COOPERATIVE RELAYING IN CELLULAR NETWORKS FOR IMPROVING

RECEIVER DIVERSITY AND CELL RADIUS

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BY

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ABSTRACT

Wireless network sharing has been the principal idea in the recent developments of wireless communication systems not only for improvement in capacity, data rates and coverage area but when considering an emergency service model, establishing reliable communication is the foremost requirement. With the inception of cooperative relaying technology, a novel wireless relaying method of sharing the terminal node capabilities to forward the signal created a new paradigm to greatly improve the quality of the services and soon became the significant research area in 3G/4G cellular networks. The cooperative terminals (relays) exploit a larger form of space diversity to relay signals to destinations when placed in between source and destination to combat the effects of fading induced by multipath signal propagation. However, the position of the relay in between the source and destination plays a significant role in affecting the overall network performance. Our attempt in this thesis is to show how a cooperative relay can be used to provide improved coverage at the cell edge with certain reliability and also extend the cell radius by effectively positioning the relay. First, we investigate the famous 3-node relay assisted cellular system model and study the receiver diversity combining results by changing the relay positions with a relay forwarding the signal using the amplitude and forward protocol (AAF). The figure of merit of the considered 3-node system model is expressed in terms of Bit error rate (BER) and signal to noise ratio

(SNR). The BER vs. SNR plots are computed for various linear receiver diversity combining techniques and are used to evaluate performance of the system. These results are also compared to the conventional cellular network performance with a single point-to-point link between source and destination.

Second, we provide the problem formulation of the diversity results observed and solve to find the effective relay position with respect to the source and also compute the effective cell radius of the 3-node system model. To compute effective relay position, we use the Bernardin's coverage area probability relation with cell radius at the cell edge of the source where the relay is assumed to be placed with its probability of successfully forwarding the signal conditionally depending on its cell edge probability.

We have obtained results of the two above problem formulations using MATLAB simulations. We have emulated the cooperative relaying technique in a cellular system to achieve 2nd order diversity when compared to the conventional cellular system. The BER vs. SNR plots for each of the combining techniques show the significant difference in the diversity results when the channel quality estimations are used compared to the other methods which don't. Signal to noise ratio combining (SNRC) and Estimated SNRC (ESNRC) perform $4 \cong 5$dB better than the other combining methods provided their SNR estimation is accurate. The highest diversity order (2nd) is achieved when the relay is placed close to the source and drops as the relay is moved towards the destination. Cell range extension results show that moving the relay to its optimal position between source and destination in a cell provides capabilities to extend the cell range to nearly 1.5 times the cell radius of the source and still performs within the acceptable coverage area probabilities.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined the thesis titled "Cooperative Relaying In Cellular Networks for Improving Receiver Diversity and Cell Radius" presented by Venkat Reddy Marepally, Candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

1.1 Overview

According to the reports from the ITU, there were approximately 6 billion cellular subscriptions at the end of 2011 which is a huge increase from 4.7 billion and 5.3 billion in the years 2009, 2010 respectively. This tremendous increase in the demand has come with the demanding developing world. The inadequacy of the frequency spectrum due to increase in growth has caused a drop in the quality of service especially to users in the cell edges. In a worst case scenario, a receiver in an area is affected by hazards like fire, flood, earthquake or even right in the middle of poorly planned urban environment, referred to as deep fade regions, where cellular services are unavailable or least unreliable, which is unacceptable. In such cases, the signal strength diminishes at a rate far greater than the square law observed in free space [1]. Such issues can be ineffectively dealt with by increasing power requirements or installing more base stations or even reducing the cell radius but at a greater cost or need for good frequency reuse techniques.

Another significant factor affecting the signal quality at the receiver is fading. Fading can be caused either due to multipath propagation or obstacles in the path to the receiver. