{1}{\sin^2 \theta} \right)^{K_i \overline{\gamma}}}{1 + K_i + \left(\frac{1}{\sin^2 \theta} \right)^{\overline{\gamma}}} \right)} d\theta \quad (3.21)$$

The overall ASER for this scheme is obtained as described in the SRP scheme above.

Equal Gain Route Path Micro Network Diversity (EGRP):

The ASER for this combination scheme can be computed in a closed form expression using the CHF of the output SNR at the receiver and making use of Parseval's theorem as described in [32].

The CHF of γ in a Rice fading environment is given as

$$\begin{aligned} \phi(w) = \prod_{i=1}^L \left[\exp(-K_i) \left[\sum_{j=0}^{\infty} \frac{K_i^j}{j} {}_1F_1 \left(j+1, \frac{1}{2}, \frac{-\bar{\gamma}_i w^2}{4L(1+K_i)} \right) \right] \dots \right. \\ \left. \dots + jw\sqrt{2\xi} \sum_{i=0}^{\infty} \frac{\Gamma(j+3/2)K_i^j}{(j!)^2} {}_1F_1 \left(j+\frac{3}{2}, \frac{3}{2}, \frac{-\bar{\gamma}_i w^2}{4L(1+K_i)} \right) \right] \end{aligned} \quad (3.22)$$

where, $\xi = 1/\sqrt{2L(1+K_i)/\bar{\gamma}_i}$, and $\lambda = m/\gamma$

The use of the Parseval's theorem circumvents the need to find the PDF of the signal and involves the Fourier transform of the conditional SER of the modulation scheme used. The expression derived in [32] is as given below

$$\begin{aligned} P_s(E) &= \int_0^{\infty} P_s(E/\alpha) \left[\frac{1}{2\pi} \int_{-\infty}^{\infty} \phi(w) \exp(-jw\alpha) dw \right] d\alpha \\ P_s(E) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} FT[P_s(E/\alpha)] \phi^*(w) dw \\ P_s(E) &= \frac{1}{\pi} \int_0^{\infty} \Re\{G(w)\phi^*(w)\} dw \\ P_s(E) &= \frac{2}{\pi} \int_0^{\pi/2} \frac{\Re\{\tan \zeta G(\tan \zeta)\phi^*(\tan \zeta)\}}{\sin(2\zeta)} d\zeta \end{aligned} \quad (3.23)$$

where, $FT(\cdot)$ is the Fourier transform of $P_s(E/\alpha)$ and $\phi^*(\cdot)$ denotes the complex conjugate of the CHF of α .

In [32], the FT of the various modulation schemes is presented, for BPSK we have

$$G(w) = \frac{0.5}{w} \left[\frac{2}{\sqrt{\pi}} F\left(\frac{w}{2}\right) + j \left(1 - \exp\left(\frac{-w^2}{4}\right) \right) \right] \quad (3.24)$$

where, $F(\cdot)$ denotes Dawson's integral which is defined by

$$F(x) = \exp(-x^2) \int_0^{\infty} \exp(-t^2) dt \quad (3.25)$$

The overall outage probability for this scheme is also obtained as described in the SRP scheme above.

Generalized Route Path Micro Network Diversity (GRP (N, L)):

The ASER of the GRP (N,L) combination scheme can be computed using the MGF expression in (3.20) above and the subsequent overall ASER computed using equation (3.19)

3.3. CORRELATION EFFECTS ON THE PERFORMANCE OF NETWORK DIVERSITY COMBINATION SCHEMES:

In the previous sections, the ad hoc network system topology defined is analyzed with the assumption of independent multiple diversity paths present in the system. Research has shown [8][30], based on empirical data, that large spatial separations are needed among adjacent nodes in a system to achieve independency among multiple paths in any given mobile communication system, therefore, many practical scenarios exist where the independent assumption is not valid. Correlated shadowing is a phenomenon that usually occurs in nodes that co-exist with small spatial separations as they are likely to undergo shadowing by the same obstacles [35], and it is also a known fact that correlated fading conditions does not allow the maximum achievable gain that correlation provides. It is therefore necessary to study the effects of branch correlations on the various afore-mentioned diversity combination schemes. The analysis of correlation effects in a system can be characterized by the power correlation coefficient ρ , which is mathematically defined as

$$\rho = \frac{E\{xy\} - E\{x\}E\{y\}}{\sqrt{\sigma_x^2 \sigma_y^2}}, 0 \leq \rho \leq 1 \quad (3.26)$$

Many variations of the correlation model have been described and analyzed due to their pertinence to practical scenarios in communication. Some of the models utilized as stated in this thesis are

- Constant Correlation model

This model is usually used in the analysis of scenarios using multi-channel reception from diversity antennas that are close in proximity.

- Exponential Correlation model

This model is characterized by $\rho_{ii'} = \rho^{|l-l'|}$. This is applicable to the scenario of multiple channel reception with equally spaced diversity antennas.

- Arbitrary Correlation model

This model is used to characterize diversity systems in which the correlation between pairs of combined signals decay as antenna spacing increases.

In the following section, we investigate the effects of correlated lognormal shadowing on the performance of packet transmissions as regards the average Symbol Error Rate (ASER) in an ad hoc network via the Rice fading propagation channel with the Rayleigh propagation channel as a special case. Due to the difficulty involved in evaluating the closed form expression for the output SNR in diversity schemes with correlated paths for $L > 2$, we present expressions for arbitrary L in a BPSK modulation scheme, only where obtainable.

For this fading channel, a unified MGF based approach is chosen that presents tractable closed form expressions for the easy computation of the ASER performance metric.

Selection Based Route Path Combining Micro Network Diversity (SRP):

The performance analysis for correlation in SRP type schemes have proven to be non-trivial because of the difficulty in obtaining the PDF for L diversity paths (this is as result of the inherent L fold integral needed to compute the PDF). In the literature, there exist analytical expressions in closed form for only dual diversity schemes. In [37], Zhang takes a different approach by using the CHF and circumventing the need to obtain the PDF.

The expressions derived for this type of diversity scheme are as given below:

$$P_e = \underbrace{\int_0^\infty \cdots \int_0^\infty}_{\substack{L\text{-fold} \\ \text{integral}}} \phi(t_1 \cdots t_L) w(t_1 \cdots t_L) dt_1 \cdots dt_L \quad (3.27)$$

where, $w(t_1 \cdots t_L) \cong \frac{1}{(2\pi)^L} \int_0^\infty P(e/\gamma) h(\gamma, t) d\gamma$

$$\text{and } h(\gamma, t) = \left[\prod_{k=1}^L (jt_k) \right]^{-1} \left[\sum_{l=1}^L (-1)^{l+1} \times \sum_{b_1 + \cdots + b_l = l} \frac{j(b_1 t_1 + \cdots + b_l t_L)}{\exp(jx[b_1 t_1 + \cdots + b_l t_L])} \right]$$

$b_1 \cdots b_L$ is a binary sequence whose elements assumes the value of zero or one and $\phi(t_1 \cdots t_L)$ is as defined in equation (3.28) below.

Maximal Ratio Route Path Micro Network Diversity (MRRP):

The ASER for a BPSK modulation scheme in the presence of constant correlated and exponential correlated branches can be determined by using the CHF of L Rice faded signals at the output of the combiner [36]. Since Rice fading can be modeled by non-zero mean Gaussian random processes in quadrature, the CHF is given as

$$\phi(jv) = \frac{\exp[jvc^H (I - 2jvR)^{-1} c]}{\det(I - 2jvR)} \quad (3.28)$$

where, R is the covariance matrix, c is the expectancy of the Gaussian random processes, I is the $L \times L$ identity matrix, \det denotes the determinant of the matrix and c^H denotes a Hermitian matrix

The correlated samples can be represented by uncorrelated samples using a transformation matrix Q , which is an orthonormal set derived from the eigen vectors of R to transform R into a diagonal matrix composing of its eigen values λ where $\lambda_i > 0$ for $i = 1, 2, \dots, L$.

i.e.,
$$QRQ^T = Q^T R Q = A$$

After manipulation, the CHF is given as,

$$\phi(jv) = \exp \left[\sum_{i=1}^L jv\mu_i (I - 2jv\lambda_i)^{-1} c \right] \prod_{i=1}^L \frac{1}{1 - 2jv\lambda_i} \quad (3.29)$$

The ASER can then be computed using an alternate representation of the complementary error function, which is given in [32] as

$$\operatorname{erfc}(\sqrt{\gamma}) = \frac{2}{\pi} \int_0^{\pi/2} \exp(-\gamma \csc^2 \theta) d\theta \quad (3.30)$$

3.4. Analysis and Numerical Examples

In this section, numerical results of the outage probability (for a single hop) and end-to-end average SER are provided to study and analyze the performance of the different combination techniques over i.i.d. and i.n.d. Rice fading channels. For a thorough analysis of the i.n.d. case (i.e. where the nodes in the receiving cluster have varying values of the local mean SNR from the signal transmitted by the sender), the system is modeled using an exponentially decaying power delay profile (PDP) which is defined mathematically as,

$$\bar{\gamma}_l = \bar{\gamma}_1 \exp(-d(l-1)), \quad d > 0 \quad (3.31)$$

where, d is the power decay factor, l is $1, \dots, L$ depending on the path being considered and $\bar{\gamma}_l$ is the local mean SNR value of the l th being considered.

The above model has received extensive usage in the modeling of power delay profiles in frequency selective fading channels. Research in ultra-wideband (UWB) and UMTS/ WCDMA have shown that resolvable multipaths in different propagation environments have different fading statistics [31]; therefore, it is necessary to also analyze mixed fading scenarios.

We analyze the performance of the network diversity schemes via the changes and improvements it brings about in the physical layer. In our analysis, we consider both single and multiple hop scenarios that consists of L multiple paths (where, $L = 1 \rightarrow 5$) using i.i.d. and i.n.d. scenarios as stated. In the comparison of the SRP, MRRP, EGRP and GRP (N,L) schemes, the PDFs of the L paths with the largest local mean power levels chosen in the receiving cluster is neglected, since these schemes undergo the same operation.

Figure [3.1], analyzes the outage probability of the given network diversity schemes given a specific outage threshold of $\gamma_{\text{th}} = 5\text{dB}$ for different values of the Rice K factor for $L = 4$ i.i.d.

multiple paths. It can be seen that for the same average SNR value, the MRRP micro selection based network diversity scheme provides the highest probability of outage as compared to the other network diversity schemes and that the probability of outage reduces with increasing strength of the specular component present in the system, i.e. for the SRP scheme at an average SNR of 10dB, the probability reduces from 8×10^{-3} to 7.5×10^{-5} for K factor value of 0 and 7dB respectively. The performance gain received from using the MRRP scheme in both situations is 8×10^{-3} and 7.49×10^{-5} respectively.

Figure [3.2] analyzes the GRP (N,L) as compared to the other diversity schemes; the performance of this scheme varies from the SRP scheme to the MRRP scheme based on the number of multiple paths combined in the system. As can be seen, combining a selective number of paths can give performances relative to the optimum combination of multiple paths for a trade-off in receiver complexity structure. This system can also be used in achieving enhanced performance relative to the average end-to-end transmission delay in the system. GRP (2,4) provides outage probability performance comparable to the EGRP (within 0.5dB) and about 2dB better than the selection based scheme at an outage probability of 10^{-4} .

The effect of unbalanced local mean powers among the multiple received paths is studied in Figure [3.3] for varying values of the power decay constant δ . As expected the outage probability performance increases with reducing values of δ , i.e. for $\delta = 0$ at P_{out} of 10^{-4} , the gain between the MRRP and the SRP schemes is about 2.7dB, while for $\delta = 1$, it is about 2.5 dB. The performance loss for the MRRP at 10^{-4} is about 3.2 dB from $\delta = 0$ to $\delta = 1$. The convergence of the curves at 10^{-10} is as a result of the truncation error introduced in the mathematical expression used in the analysis of the system.

Figure [3.4] shows the effect that the number of hops on a route path has on the outage probability of a network system using the various network diversity schemes. For all the network diversity schemes, the higher the number of hops, the more the impact on system performance, i.e. for example, for MRRP, the performance loss from a route with one hop at 10^{-3} is 0.6dB, 0.9dB and 1.1dB for a route path with 2, 3 and 4 hops respectively.

Figure [3.5] compares the performance gain from picking the node with highest local mean SNR level at the receiving cluster over conventional routing methods such as the shortest hop algorithm in the presence of i.i.d. Rice fading ($K = 5\text{dB}$ and $\sigma = 6\text{dB}$). As it can be seen, significant performance is gained from making a choice from $L \geq 2$ monitored paths within a hop in the network system, i.e. for an ASER of 5×10^{-2} , there is gain of 3.4dB and 15.2 dB from making a choice out of 2 and 3 paths respectively.

Figure [3.6] looks at the End-to-end ASER for the MRRP, EGRP and the SRP schemes. It is shown that a good percentage of the performance gain is achieved from combining 2 paths and that the performance gain obtainable starts to diminish as the number of multiple route paths combined is increased for the various network diversity schemes. The performance gain for the MRRP increases as compared to the EGRP and SRP schemes when there is an increase in the number of combined paths.

The effect of the number of hops traversed in getting to the destination host is also analyzed in Figure [3.7]. The performance of the system reduces (probability of an error occurring increases) with increasing number of hops in the system. This effect is maximum when a low number of paths are combined (for $L = 2$, about 3 dB to achieve a SER of 10^{-4}) and reduces with the increasing number of multiple paths combined as in the case of $L = 5$ (about 1dB at 10^{-4}).

Figure [3.8] compares the performance of the GRP (N,L) for $L = 4$ with the EGRP and MRRP schemes. As can be seen, the combination of 3 paths provides performance slightly better than the EGRP and relative to the MRRP with the advantage of using a much simpler receiver structure.

Figure [3.9] studies the effect of local mean power unbalance in the system with 5 paths combined by analyzing the system using different modulation schemes namely BPSK and 8PSK. As can be determined intuitively, the BPSK schemes performs better than the 8PSK scheme and as the power unbalance increases (i.e. increasing δ), the system performance degrades.

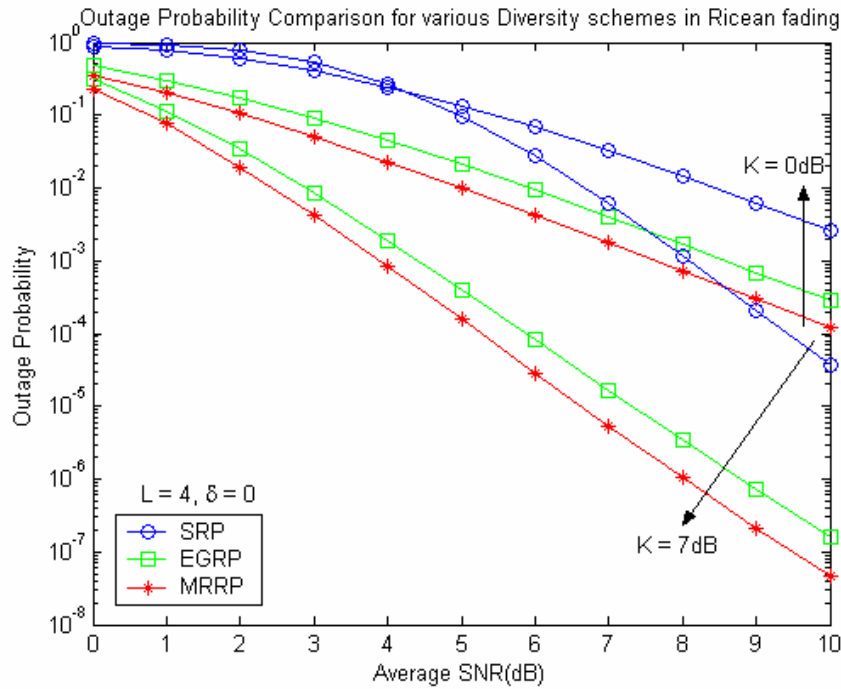


Figure 3.1: Outage probability comparison for SRP, EGRP and MRRP in i.i.d. Rice fading channel ($L = 4, \gamma_{th} = 5\text{dB}$).

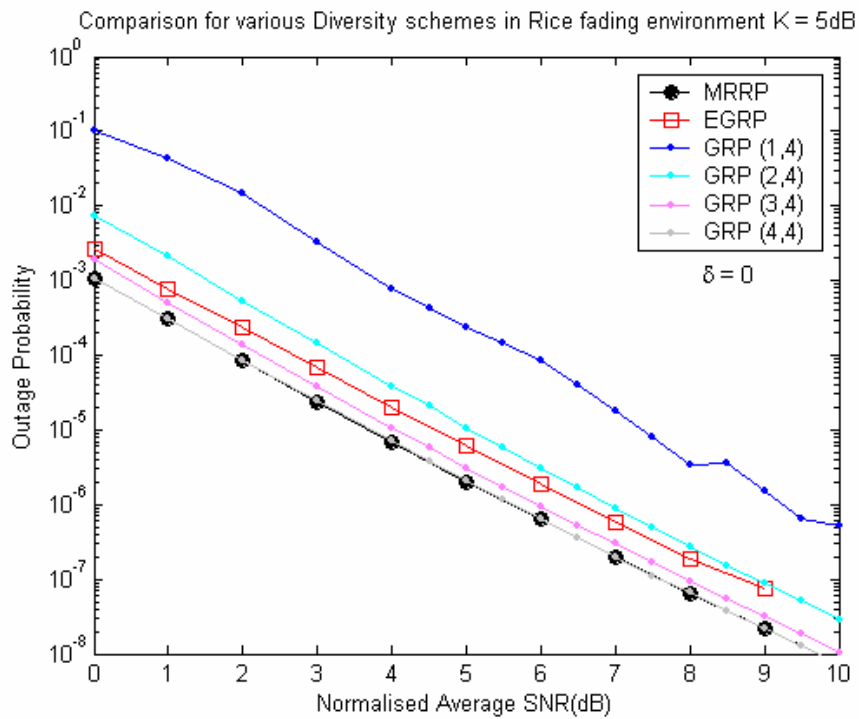


Figure 3.2: Outage probability comparison of GRP (N, L), EGRP and MRRP in i.i.d. Rice fading channels.

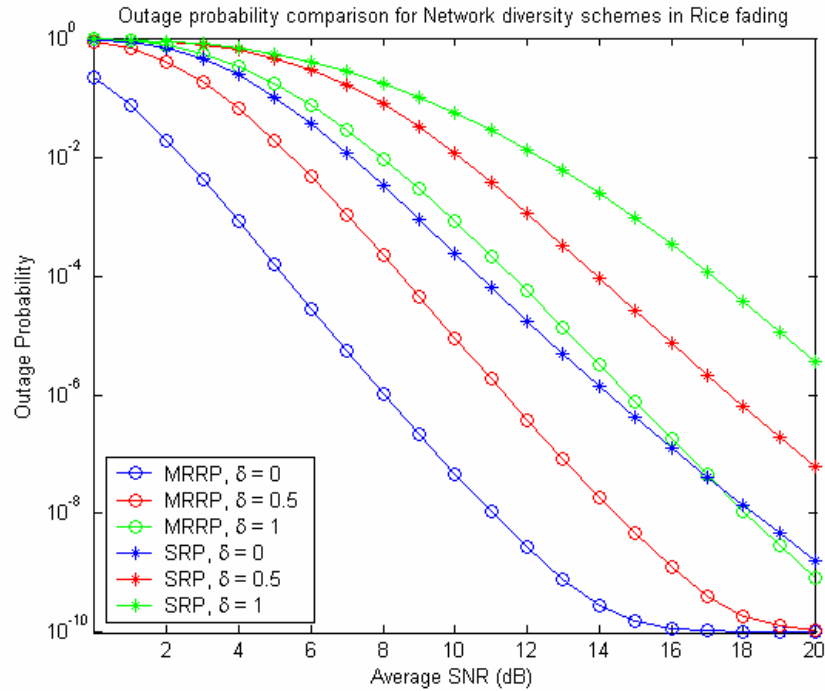


Figure 3.3: Effect of local mean power unbalance for SRP and MRRP for i.i.d. Rice fading with $L = 4$, $K = 5\text{dB}$ and $\gamma_{\text{th}} = 5\text{dB}$.

Performance comparison for network diversity schemes in i.i.d. Nakagami-m fading channels

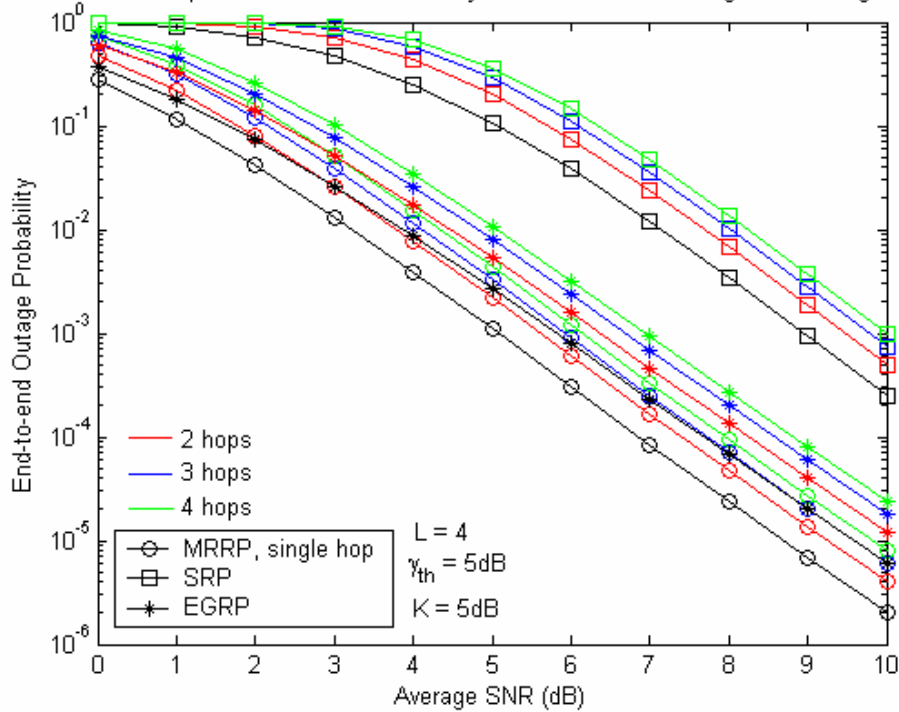


Figure 3.4: Effect of increasing number of hops on the outage probability performance for the various network diversity schemes in i.i.d. Rice fading channels

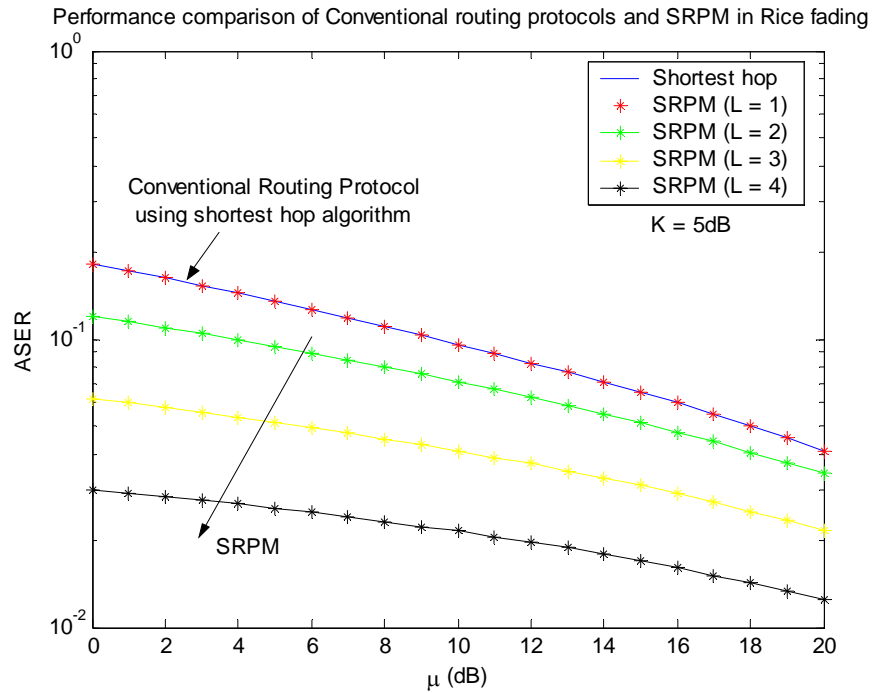


Figure 3.5: ASER Performance comparison of Conventional Route Protocol and SRPM in i.i.d. Rice channels for varying L ($K = 5\text{dB}$).

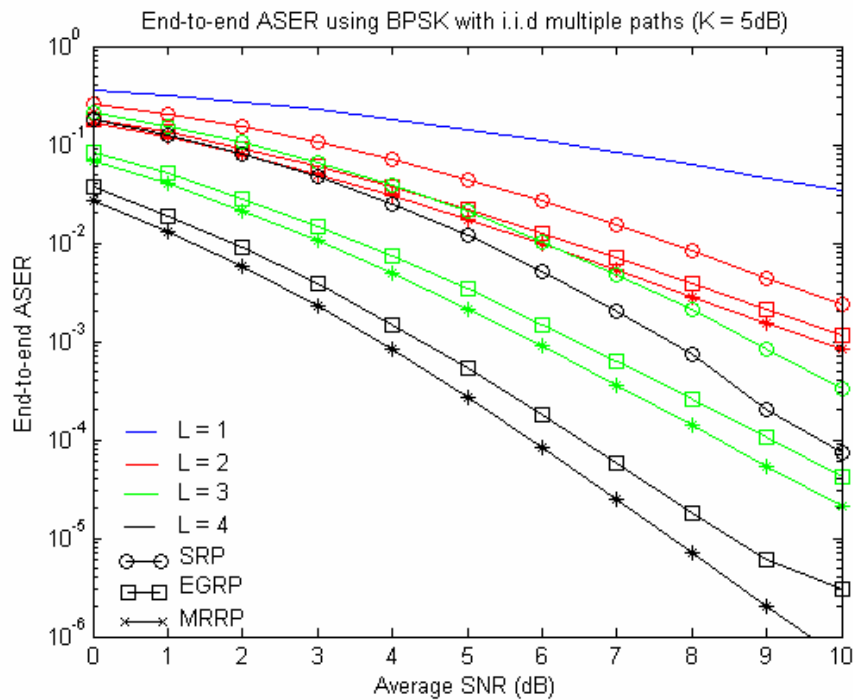


Figure 3.6: ASER performance for the various network diversity schemes in the presence of i.i.d. Rice fading for increasing L paths combined.

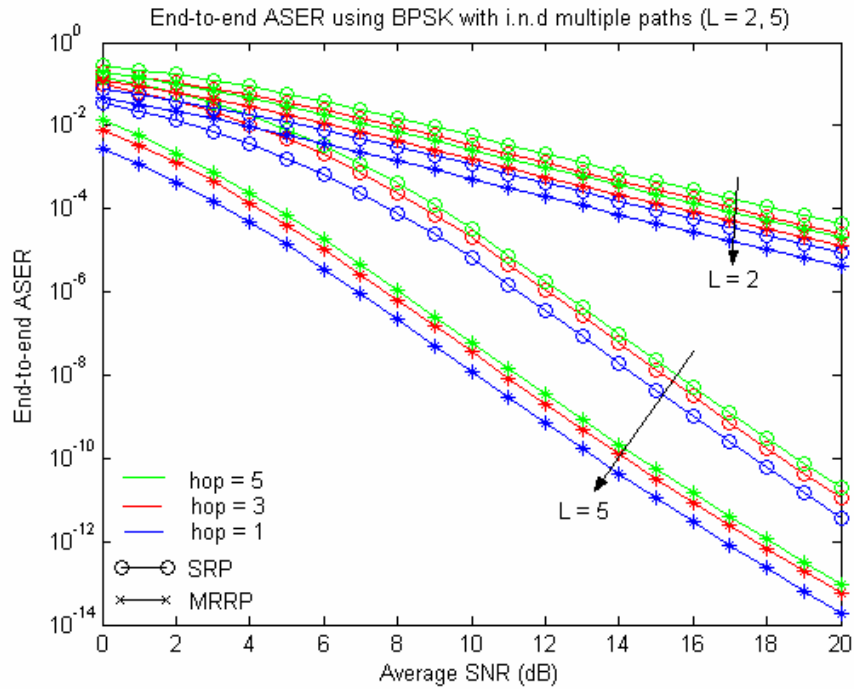


Figure 3.7: Comparison of the end-to-end ASER for BPSK for various numbers of hops in i.n.d. Rice fading ($L = 2$ and 5 , $K = 3\text{dB}$, 2dB , 5dB , 7dB and 0dB).

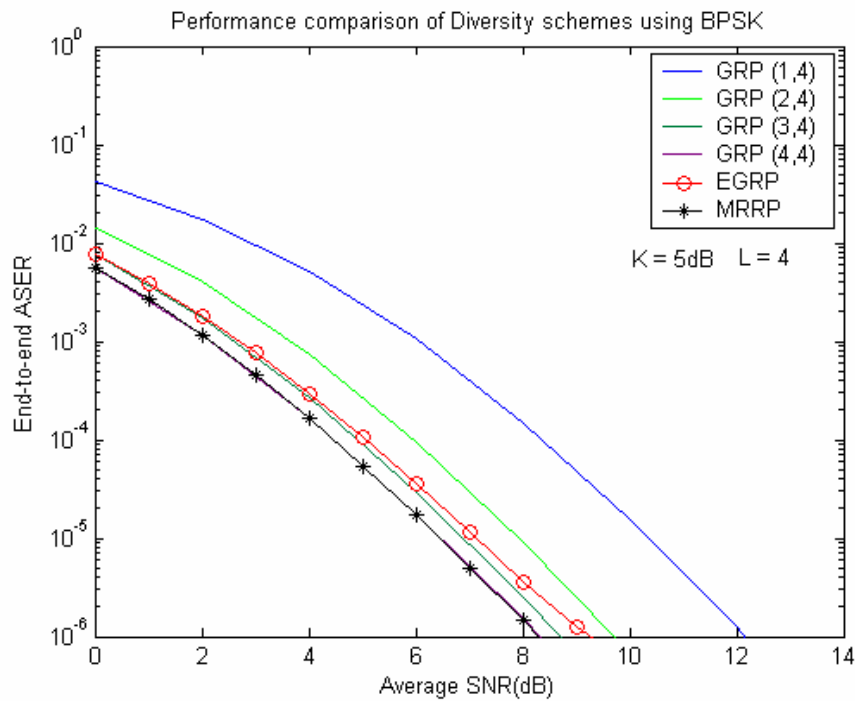


Figure 3.8: Comparative study of GRP (N, L), EGRP and MRRP in i.i.d. Rice fading environment for $L = 4$ and $K = 5\text{dB}$.

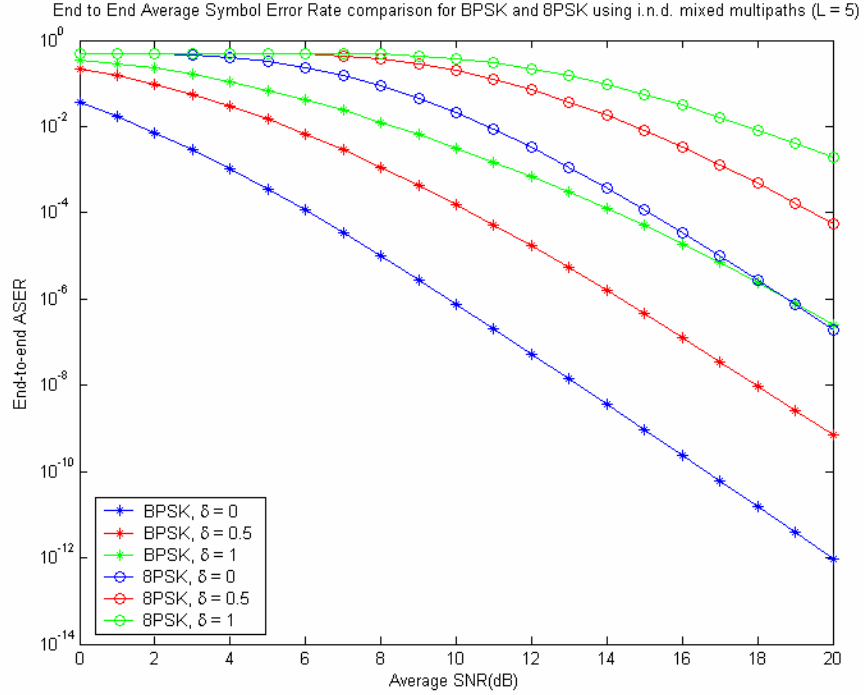


Figure 3.9: Power unbalance effect on BPSK and 8PSK in a mixed fading scenario with $L = 5$ and $K_1 = 3\text{dB}$, $K_2 = 2\text{dB}$, $m_3 = 2.5$, $m_4 = 0.5$, $K_5 = 0\text{dB}$.

The effects of correlation on the system are analyzed as described using the MRRP scheme in the figures below:

Figure [3.10] shows the effect of correlation factor ρ in a constant correlation model. As can be seen, the performance of the system decreases with increasing values of ρ i.e. at 0dB , $\rho = 0$, gives an ASER performance of 9×10^{-3} while at $\rho = 1$, the ASER performance drops to about 9×10^{-2} . Figure [3.11] compares the constant and exponential correlation models and also shows the effect on ρ for increasing K factor values. The exponential correlation model performs better than the constant correlation model for any given value of ρ (except for $\rho = 0$) and this effect increases as ρ increases.

Figure [3.12] shows the effect of power unbalance for the various combined multiple route paths. It can be seen that as the value of δ increases, the performance loss due to increase in the value of ρ tends to increase. For example, at an outage probability of 10^{-4} , the performance loss at $\delta = 0$, from increasing $\rho = 0.2$ to $\rho = 0.8$ is 3.6dB , while at $\delta = 0.5$, the performance loss is about 4dB .

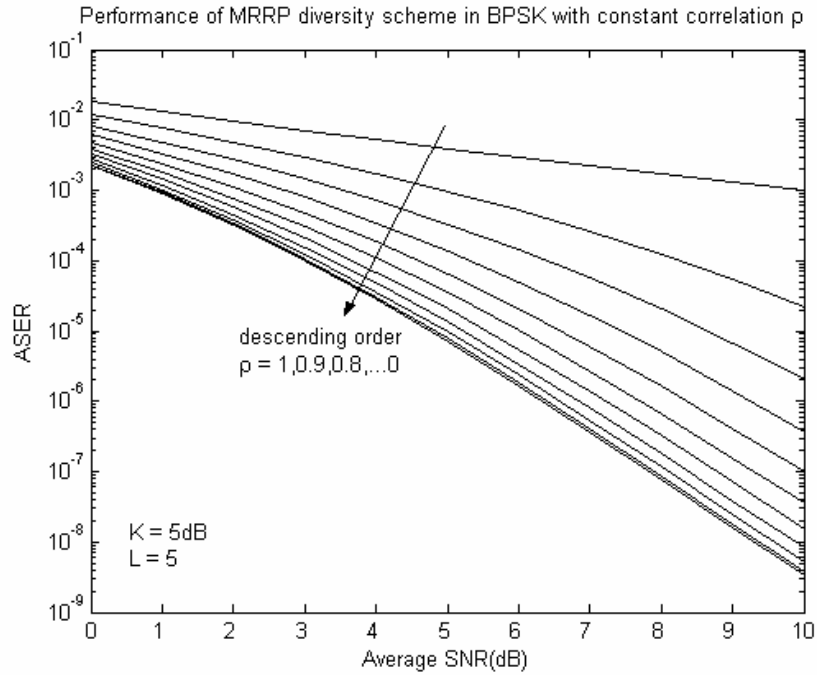


Figure 3.10: Effect of constant correlation on system performance in i.i.d. Rice fading.

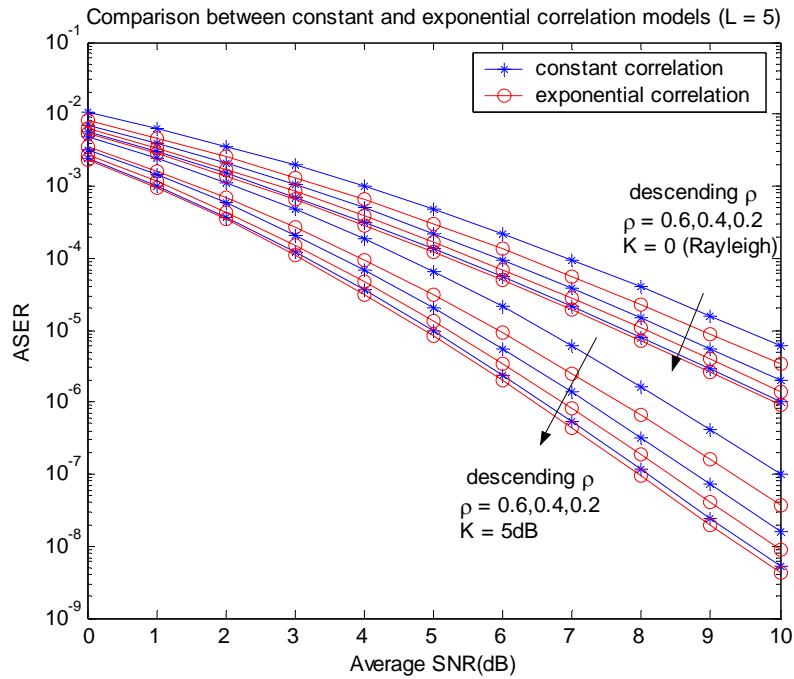


Figure 3.11: Constant and exponential correlation model study in the presence of i.i.d. Rice fading for varying K factor values.

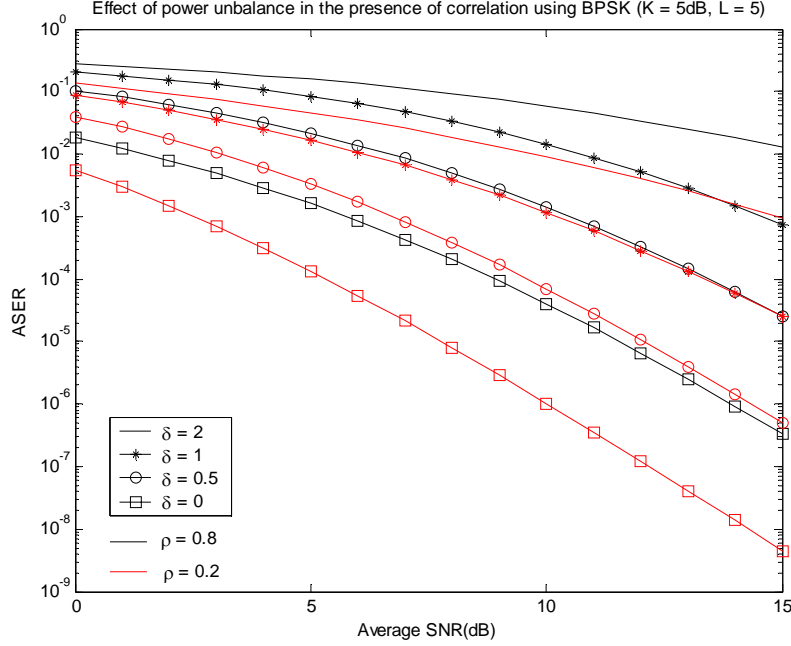


Figure 3.12: ASER performance for BPSK with unbalanced local mean powers for varying PDP decay factor δ and different values of ρ .

3.5. Power Consumption Efficiency Analysis

The efficient utilization of energy resource in ad hoc networks is of utmost concern. To this end, the analysis of the power efficiency performance of the various combination schemes is necessary to determine the cost due to power usage in implementing these algorithms. The analytical breakdown of the power consumption inherent in the implementation of these network diversity schemes from the sender's perspective is as discussed below. In all cases, except the MRRP and EGRP, only the selected nodes with the largest SNRs in the subset of the monitored nodes actually process the received packets while the other nodes simply drop the packets after making sure it is not intended for them.

Suppose there are L nodes that are being monitored for receiving the packets in the next hop, the average SNR from the sending node to these L nodes are $\bar{\gamma}_1, \bar{\gamma}_2, \dots, \bar{\gamma}_L$ and they are log-normally distributed i.e. $\bar{\gamma}_i \sim LN(\mu_i, \sigma_i^2)$, therefore the probability P that a node l is selected for transmission is given as

$$P = \sum_{i=1}^L P_i \quad (3.32)$$

where, P_i is the probability that $\bar{\gamma}_i$ has the i th largest average SNR. The marginal density of the ordered statistic $p_{\gamma_{L-iL}}(\gamma)$ is mathematically defined as

$$p_{\gamma_{L-iL}}(\gamma) = \sum_{\substack{\sigma \in S_L, \sigma(1) < \dots < \sigma(i-1) \\ \sigma(i+1) < \dots < \sigma(L)}} p_{\sigma(L-i)}(\gamma) \left[\prod_{i=1}^{(L-i)-1} P_{\sigma(i)}(\gamma) \right] \left[\prod_{j=(L-i)+1}^L (1 - P_{\sigma(j)}(\gamma)) \right] \quad (3.33)$$

Therefore, finding the probability of selecting the node with the largest SNR is the integration of the marginal PDF of the L ordered set over the desired statistics of that node i.e. if the probability to pick a node 1 with the highest average SNR is P_1 and its statistical distribution is defined by $f_{\gamma}(\bar{\gamma}_1)$, then P_1 can be written as

$$\begin{aligned} P_1 &= \int_{-\infty}^{\infty} f_{\gamma}(\bar{\gamma}_1) P(\bar{\gamma}_2 < \bar{\gamma}_1, \dots, \bar{\gamma}_n < \bar{\gamma}_1 | \bar{\gamma}_1) d\bar{\gamma}_1 \\ &= \frac{1}{\sqrt{2\pi\sigma_1^2}} \int_{-\infty}^{\infty} \exp(-(\bar{\gamma}_1 - \mu_1)^2 / 2\sigma_1^2) \prod_{i=2}^n Q\left(\frac{\mu_i - \bar{\gamma}_1}{\sigma_1}\right) d\bar{\gamma}_1 \end{aligned} \quad (3.34)$$

The probability of selecting a node l from a group of L nodes is directly impacted by the mean and variance of the nodes average SNR. An example is given below of 5 nodes with varying distribution statistics. The analysis and results are as given in the table below.

From the table below, if the nodes with the largest SNRs are monitored (i.e. P_1, P_2), it can be seen that nodes with relatively high mean values μ and large standard deviations σ are likely candidates for being the next hop node if the SRPM scheme is to be used. It can also be observed that for groups of nodes with similar μ values, the node with the larger σ (standard deviation) has a higher probability of pre-selection. Nodes with relatively low μ and σ values are the least likely nodes to be selected as the next hop. The analysis presented here, coincide with results in [27].

Table 3.1: Probability of a node being selected for next hop transmission

	P_1	P_2	P_3	P_4	P_5
$\mu = 2, \sigma = 8$	0.2189	0.1449	0.1172	0.1653	0.3537
$\mu = 2, \sigma = 5$	0.1227	0.1642	0.1835	0.2546	0.2750
$\mu = 5, \sigma = 3$	0.2303	0.3293	0.2468	0.1417	0.0519
$\mu = 5, \sigma = 8$	0.3684	0.1558	0.1177	0.1486	0.2095
$\mu = 3, \sigma = 2$	0.0596	0.2058	0.3350	0.2897	0.1099

The determination of the node to be the next hop is also hinged on the node's instantaneous SNR γ conditioned on their average SNRs $\bar{\gamma}$ being greater than all the other nodes monitored in the system (for the SRP, MRRP, EGRP and GRP (N,L) schemes). Therefore, at the beginning of transmission, the probability that a node l is chosen as the next hop in a Rice fading environment for the different combination techniques is given below.

Selection Route Path Combining Macro Network Diversity (SRPM):

The power consumption formulation for the SRPM scheme is given as

$$\sum_{l=1}^L P_l \cdot P[x > \gamma_{SRPM} / \bar{\gamma}_1, \dots, \bar{\gamma}_L] \quad (3.35)$$

Selection Based Route Path Combining Micro Network Diversity (SRP):

In this case, the probability that the nodes' instantaneous SNR is greater than that of all the other nodes conditioned on their average SNRs is given by

$$P = \prod_{\substack{j=1 \\ j \neq l}}^L P(\gamma_l > \gamma_j / \bar{\gamma}_1, \dots, \bar{\gamma}_L) \quad (3.36)$$

where, $P(\gamma_l > \gamma_j / \bar{\gamma}_l, \bar{\gamma}_j)$ is defined from [27][34] as

$$P(\gamma_l > \gamma_j / \bar{\gamma}_l, \bar{\gamma}_j) = Q_1 \left(\sqrt{\frac{2K_l}{b+1}}, \sqrt{\frac{2K_j b}{b+1}} \right) - \frac{b}{b+1} \exp \left(-\frac{K_l + K_j b}{b+1} \right) I_0 \left(\frac{2\sqrt{K_l K_j b}}{b+1} \right) \quad (3.37)$$

where, $b = \frac{K_j}{\gamma_j} \cdot \frac{\bar{\gamma}_l}{K_l}$

Unconditioning on the average SNRs $\bar{\gamma}$, we have

$$P(\gamma_i > \gamma_j / \gamma_1 \dots \gamma_L) = \prod_{\substack{j=1 \\ j \neq i}}^L \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(\bar{\gamma}_l) p(\bar{\gamma}_j) P(\gamma_i > \gamma_j / \bar{\gamma}_l, \bar{\gamma}_j) d\bar{\gamma}_l d\bar{\gamma}_j \quad (3.38)$$

Hence, the overall short-term power consumption is given by

$$\sum_{l=1}^L P_i \cdot \prod_{j=1}^L P(\gamma_i > \gamma_j) P[x > \gamma_{SRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L].$$

Maximal Ratio Route Path Micro Network Diversity (MRRP):

For this network diversity scheme, the power consumption expression is defined as follows

$$\sum_{l=1}^L P_i \cdot P[x > \gamma_{MRRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (3.39)$$

where, $P[x > \gamma_{MRRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L]$ is the outage probability in a Rice fading channel

Equal Gain Route Path Micro Network Diversity (EGRP):

The EGRP case is similar to (3.35) above, and is given as

$$\sum_{l=1}^L P_i \cdot P[x > \gamma_{EGRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (3.40)$$

Generalized Route Path Micro Network Diversity (GRP (N, L)):

The derivation of the power consumption expression for the GRP (N,L) can be done by ordering the received average SNR ratios in descending order (since it is assumed that the paths with the highest average SNR will be used in combination) and determining the marginal density for each of the N selected paths that will be used for transmission from the L monitored paths. The CDF of the marginal densities can then be found by integrating over the range of ordered values. Mathematically, the Power Consumption Probability is given as

$$\sum_{l=1}^N P_i \cdot P[x > \gamma_{GRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (3.39)$$

For the special case of the SRP scheme, if the probability densities $\overline{\gamma}_i$ for $1 \leq i \leq L$ are assumed to be i.i.d., the probability that a station will be picked for transmission will reduce to $\sum_{i=1}^L P_i$ where $P = (1/N)$. Without loss of generality, if γ_i for $1 \leq i \leq L$ are i.i.d.,

$P(\gamma_i > \gamma_1, \dots, \gamma_L) = \prod_{j=1, j \neq i}^L P(\gamma_i > \gamma_j / \gamma_1, \dots, \gamma_L)$ will reduce to $(1/L)$. Therefore, the overall long-term

Power Consumption Probability that the station 1 is selected will be

$P = \sum_{i=1}^L P_i \prod_{j=1, j \neq i}^L P(\gamma_i > \gamma_j / \gamma_1, \dots, \gamma_L)$ which reduces to $(1/N)$ times the probability that the station is

below the outage threshold, where N is the number of nodes in the receiving cluster.

To compare the power consumption of the network diversity schemes presented above, the probability of selecting any node based on its local mean levels is neglected since all the L nodes monitored are being considered. This factor however comes into play when comparing the performance of the GRP (N, L) scheme with all the other schemes, since only a subset of the paths monitored are combined. For all plots, the standard deviation is chosen to be between 6 – 12 dB [35]. Also, the probability of a nodes received instantaneous levels being greater than the other nodes considered in the receiving cluster is only inherent to the SRP scheme and is therefore also neglected in the comparison of the various schemes

In Figure [3.13], the relative power consumption efficiency is analyzed for the MRRP and SRP scheme for $L = 2$ i.i.d. Rice multiple paths. For all values of K , the MRRP provides the best power consumption efficiency, i.e. for $K = 10$ dB at $\mu = 10$ dB, the PCP is 4.5×10^{-2} and 8.5×10^{-2} for SRP and MRRP respectively. The relative power consumption performance gain of the MRRP over the SRP can also be seen to increase with increasing values of the K factor.

Figure [3.14] depicts the effect of the outage threshold γ_{th} on the relative power consumption performance of the various network diversity schemes. For very high values of γ_{th} , the power consumption efficiency becomes very low; this is intuitive due to the fact that much more power will needed to exceed the limit of such thresholds. It can also be seen that increasing mean values of the local mean distribution improves the performance thereby increasing the power consumption efficiency for any given network diversity scheme, but at very high γ_{th} values, the

power consumption efficiency presented by each scheme tends to converge and the performance gain of the MRRP over the EGRP and the SRP becomes very minimal. For example, at $\gamma_{th} = 0\text{dB}$, the performance gain of the MRRP and EGRP schemes over the SRP scheme is 3.09 and 2.18 folds respectively. At $\gamma_{th} = 5\text{dB}$, the performance gain of the MRRP and EGRP is about 1.67 and 1.49 folds more than the SRP, while at 10dB, the gains are 1.008 and 1.005 folds respectively.

The standard deviation σ also affects the relative power consumption efficiency in the system as shown in Figure [3.15]. For all values of σ , there is a cross-over point close to the value of γ_{th} . This shows that for mean values exceeding the γ_{th} , lower values of σ provide the best performance in terms of PCP for paths with the same Rice fading statistics while for mean values lower than γ_{th} , high values of σ provides the best power consumption efficiency.

Figure [3.16] analyzes the effect of increasing mean and outage threshold values. In all cases, the MRRP scheme provides better power consumption efficiency than the SRP scheme and this improves with increasing mean values. The performance gain however, is negligible for small mean values with large values of outage threshold γ_{th} .

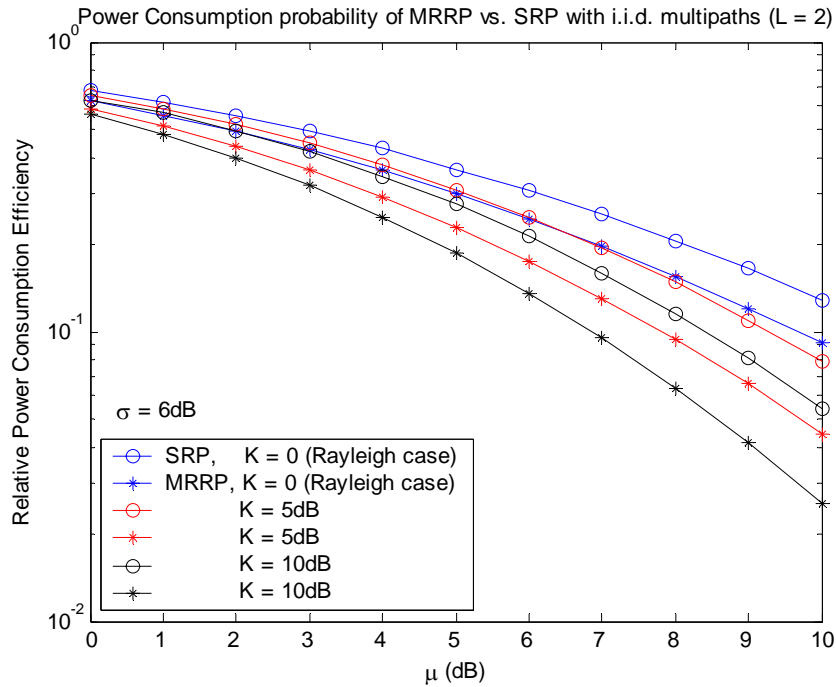


Figure 3.13: Relative power consumption efficiency comparison between MRRP and SRP for i.i.d. Rice fading channels for varying K factor values.

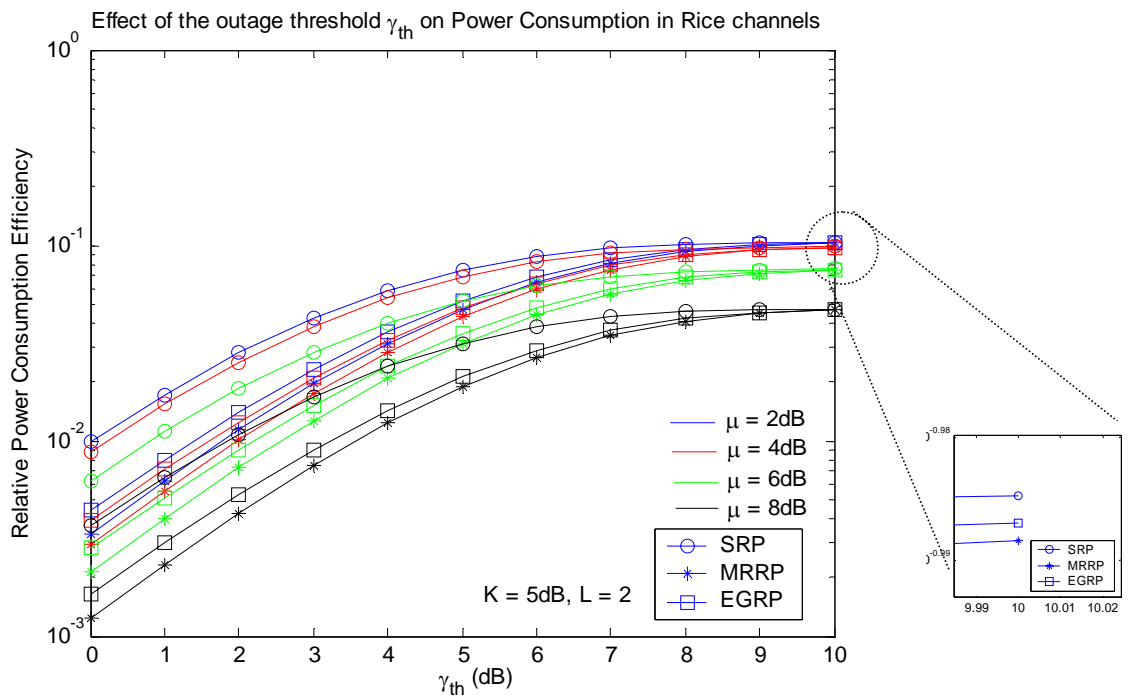


Figure 3.14: Outage threshold effects on the relative power consumption efficiency in i.i.d. Rice fading channels ($\sigma = 6\text{dB}$).

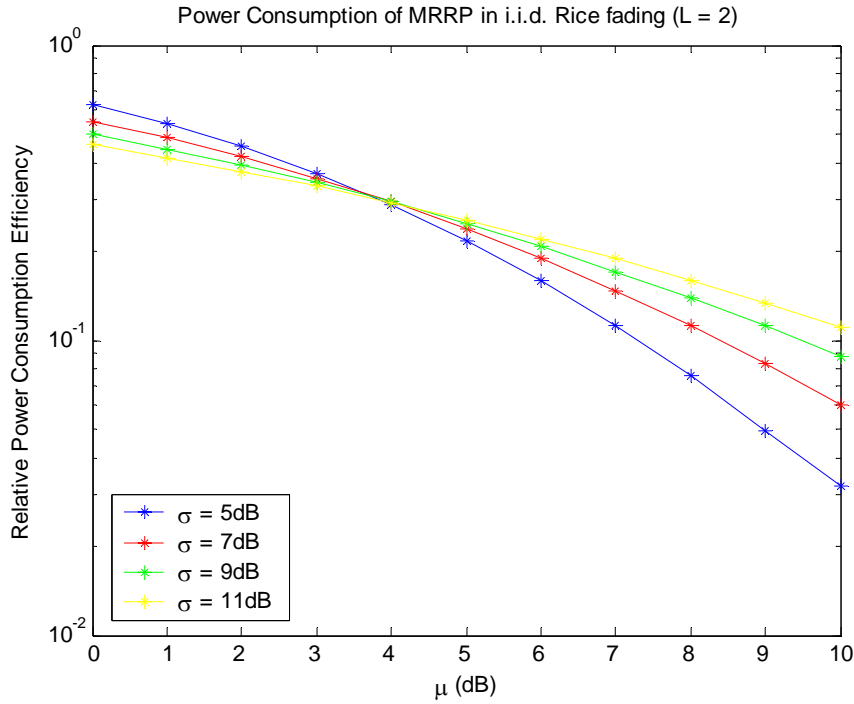


Figure 3.15: Effect of standard deviation σ and the distribution of the average SNR on power consumption in the network ($L = 2$, $\gamma_{th} = 4\text{dB}$, $K = 5\text{dB}$).

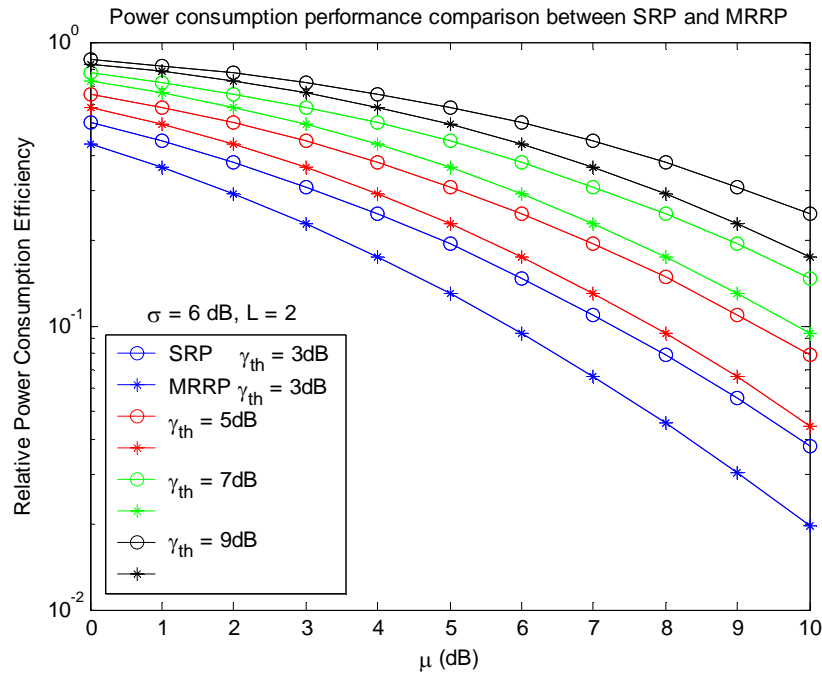


Figure 3.16: Effect of the outage threshold γ_{th} on the relative power consumption efficiency for SRP and MRRP in i.i.d. Rice fading channels.

CONCLUSION:

This chapter studies the performance of the introduced network diversity schemes in the Rice fading model. Performance metrics such as the outage probability and end-to-end ASER are used to analyze the diversity schemes. The number of hops in the route path, correlation among received paths and unbalance local mean levels received moderately impacts the performance of the scheme, but enough improvement is introduced via the diversity schemes to enable network enhancements such as reduced transmission power, adaptive modulation techniques based on channel deterioration, etc.

Table 3.2: PDF, CDF and MGF of different types of distribution models

Distribution models	Fading parameter	PDF	CDF	MGF
Rayleigh		$\frac{1}{\gamma} e^{-\frac{\gamma}{\gamma}}$	$1 - e^{-\frac{\gamma}{\gamma}}$	$\frac{1}{1 + s\bar{\gamma}}$
Rice	$K \geq 0$	$\frac{K+1}{\gamma} \exp\left\{-\frac{K+1}{\gamma}\right\} I_0\left(2\sqrt{\frac{K(K+1)\gamma}{\gamma}}\right)$	$1 - Q\left(\sqrt{2K}, \sqrt{\frac{2(1+K)\gamma}{\gamma}}\right)$	$\frac{1+K}{1+K+s\bar{\gamma}} e^{\left(-\frac{sK\bar{\gamma}}{1+K+s\bar{\gamma}}\right)}$
Nakagami-m	$m \geq 0.5$	$\frac{1}{\Gamma(m)} \left(\frac{m}{\gamma}\right)^m \gamma^{m-1} e^{-\left(\frac{m\gamma}{\gamma}\right)}$	$\frac{\Lambda\left(m, \frac{m\gamma}{\gamma}\right)}{\Gamma(m)}$ ^{*a}	$\left(\frac{m}{m+s\bar{\gamma}}\right)^m$
Nakagami-q	$b = \frac{(1-q^2)}{(1+q^2)}$ $-1 \leq b \leq 1$ $0 \leq q \leq \infty$	$\frac{1}{\gamma\sqrt{1-b^2}} e^{\left(-\frac{\gamma}{(1-b)^2\bar{\gamma}}\right)} I_0\left(\frac{b\gamma}{(1-b)^2\bar{\gamma}}\right)$	$I_e\left(b, \gamma(1-b)^2\bar{\gamma}\right)$ ^{*b}	$\left(1 + 2s\bar{\gamma} + \frac{(2s\bar{\gamma})^2 q^2}{(1+q^2)^2}\right)^{-1/2}$
3 parameter Weibull		$\frac{\beta(T-\gamma)^{\beta-1}}{\eta^\beta} e^{\left(-\left(\frac{T-\gamma}{\eta}\right)^\beta\right)}$	$1 - e^{\left(-\left(\frac{T-\gamma}{\eta}\right)^\beta\right)}$	

where, γ is the instantaneous SNR

$\bar{\gamma}$ is the average SNR

^{*a} $\Lambda(a,x)$ is the incomplete gamma function, $\Gamma(x)$ is the gamma function

^{*b} I_e is related to the first order Marcum Q function as

$$I_e(V/U, U) = \frac{U}{W} \left[Q\left(\sqrt{U+W}, \sqrt{U-W}\right) - Q\left(\sqrt{U-W}, \sqrt{U+W}\right) \right]$$

where, $W = \sqrt{U^2 - V^2}$

Table 3.3: Negative derivative table for the CEP of various modulation schemes

Modulation scheme		$-P_e(\gamma)$
BPSK	$a = 1$	$0.5ae^{-a\gamma}$
CFSK	$a = 1/2$	$\frac{0.5ae^{-a\gamma}}{\sqrt{\pi}\sqrt{a\gamma}}$
NCFSK	$a = 1/2$	$0.5ae^{-a\gamma}$
DPSK	$a = 1$	$0.5ae^{-a\gamma}$
QPSK	$[q = a = 1/2]$	$2\frac{qae^{-a\gamma}}{\sqrt{\pi}\sqrt{a\gamma}} - 2\frac{q^2\text{erfc}(\sqrt{a\gamma})e^{-a\gamma}}{\sqrt{\pi}\sqrt{a\gamma}}$
MSK	$[q = a = 1/2]$	
M-QAM*	$\left[q = 1 - \frac{1}{\sqrt{M_e}} \right]$	
CDE-BPSK**		$\frac{e^{-\gamma}}{\sqrt{\pi}\sqrt{\gamma}} - 1.0\frac{\text{erfc}(\sqrt{\gamma})e^{-\gamma}}{\sqrt{\pi}\sqrt{\gamma}}$
MPSK		$\frac{1}{\pi} \int_0^{\pi-\frac{\pi}{m}} h(\theta)e^{(-h(\theta))} d\theta$ ***
MDPSK		$\frac{1}{\pi} \int_0^{\pi-\frac{\pi}{m}} g(\theta)e^{(-g(\theta))} d\theta$ ****

where $* a = \frac{3/2}{M_e - 1}$, $*** h(\theta) = \frac{\sin^2(\pi/M)}{\sin^2 \theta}$, $**** g(\theta) = \frac{\sin^2(\pi/M)}{1 + \cos(\pi/M)\cos \theta}$

** is the coherent detection of differentially encoded BPSK

*“The battle is not to the mighty, nor
the race to the swift,
but time and chance
happeneth to them all.
Be prepared”.*
Ecc. 9:11

Chapter 4

NETWORK LAYER DIVERSITY IN THE NAKAGAMI-m CHANNEL MODEL

This chapter analyzes the performance of our network system in the presence of Nakagami-m propagation fading model for the various network diversity combination techniques described above. Analytical expressions based on the end-to-end outage probability, end-to-end ASER and power consumption efficiency are presented.

The Nakagami-m distribution model has been of increased interest in the realm of researchers due to its simple analytical tractability in performance analysis. Its flexibility to account for both weak and strong fading models that includes the Rayleigh and a variation of the Rice distribution (i.e. fits experimental data well around the mean or median but not so well in the tails of the distribution) [30] makes it very acceptable to model modern communication propagation channels today. Expressions for both the integral and non-integral fading severity parameters will be presented for the various performance metrics mentioned above.

4.1. Outage Probability Analysis

Selection Route Path Combining Macro Network Diversity (SRPM):

The outage probability for the SRPM scheme can be obtained using (3.2) with the MGF obtained from the PDF of the output combiner (as in (3.4) and (3.5)) which is given as

$$f(\gamma) = \int_{-\infty}^{\infty} \sum_{i=1}^L \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left(-\frac{(\ln \bar{\gamma} - \ln \mu_i)^2}{2\sigma_i^2}\right) \prod_{\substack{j=1 \\ j \neq i}}^L \mathcal{Q}\left(\frac{\ln \bar{\gamma} - \ln \mu_j}{\sigma_j}\right) \frac{\gamma^{m_i-1} \left(\frac{m}{\gamma}\right)^m}{\Gamma(m_i)} \exp\left(-\frac{m_i \gamma}{\gamma}\right) d\bar{\gamma} \quad (4.1)$$

Selection Based Route Path Combining Micro Network Diversity (SRP):

The outage probability in a Nakagami-m fading channel for a single hop combining L multiple paths can be mathematically defined as given below

$$P_{out} = \prod_{i=1}^L \left[\int_0^{\gamma_{th}} \frac{1}{\Gamma(m_i)} \left(\frac{m_i}{\gamma_i}\right)^{m_i} \gamma_i^{m_i-1} \exp\left(-\frac{m_i \gamma_i}{\gamma_i}\right) d\gamma_i \right] \\ \text{i.e., } P_{out} = \prod_{i=1}^L \frac{\Lambda\left(m_i, \frac{m_i \gamma_{th}}{\gamma_i}\right)}{\Gamma(m_i)} \quad (4.2)$$

where, $\Gamma(\cdot)$ is the gamma function and $\Lambda(\cdot, \cdot)$ is the incomplete gamma function and γ_{th} is the outage threshold level.

The overall outage probability for the Nakagami-m fading channel case is obtained by averaging over the PDFs of the signal received by the L nodes in the receiving cluster based on their local mean power levels as defined in the equation below

$$\overline{P_{out}} = \underbrace{\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty}}_{\substack{L\text{-fold} \\ \text{integral}}} P_{out} f(\gamma_1) \cdots f(\gamma_L) d\gamma_1 \cdots d\gamma_L \quad (4.3)$$

Maximal Ratio Route Path Micro Network Diversity (MRRP):

The outage probability of the MRRP scheme in a Nakagami-m fading channel can be computed using the Laplacian Conversion of CDFs method as described in Chapter 4.

The MGF of the output SNR for i.i.d. channels is as defined below.

$$M(s) = \prod_{i=1}^L \left(\frac{m_i}{m_i + s\gamma_i} \right)^{m_i} \quad (4.4)$$

The overall outage probability is computed as described in equation (4.3).

Equal Gain Route Path Micro Network Diversity (EGRP):

The PDF of the output SNR for a EGRP scheme is not a trivial task and has therefore been unobtainable for large L, analysis is therefore carried out using the MGF of the output combiner whose closed form expression can be obtained in [29] as

$$M_{cd}(s) = \frac{\Gamma(2m_l)}{2^{2m_l-1}\Gamma(m_l)} \left(\frac{\sqrt{\pi}}{\Gamma(m_l + 1/2)} {}_1F_1 \left[m_l, \frac{1}{2}; \frac{\Omega_l s^2}{4m_l} \right] + \frac{\sqrt{\pi\Omega_l} s}{\Gamma(m_l)\sqrt{m_l}} {}_1F_1 \left[m_l + \frac{1}{2}, \frac{3}{2}; \frac{\Omega_l s^2}{4m_l} \right] \right) \quad (4.5)$$

where, $\Omega = E[\alpha^2]$ is the amplitude of the l th received signal and ${}_1F_1(\cdot; \cdot; \cdot)$ is the confluent hypergeometric function which is defined in [31] as

$${}_1F_1(a, b, c) = \frac{\Gamma(b)}{\Gamma(a)\Gamma(b)} \int_0^1 \exp(ct) t^{a-1} (1-t)^{b-a-1} dt \quad (4.6)$$

therefore, to compute the MGF of the output signal for this combining technique using L multiple paths will be simply the product of the MGF of the individual paths combined. The outage probability P_{out} is then evaluated by using the expression (3.2) in the previous chapter. The overall outage probability for this scheme is as described in equation (4.3).

Generalized Route Path Micro Network Diversity (GRP (N, L)):

For the GRP scheme, the MGF is defined as,

$$M_\gamma(s) = E \left[\exp \left(-s \sum_{i=L-N+1}^L \gamma_{i:L} \right) \right], s \geq 0$$

Simplifying further for the i.i.d. case, we have [15]

$$M_\gamma(s) = N \binom{L}{N} \int_0^\infty \exp(-s\gamma) f(\gamma) [F(\gamma)]^{L-N} [M(s, \gamma)]^{N-1} d\gamma, \quad 1 \leq N \leq L/2$$

$$M_\gamma(s) = (L-N) \binom{L}{N} \int_0^\infty f(\gamma) [F(\gamma)]^{L-N-1} [M(s, \gamma)]^N d\gamma, \quad L/2 \leq N \leq L$$

$$M_\gamma(s) = \prod_{i=1}^L M_i(s), \quad L = N \quad (4.7)$$

The outage probability is computed using the MGF derived above in equation (3.2) and the overall outage probability is as described in the SRP scheme above.

4.2. ASER Analysis

The breakdown for the ASER computation for the different combination schemes is as given below.

Selection Route Path Combining Macro Network Diversity (SRPM):

The ASER can be computed using the MGF derived from the Laplacian transformation of (4.1) and (3.20).

Selection Based Route Path Combining Micro Network Diversity (SRP):

Using expression (3.17) in the previous chapter, the ASER can be computed as

$$P_s(E) = -\int_0^\infty \prod_{i=1}^L \frac{\Lambda\left(m_i, \frac{m_i \gamma}{\gamma_i}\right)}{\Gamma(m_i)} \left[\frac{0.5e^{-\gamma}}{\sqrt{\pi} \sqrt{\gamma}} \right] d\gamma \quad (4.8)$$

where, $P_\gamma(\gamma)$ is $\prod_{i=1}^L \frac{\Lambda\left(m_i, \frac{m_i \gamma}{\gamma_i}\right)}{\Gamma(m_i)}$ for a Nakagami-m fading channel

The overall ASER is also computed by averaging the ASER for the combined signals over the PDFs of the signals received by the nodes at the receiving cluster due to their local mean power levels. The overall ASER is mathematically defined by the L-fold integral shown in the equation below.

$$\overline{P_{ov}}(E) = \underbrace{\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty}}_{\substack{L\text{-fold} \\ \text{integral}}} P_s(E) f(\gamma_1) \cdots f(\gamma_L) d\gamma_1 \cdots d\gamma_L \quad (4.9)$$

Maximal Ratio Route Path Micro Network Diversity (MRRP):

The ASER for the MRRP scheme can be obtained using the MGF expression as given in equation (4.4) above for integral parameters of m . For non-integral m , we use the inverse Fourier transform of the CHF given in expression (4.12) below and the equation derived by Zhang [30]. The expression derived involves Parseval's theorem, where the conditional SER is computed using its error function complement definition and the Fourier transform of the given modulation scheme. The derived closed form expression for BPSK is given as

$$P_s(E) = \frac{1}{2} \int_{-\infty}^{\infty} \frac{1}{j2\pi} \left(1 - \sqrt{\frac{1}{jt+1}} \right) \prod_{i=1}^L (1 - j\lambda_i t)^{-m} dt \quad (4.10)$$

Since we are only considered with the real part of the argument, we have

$$P_s(E) = \int_0^{\infty} \frac{\eta(t) \sin\left(\varphi(t) + m \sum_{i=1}^L \tan^{-1}(\lambda_i t)\right)}{2\pi \prod_{i=1}^L [1 + (\lambda_i t)^2]^{m/2}} dt \quad (4.11)$$

where, $\eta(t) = \sqrt{1 + \left(\frac{1}{t^2 + 1}\right)^{1/2} - 2\left(\frac{1}{t^2 + 1}\right)^{1/4} \cos\left[\frac{1}{2} \tan^{-1}(t)\right]}$

and $\varphi(t) = \tan^{-1}\left(\frac{\sin\left[\frac{1}{2} \tan^{-1}(t)\right]}{\left(\frac{1}{t^2 + 1}\right)^{-1/4} - \cos\left[\frac{1}{2} \tan^{-1}(t)\right]}\right)$

The CHF of the Nakagami- m distribution is defined as below

$$\phi(w) = \prod_{i=1}^L (1 - w\lambda_i)^{-m} \quad (4.12)$$

where, λ_i stands for the eigen values of matrix Γ , which is the positive definite matrix determined by the covariance matrix. The overall ASER is computed as described in the SRP scheme above.

Equal Gain Route Path Micro Network Diversity (EGRP):

The ASER for this combination scheme can be computed in a closed form expression using the CHF of the output SNR at the receiver and making use of Parseval's theorem as described in [32].

The CHF of γ in Nakagami-m fading is given by

$$\phi(w) = \prod_{i=1}^L \left[{}_1F_1\left(m_i, \frac{1}{2}; \frac{-w^2}{4L\lambda_i}\right) + jw \frac{\Gamma(m_i + 1/2)}{\Gamma(m_i)\sqrt{L\lambda_i}} {}_1F_1\left(m_i + \frac{1}{2}, \frac{3}{2}; \frac{-w^2}{4L\lambda_i}\right) \right] \quad (4.13)$$

where, $\lambda = \frac{m}{\gamma}$, and ${}_1F_1(\cdot, \cdot; \cdot)$ is the confluent hypergeometric function of the first kind and $\Gamma(\cdot)$ is the gamma function.

The ASER can be computed using the expression defined in (3.23) and the Fourier transforms of the various modulation schemes as given in [32]. For BPSK, we have

$$G(w) = \frac{0.5}{w} \left[\frac{2}{\sqrt{\pi}} F\left(\frac{w}{2}\right) + j \left(1 - \exp\left(\frac{-w^2}{4}\right) \right) \right] \quad (4.14)$$

The overall ASER for this scheme is computed using equation (4.9) above.

Generalized Route Path Micro Network Diversity (GRP (N, L)):

Since the MGF of the GRP (N, L) can be easily obtainable, to compute the ASER for BPSK, equation (4.6) is used

$$P_s(E) = \frac{1}{\pi} \int_0^{\pi/2} \prod_{i=1}^L M_{\gamma_i} \left(\frac{1}{\sin^2 \theta} \right) d\theta \quad (4.15)$$

The expression for computing the ASER for MPSK is as given below

$$P_s(E) = \frac{1}{\pi} \int_0^{\pi-\pi/m} \prod_{i=1}^L M_{\gamma_i} \left(\frac{\sin^2(\pi/m)}{\sin^2 \theta} \right) d\theta \quad (4.16)$$

where, m is the number of symbols in the modulation scheme

4.3. CORRELATION IN NAKAGAMI-m FADING CHANNEL

The unified MGF based approach is also used to effectively compute the ASER performance metric for the Nakagami-m fading model in a correlated scenario. The expressions defined

for this scenario are as given below for the respective diversity schemes.

Selection Based Route Path Combining Micro Network Diversity (SRP):

The ASER is computed using equation (3.18) for BPSK with the MGF defined in [31] as

$$M_{\alpha}(s) = \frac{2^{2m} \Gamma(2m)}{\Gamma(m)\Gamma(m+1)} {}_2F_1\left(1-m, m; 1+m; \frac{1-1/B_{ij}}{2}\right) \sum_{i=1, j \neq i}^2 \frac{A_{ij}^{2m}}{[\bar{\gamma}_j B_{ij} (1+B_{ij})]^m} \quad (4.17)$$

where, ${}_2F_1$ is the Gaussian hypergeometric function,

$$A_{ij} = \frac{\sqrt{\bar{\gamma}_j(1-\rho)}/2}{\bar{\gamma}_j/\bar{\gamma}_i - 1 + s\bar{\gamma}_j(1-\rho)}, \text{ and } B_{ij} = \frac{\sqrt{[s\bar{\gamma}_i\bar{\gamma}_j(1-\rho) + \bar{\gamma}_i + \bar{\gamma}_j]^2 - 4\rho\bar{\gamma}_i\bar{\gamma}_j}}{s\bar{\gamma}_i\bar{\gamma}_j(1-\rho) + \bar{\gamma}_i - \bar{\gamma}_j}$$

Maximal Ratio Route Path Micro Network Diversity (MRRP):

In [38], the MGF of the combined SNR per symbol for two correlated multiple paths with non-identical fading is given as

$$M_{\alpha}(s) = \left(1 - \frac{(\bar{\gamma}_1 + \bar{\gamma}_2)}{m} s + \frac{(1-\rho)\bar{\gamma}_1\bar{\gamma}_2}{m^2} s^2\right)^{-m}; s \geq 0 \quad (4.18)$$

- For a constant correlation model with L i.i.d. multiple paths, the PDF of the output signal is given by;

$$f_{\gamma}(\gamma) = \frac{\left(\frac{m\gamma}{\bar{\gamma}}\right)^{Lm-1} \exp\left(-\frac{m\gamma}{(1-\sqrt{\rho})\bar{\gamma}}\right) {}_1F_1\left(m, Lm; \frac{Lm\sqrt{\rho}\gamma}{(1-\sqrt{\rho})(1-\sqrt{\rho}+L\sqrt{\rho})\bar{\gamma}}\right)}{\left(\frac{\bar{\gamma}}{m}\right) (1-\sqrt{\rho})^{m(L-1)} (1-\sqrt{\rho}+L\sqrt{\rho})^m \Gamma(Lm)} \quad (4.19)$$

while the MGF is given by,

$$M_{\gamma}(s) = \left(1 - \frac{\bar{\gamma}(1-\sqrt{\rho}+L\sqrt{\rho})}{m} s\right)^{-m} \left(1 - \frac{\bar{\gamma}(1-\sqrt{\rho})}{m} s\right)^{-m(L-1)} \quad (4.20)$$

- For an exponential correlation model with L i.i.d. multiple paths, the MGF of the combined output signal is given by;

$$M_\gamma(s) = \left(-\frac{s\bar{\gamma}}{m} \right)^{-mL} \prod_{i=1}^L \left(\frac{1-\rho}{1+\rho+2\sqrt{\rho}\cos\theta_i} \right)^{-m} \quad (4.21)$$

where, θ_i ($i = 1,2,3 \dots L$) are the L solutions of the transcendental equation given by

$$\tan(L\theta_i) = \frac{-\sin\theta_i}{\left(\frac{1+\rho}{1-\rho}\right)\cos\theta_i + \frac{2\sqrt{\rho}}{1-\rho}}$$

- For an arbitrary correlation model with L multiple paths, the MGF of the combined output signal is given in [29][38] by,

$$M_\gamma(s) = \prod_{i=1}^L \left(1 - \frac{s\bar{\gamma}_i}{m} \right)^{-m} \left[\begin{array}{cccc} 1 & \sqrt{\rho_{21}} \left(1 - \frac{m}{s\bar{\gamma}_2} \right)^{-1} & \dots & \sqrt{\rho_{L1}} \left(1 - \frac{m}{s\bar{\gamma}_L} \right)^{-1} \\ \sqrt{\rho_{12}} \left(1 - \frac{m}{s\bar{\gamma}_1} \right)^{-1} & 1 & \dots & \sqrt{\rho_{L2}} \left(1 - \frac{m}{s\bar{\gamma}_L} \right)^{-1} \\ \vdots & \vdots & \ddots & \vdots \\ \sqrt{\rho_{1L}} \left(1 - \frac{m}{s\bar{\gamma}_1} \right)^{-1} & \sqrt{\rho_{2L}} \left(1 - \frac{m}{s\bar{\gamma}_2} \right)^{-1} & \dots & 1 \end{array} \right]_{L \times L}^{-m} \quad (4.22)$$

where, $[[M]]_{L \times L}$ denotes the determinant of the $L \times L$ matrix M

4.4. Analysis and Numerical Examples

The numeric results for the end-to-end outage probability and end-to-end average SER are provided in this section to study and analyze the performance of the different combination techniques over i.i.d. and i.n.d. Nakagami- m fading channels. For the i.n.d. case the PDP model defined in the previous Chapter is used.

Figure [4.1] depicts the effect of the severity of the fading index parameter m in Nakagami- m fading channels. As can be seen, the higher the fading index, the better the performance in terms of outage probability. For low value of average SNR in SRP (< 5 dB), high values of m tend to have a worse performance, but improve drastically with increase in the average SNR. The

relative improvement in performance increases gradually as the value of the m parameter increases. For example at 10^{-4} , for $m = 2$, the MRRP scheme has a gain of 0.5dB and 4.2dB over EGRP and SRP respectively, while for $m = 8$, it gradually reduces to 0.15dB for EGRP but increases to 4.9 dB for the SRP scheme.

The performance improvement received in the system by combining L arbitrary paths is shown in Figure [4.2], as expected, the outage probability performance improves with increasing paths combined. The performance of the MRRP scheme over the other network schemes also increases with increasing L . For example at 10^{-4} , the MRRP scheme has a gain of 0.4dB and 3dB over the EGRP and SRP schemes at $L = 3$, while at $L = 4$, 0.6dB and 3.9dB improvements can be seen respectively.

Figure [4.3] shows the effect of local mean power unbalances on the outage probability performance in the system. For high values of δ (i.e. $\delta = 3$), the EGRP system tends to be worse than the other diversity schemes due to its equal weighting of the entire received multiple paths, thereby the badly faded paths have a serious impact on the entire output if this scheme is used. The MRRP is still the best system even for very high PDP decay factor values due to weighting of the multiple paths according to their signal strength. For lower values of δ (i.e. $\delta > 3$), the SRP scheme tends to perform worse than the other scheme and these increases with reducing δ values.

Figure [4.4] shows the impact of routing through multiple hops on the outage probability of the network system using the various diversity schemes. As can be seen from the plot, the more hops traversed in the system, the increase in the probability of system outage for a defined outage threshold ($\gamma_{th} = 5$ dB, for this case). The performance impact of multiple hop transmissions lessen for large values of the fading severity index, for example, at an outage probability of 10^{-5} , the performance loss going through 5 hops for $m = 8$ is about 0.4 dB, while the performance loss for $m = 4$ and 2 are 0.6dB and 1.1dB respectively.

Figure [4.5] show the performance of the network diversity schemes in a mixed fading scenario with $L = 5$ possible paths. The fading distribution of each path is given as $K_1 = 0$ dB, $K_2 = 2$ dB, $m_3 = 2.5$, $m_4 = 0.5$, $K_5 = 5$ dB. For $L = 2$, the performance improvement of the various network

diversity schemes are moderate with MRRP being the best. At $L = 3$ the performance improves a great deal and that can be attributed to the inclusion of the third path with $m = 2.5$. At $L = 4$, the $m = 0.5$ path is added and due to the weak component in the signal, the diversity improvement is also moderate. With the addition of the last component (i.e. $K = 5\text{dB}$), we can see that the diversity gain in the system performance improves a great deal and this is intuitive due to the strength of the path component.

The effect of local mean power unbalance is shown for a mixed fading scenario in Figure [4.6]. As expected, $\delta = 0$, provides the best performance. The effect on performance worsens as the value of δ increases. For large values of δ , the first received multiple path becomes dominant while the other received paths appear non-existent, therefore, the gain received from applying the network diversity scheme becomes heavily impacted and the SRP scheme performs relatively well as compared to the EGRP and MRRP schemes respectively.

Figure [4.7], gives a comparative analysis of the performance of the GRP diversity scheme for i.i.d. Nakagami- m channels for $m = 2$. As expected, the case GRP (1,4) case gives the same performance as the SRP case, since only the strongest path is selected in the system, while the GRP (4,4) case is synonymous in performance to that of the MRRP diversity scheme, because all paths are considered and weighted according to their signal strength. By combining 3 out of the 4 possible paths, we get a performance relative to that of the EGRP scheme. At 10^{-4} , the GRP (2,4) scheme provides a performance gain of 2.2 dB to the SRP scheme and is about 1.2dB worse than the EGRP scheme. Definitely, the study of the GRP system becomes imperative due to the fact that by combining a small subsection of multiple paths received, a good percentage of diversity improvement can be achieved for a much less complex receiver system.

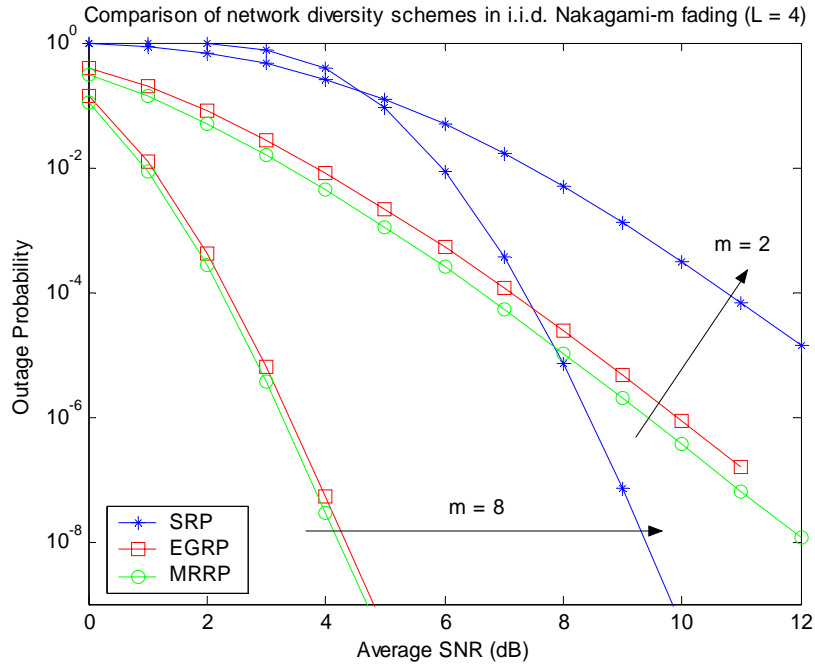


Figure 4.1: Outage probability comparison for SRP, EGRP and MRRP in i.i.d. Nakagami- m fading channels ($L = 4$, $\delta = 0$, $\gamma_{th} = 5\text{dB}$)

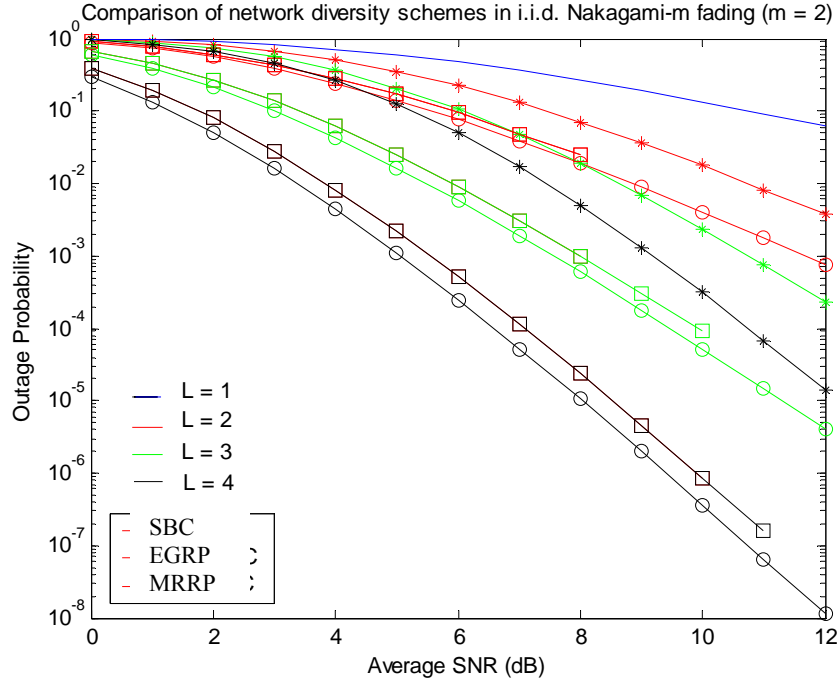


Figure 4.2: Effect of multiple path combination on outage probability in i.i.d. Nakagami- m fading ($L = 1, 2, 3$ and 4 , $m = 2$, $\delta = 0$, $\gamma_{th} = 5\text{dB}$)

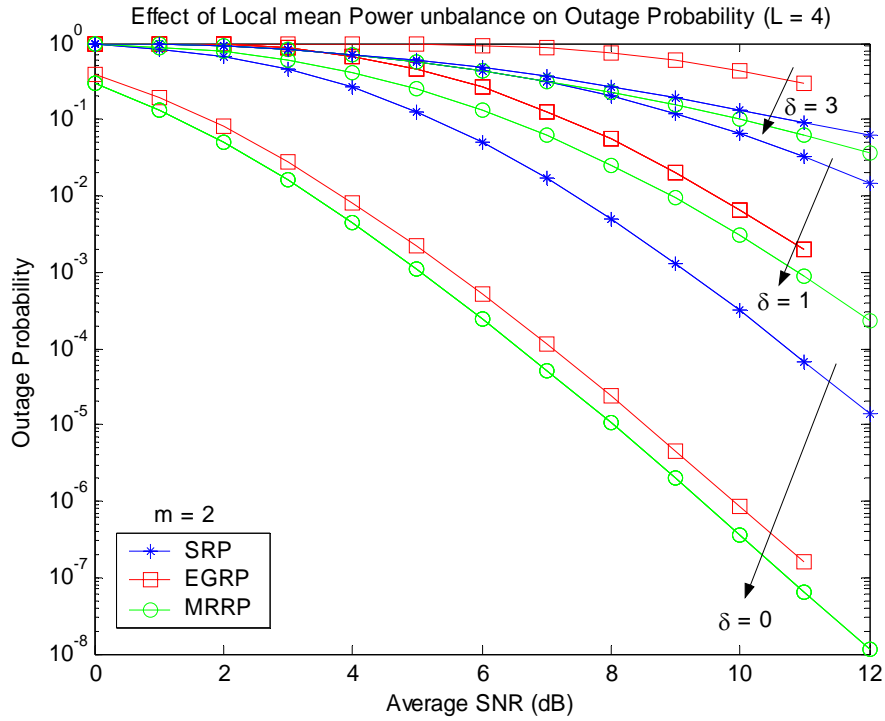


Figure 4.3: Local mean power unbalance effect on outage probability for various network diversity schemes in i.i.d. Nakagami fading ($m = 2$, $\gamma_{th} = 5\text{dB}$)

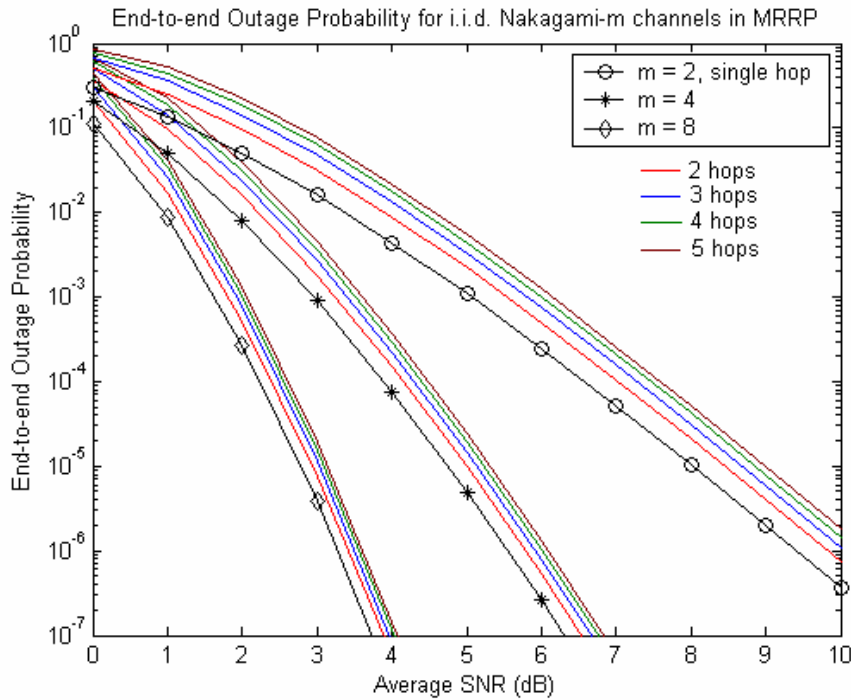


Figure 4.4: Comparison of the end-to-end outage probability for various numbers of hops traversed in the presence of i.i.d. Nakagami-m channels

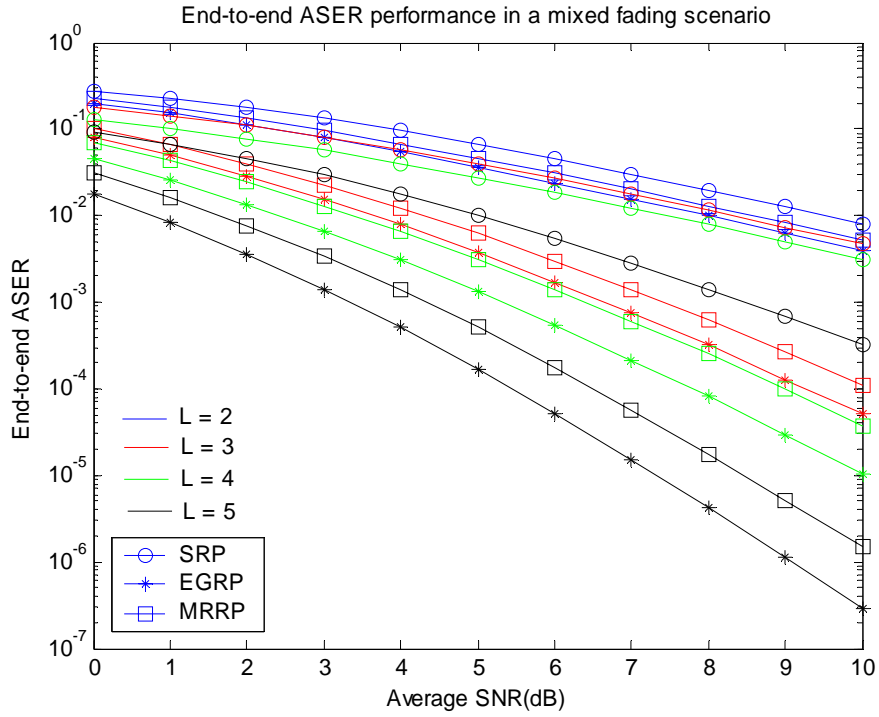


Figure 4.5: End-to-end ASER performance in a mixed fading scenario for varying paths combined ($K_1 = 0\text{dB}$, $K_2 = 2\text{dB}$, $m_3 = 2.5$, $m_4 = 0.5$, $K_5 = 5\text{dB}$).

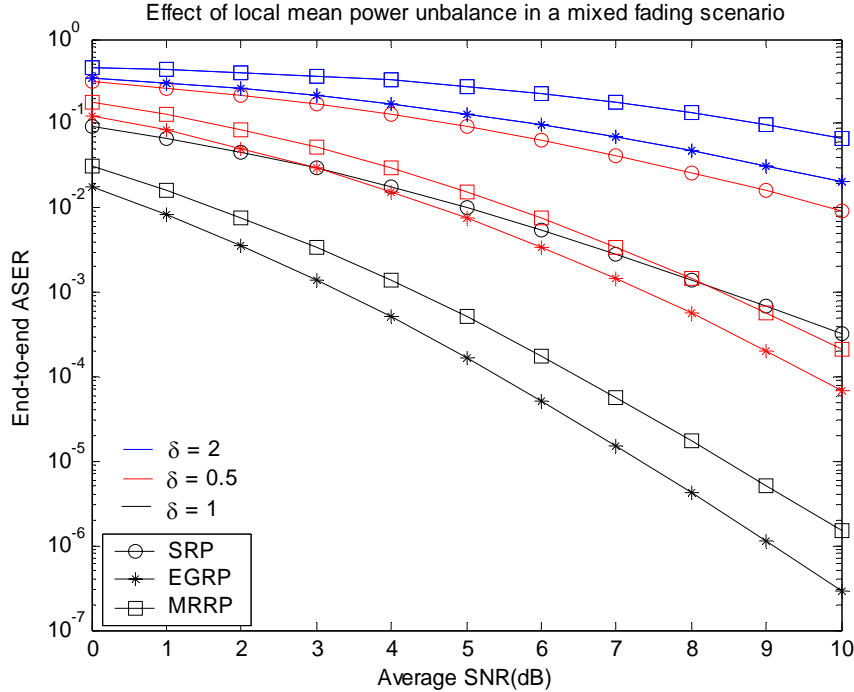


Figure 4.6: Effect of local mean power unbalance on end-to-end ASER performance in a mixed fading scenario ($K_1 = 0\text{dB}$, $K_2 = 2\text{dB}$, $m_3 = 2.5$, $m_4 = 0.5$, $K_5 = 5\text{dB}$).

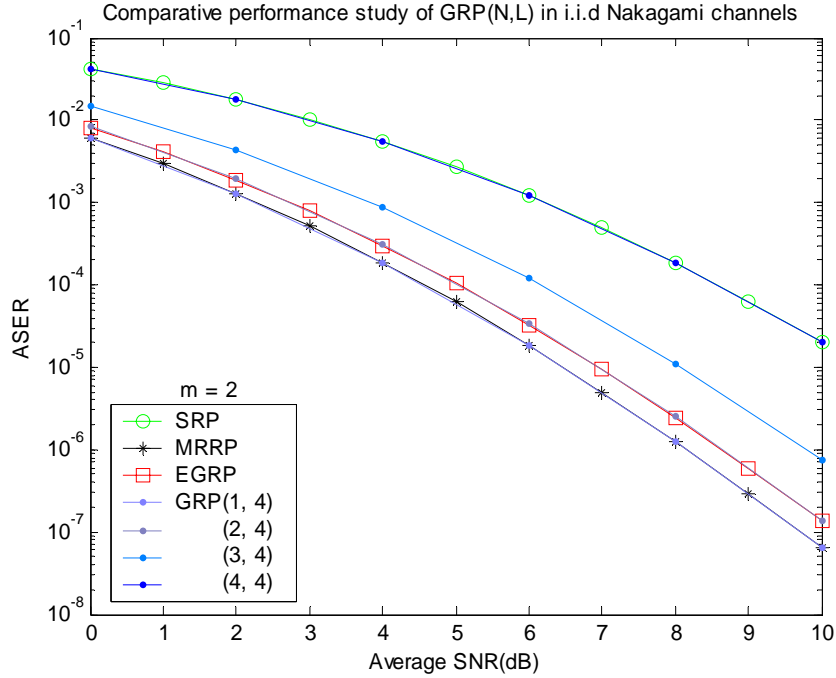


Figure 4.7: Comparative study of ASER performance using GRP with the other network diversity schemes for i.i.d. Nakagami-m channels ($m=2$)

The effects of correlation on the proposed network diversity schemes in the presence of Nakagami-m fading channels using the proposed MRRP diversity scheme are as detailed below:

Figure [4.8] describes the effect of the constant correlation model defined by ρ on the performance of the system for different number of paths combined in the system. As can be seen, the effect of ρ on the performance of the system tends to diminish as the number of paths combined increases for fixed values of m i.e. for an SER of 10^{-6} at $\rho = 0.2$, the performance gained from moving from $m=4$ to $m=8$ is 1dB for 5 paths combined while for $L=2$, the difference is 2.2dB. It is also noticed that the impact of ρ on the system is reduced for larger values of m for any given number of multiple paths combined, for instance, for example at $L=5$ and $m=8$, the performance loss from $\rho=0.2$ to $\rho=0.8$ at 10^{-6} is about 1.8dB while for $m=4$, it is about 2.9 dB.

Figure [4.9] shows the effect of varying the fading index parameter m in the system. It can be seen that almost 50% of the performance is gained from when $m = 2$ and this gain in performance reduces geometrically as the m parameter increases.

The effect of the local mean power unbalance is also studied in this network diversity system as shown in Figure [4.10]. At $\delta = 0$ and $\rho = 0.8$, the exponential model performs better than the constant model and the performance improves for increasing values of average SNR ($\bar{\gamma}$). As δ increases, the performance level drops considerably and for high values of δ , the exponential and constant correlation models are almost equal. This is due to the fact that for high values of δ , only the first multiple path components received is strong while other components are almost non-existent due to severe fading. From the plot, at 10^{-3} the performance difference between both models are given as 0.8dB, 0.6dB, 0.4dB and 0.1dB for $\delta = 0, 0.5, 1$ and 2 respectively. For the exponential model, there is a performance loss of 3.7dB, 6.1dB and 8.3dB at an ASER of 10^{-3} for changes in δ from 0 to 0.5, 1 and 2 respectively.

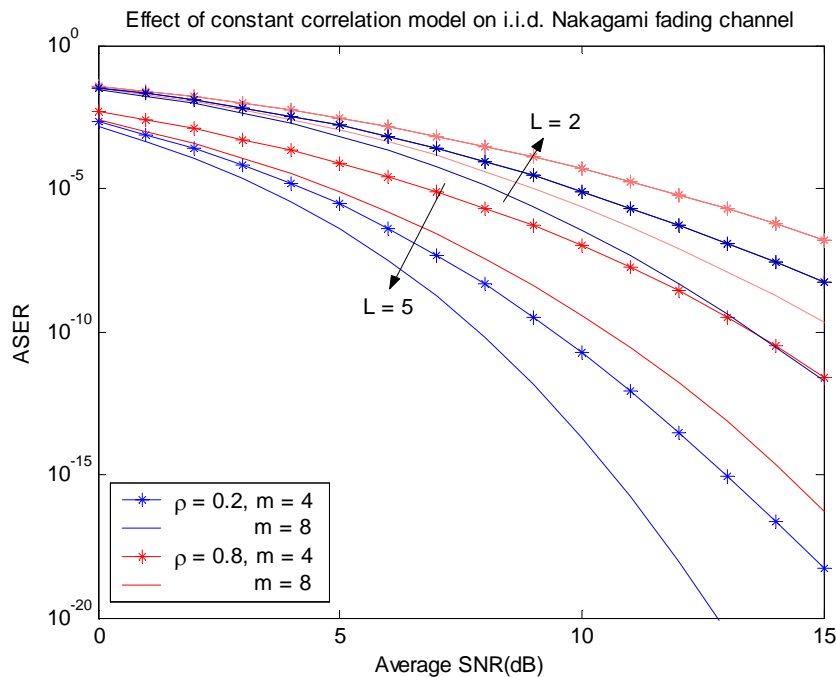


Figure 4.8: Effect of constant correlation on network diversity schemes in i.i.d. Nakagami- m fading channel for varying L multiple paths combined.

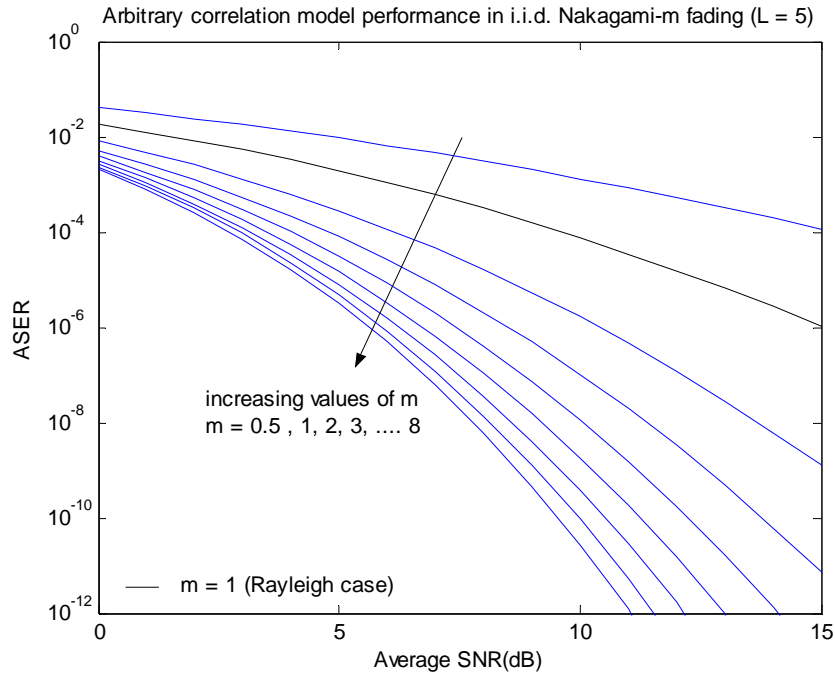


Figure 4.9: Arbitrary correlation model performance in i.i.d. fading Nakagami- m channels for varying values of the fading index m ($L = 5$)

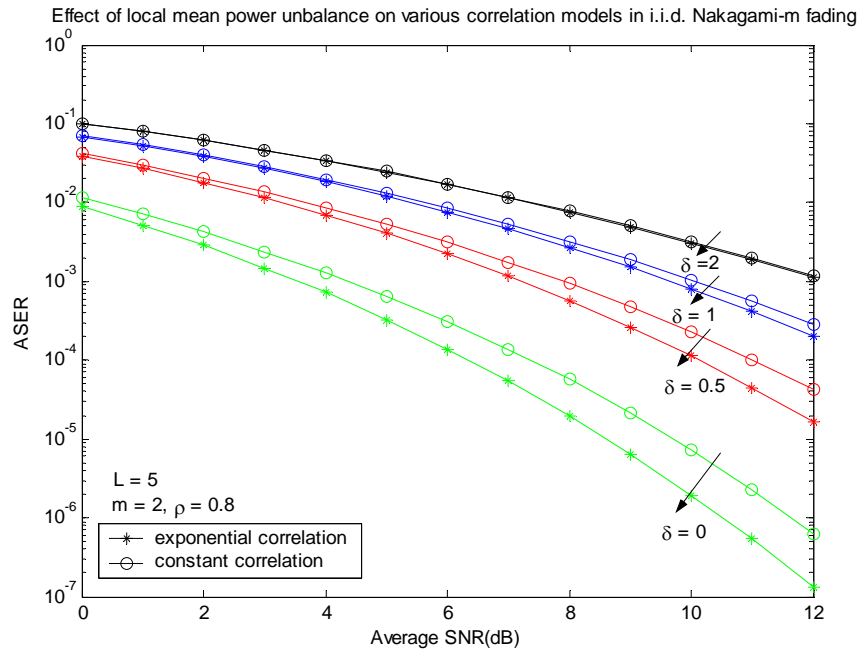


Figure 4.10: Effect of δ on network system with i.i.d. Nakagami- m fading channels using constant and exponential correlation models

4.5. Power Consumption Efficiency Analysis

The probability of selecting a node or group of nodes in the receiving cluster is as described in Chapter 3. The probability that a node is picked to be the next hop based on the instantaneous received SNRs conditioned on the average received SNRs is as given below for the various combination schemes.

Selection Route Path Combining Macro Network Diversity (SRPM):

The power consumption formulation for the SRPM scheme is given as

$$\sum_{l=1}^L P_i . P[x > \gamma_{SRPM} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (4.23)$$

Selection Based Route Path Combining Micro Network Diversity (SRP):

In this case, the probability that the node's instantaneous SNR is greater than that of all the other nodes conditioned on their average SNRs is given by

$$P = \prod_{\substack{j=1 \\ j \neq l}}^L P(\gamma_l > \gamma_j / \bar{\gamma}_1 \dots \bar{\gamma}_L) \quad (4.24)$$

Therefore, the long-term power consumption probability can be given as

$$\sum_{l=1}^L P_i . \prod_{\substack{j=1 \\ j \neq l}}^L P(\gamma_l > \gamma_j) . P[x > \gamma_{SRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (4.25)$$

Maximal Ratio Route Path Micro Network Diversity (MRRP):

In this case, the power consumption probability expression is defined as follows

$$\sum_{l=1}^L P_i . P[x > \gamma_{MRRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (4.26)$$

where, $P[x > \gamma_{MRRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L]$ is the outage probability in a Nakagami-m fading channel

Equal Gain Route Path Micro Network Diversity (EGRP):

The EGRP case is similar to (4.26) above, and is given as

$$\sum_{l=1}^L P_i . P[x > \gamma_{EGRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (4.27)$$

Generalized Route Path Micro Network Diversity (GRP (N, L)):

The GRP scheme is computed in the same manner as in Chapter 4, and is given as

$$\sum_{i=1}^N P_i \cdot P[x > \gamma_{GRP} / \bar{\gamma}_1 \dots \bar{\gamma}_L] \quad (4.28)$$

A comparison and analysis of the power consumption probability performances for the various network diversity combination schemes are given in the figures below:

Figure [4.11] shows the effect of varying the fading index parameter m on the power consumption probability of the system. At a relative power consumption efficiency of 10^{-2} , $m = 8$, MRRP gives the best performance as compared to the SRP scheme and the power consumption probability increases with decreasing value of m . This is intuitive, because, the higher the fading index, the smaller the power consumption necessary for a given outage threshold.

Figure [4.12] details the effects of the outage threshold γ_{th} on the power consumption probability in i.i.d. Nakagami- m fading channels. As in the i.i.d. Rice fading case, for very high values of γ_{th} , the relative power consumption efficiency becomes very low due to the fact that an increased power level is needed to exceed the threshold level, thereby increasing the overall power consumption in the system. For low values of γ_{th} at $m = 5$, it can be seen that there is considerable performance gain in employing the use of the other network diversity schemes over the SRP scheme, but the performance gain diminishes considerably for large values of γ_{th} . Table [4.1] below shows the power consumption efficiency for the network diversity schemes for certain values of γ_{th} .

Table 4.1: Table of relative power consumption efficiency for various network diversity schemes in i.i.d. Nakagami fading ($L = 2, m = 5, \sigma = 6\text{dB}$)

for $\mu = 6\text{dB}$	$\gamma_{th} = 2\text{dB}$	$\gamma_{th} = 4\text{dB}$	$\gamma_{th} = 6\text{dB}$	$\gamma_{th} = 8\text{dB}$	$\gamma_{th} = 10 \text{ dB}$
SRP	0.0170	0.0577	0.1239	0.1880	0.2179
EGRP	0.0024	0.0178	0.0666	0.1445	0.2044
MRRP	0.0020	0.0156	0.0600	0.1346	0.1993

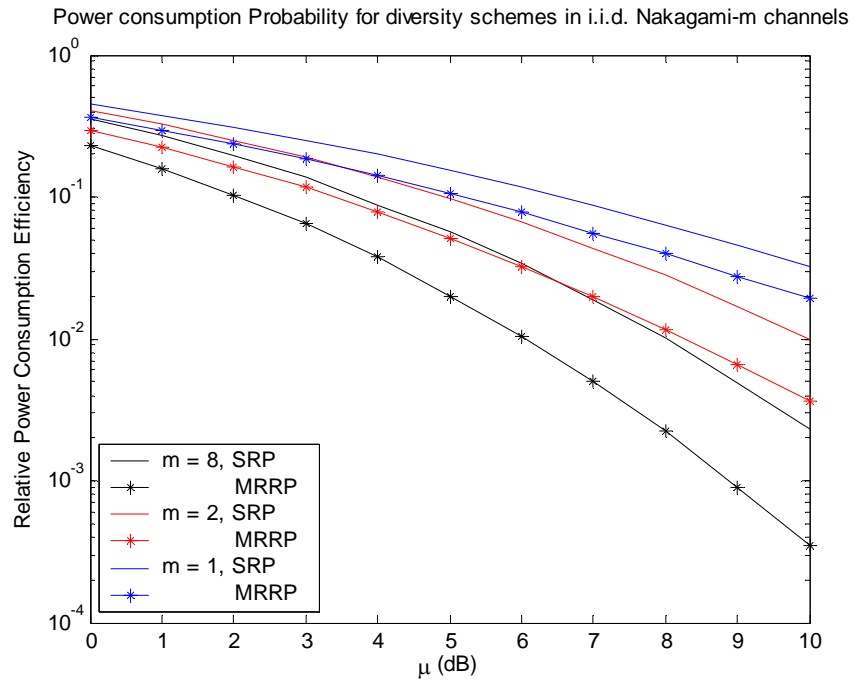


Figure 4.11: Power consumption efficiency performance evaluation for SRP and MRRP for varying values of m in i.i.d. Nakagami- m fading channels ($L = 2$, $\gamma_{th} = 1$ dB)

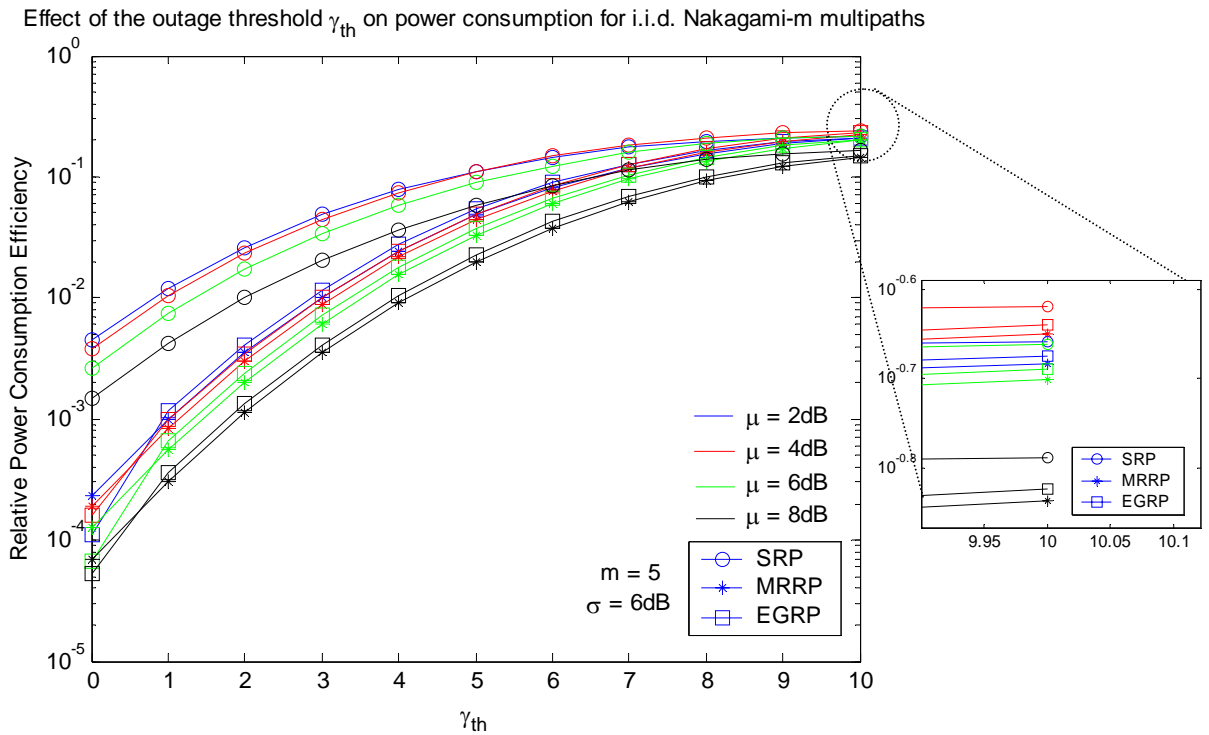


Figure 4.12: Effect of γ_{th} on power consumption for various network diversity schemes in i.i.d. Nakagami- m fading channels

CONCLUSIONS:

This chapter studies the performance of the various network diversity schemes in the presence of both the i.i.d. and i.n.d. Nakagami-m fading models. Unified expressions are derived for the analysis of the system in various network scenarios of practical importance. The impact of the end-to-end outage probability is analyzed for a given number of hops and also the impact of the diversity schemes on the long-term power consumption in a network system is also studied. As shown, the outage threshold is a strong determinant for the relative power consumption efficiency that can be gained in the overall network system due to the use of these network diversity schemes. The results depicted by the plots in this chapter are synonymous to that of Chapter 3. Advantages gained from the use of these network diversity schemes will lead to increased performance in terms of data integrity and reliability and also in the implementation of adaptive coding schemes that can provide increased data throughput in the network system.

*"Some trust in chariots and some in
horses, but we trust in the name of the
LORD our GOD
Ps 20:7"*

Chapter 5

CONCLUSIONS AND FUTURE WORK

This thesis extends the analysis of a new type of selection based network diversity scheme (SRP) proposed to combat the known fading mechanisms in wireless networks by Zhang *et al* and also proposes various alternate network diversity schemes for ad hoc wireless network systems. We propose four new network diversity schemes namely the SRPM (a less complex variation of the SRP proposed in [27]), MRRP, EGRP and GRP (N,L) schemes. The efficacies of the proposed schemes are examined in the Rice and the Nakagami-m channels (with the Rayleigh channel as a special case). The proposed schemes have been designed taking into consideration the random nature of fading mechanisms present in wireless mediums. The implementation of these schemes do not require any drastic alterations in receiver or hardware structure but introduces a minimal delay relative to the time taken for the combination of the various diversity paths (in the order of microseconds).

The performance of these schemes in a network have been determined based on numerical examples to provide increased benefits in terms of end-to-end average symbol error rates and end-to-end outage probabilities. The increased performance due to the implementation of these network schemes, allows the use of lower transmission powers to be used in the system, thereby reducing the overall power consumption of the system while providing enough leverage for capacity (i.e. spatial frequency re-use for FDMA/ TDMA and reduction in terms of possible interferers in CDMA). Various schemes have been proposed based on receiver and computational complexity and the overall performance increase can also aid in the achievement

of certain QoS services in the network system. The performance gain using these network diversity schemes is also very advantageous when opportunistic adaptive rate MAC schemes are to be implemented in the network system, i.e. the system can take advantage of the increase in SNR to reduce power and also can be used in the application of higher order signal constellations to transmit data on links with better signal quality.

From the results shown in this thesis, there is considerable performance gained from using any one of the diversity schemes defined over the conventional route protocols which generally are centered on the shortest path algorithm (protocols that base their route paths on the short hops algorithm generally have better performance than protocols using the shortest path algorithm in terms of ASER and outage probability but even these protocols show drastic improvements in performance with the inclusion of the network diversity schemes at the network layer). The MRRP scheme provides the highest performance in terms of end-to-end outage probability and end-to-end ASER. The EGRP also produces relative performance gains in comparison to the MRRP, but without the added complexity to define algorithms that consistently monitor and weight the received signals according to their strengths. The GRP(N,L) scheme provides considerable performance with a much less complex receiver structure relative to the MRRP but a bit more complex than the EGRP (since the EGRP does not share instantaneous SNR information at the receiving cluster) scheme while reducing the overall latency due to routing packets in the network system. All these schemes require communication among the nodes in the receiving cluster to allow for proper combination of the signal according to their strength (MRRP, EGRP & GRP (N,L)) and also to determine which node gets to be the next hop route (SRP). The SRPM scheme, however, does not involve communication among the nodes in the receiving cluster as it determines the node that gets to be the next hop a priori. A priori determination of the next hop node in the MRRP and EGRP scheme can also be done to reduce operational complexity since all nodes in the receiving cluster are involved in forming the signal for the next hop route. It is also shown that the proposed schemes are susceptible to the effects of local mean power unbalances and that the performance improvement diminishes greatly for large δ values of the PDP. Arbitrary branch correlation due to the dynamic topology of the member nodes in the network system as packets are being routed, also affect the network diversity schemes to a great extent. The results presented in this thesis are in line with traditional analysis of physical layer diversity schemes.

The overall long term power consumption of the proposed network diversity schemes were studied and it is shown that for varying values of the mean and variance of the local mean power distribution of each node, the MRRP scheme provides better power consumption efficiency than the EGRP and the SRP. The SRP is the worst scheme in terms of power consumption efficiency for nodes that involve communication or transmission within the receiving cluster. The effect of the outage threshold γ_{th} is also studied and it is shown that this parameter greatly affects the overall power savings of the system, i.e. for high values of γ_{th} , the power consumption efficiency is minimal which will eventually lead to a short operational network life time, while lower values of γ_{th} provide increased relative power consumption efficiency, thereby elongating the operational life time of the network system.

The following are possible extensions for the work done in this thesis:

- The effects of the network diversity schemes on other layers in the protocol stack needs to be studied to give a view of the overall performance improvement inherent to the system. Also, the overall increase in the average end-to-end delay of these algorithms introduced by the delay necessary for combination should be studied.
- The analysis done in this thesis is based on perfect channel knowledge. The performance of these schemes should also be studied for imperfect channel conditions, timing errors and jitters in the network system.
- The combination of the opportunistic routing diversity schemes and multiple path routing should be explored to analyze performances in multicast routing scenarios.

APPENDIX:

As stated in Chapter 3, the probability of an error occurring in the present hop exists only if an error occurred in the last hop and no error occurs in the present hop or if no error occurred in the last hop and an error occurs in the present hop

Using the expression in (3.15) given as

$$P_s^{m+1}(E) = P_s^{m+1}(E)(1 - P_{m+1}) + (1 - P_s^{m+1}(E))P_{m+1} \quad (\text{A-1})$$

For x hop stages, we have

$$P_{b1} = P_1, \quad \text{i.e., no previous stage}$$

$$P_{b2} = P_1 + P_2 - (2P_1P_2)$$

$$P_{b3} = P_1 + P_2 + P_3 - 2(P_1P_2 + P_2P_3 + P_1P_3) + 4 P_1P_2 P_3P_4$$

$$P_{b4} = P_1 + P_2 + P_3 + P_4 - 2(P_1P_2 + P_2P_3 + P_1P_3 + P_1P_4 + P_2P_4 + P_3P_4) + 4(P_1P_2P_3 + P_1P_2P_4 + P_2P_3P_4 + \dots + P_1P_3P_4) - 8 P_1P_2P_3P_4.$$

$$P_{bx} = S_n^1 - 2 S_n^2 + 4S_n^3 + \dots + (-2)^{n-1} S_n^n.$$

$$= \sum_{k=1}^n (-2)^{k-1} S_n^k \quad (\text{A-2})$$

where, S_n^k denotes the sum of the product of k distinctive terms selected from P_1, P_2, \dots, P_n .

i.e.

$$S_n^k = \sum_{\substack{\alpha_1 \dots \alpha_k = 1 \\ \alpha_i \neq \alpha_j}} P_{\alpha_1} P_{\alpha_2} \dots P_{\alpha_k} \quad (\text{A-3})$$

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ABBREVIATIONS AND NOTATIONS:

ASER	Average Symbol Error Rate
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CDE-BPSK	Coherent Differentially Encoded BPSK
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CEP	Conditional Error Probability
CFSK	Coherent Frequency Shift Keying
CHF	Characteristic Function
DPSK	Differential PSK
EGC	Equal Gain Combining
EGRP	Equal Gain Route Path Micro Network Diversity
GRP (N,L)	Generalized Route Path Micro Network Diversity
GSC	Generalized Selection Combining
IETF	Internet Engineering Task Force
LOS	Line-of-sight
MANET	Mobile Ad hoc Network
MDPSK	M-ary DPSK
MGF	Moment Generating Function
MPSK	M-ary PSK
M-QAM	M-ary Quadrature Amplitude Modulation
MRC	Maximal Ratio Combining
MRRP	Maximal Ratio Route Path Micro Network Diversity
MSK	Minimum Shift Keying
NCFSK	Non-coherent FSK
PCP	Power Consumption Probability
PDF	Probability Density Function
PDP	Power Delay Profile
QPSK	Quadrature PSK
SBC	Selection Based Combination
SRP	Selection Route Path Combining Micro Network Diversity
SRPM	Selection Route Path Combining Macro Network Diversity
SNR	Signal-to-Noise Ratio
UMTS	Universal Mobile Telephony System
UWB	Ultra Wideband
WCDMA	Wideband CDMA
i.i.d	independent and identically distributed
i.n.d	independent and non-identically distributed

VITA

Akinyemi Tolulope Aduwo was born on the 5th of January 1979 in Lagos, Nigeria. He started his quest for knowledge at the University of Lagos, Nigeria where he graduated with a Bachelor's degree in Electrical/ Electronics Engineering in the year 2000. After working for a while in the Telecommunications industry, he joined the M.S. program in Electrical Engineering at Virginia Tech in August 2002 to pursue an advanced education in the field of Wireless Communications. His research interests include Diversity System Performance, Ad hoc Networks, Network Architectures and Cellular Radio Systems, design and implementation.

Akinyemi is a member of the IEEE and NSBE.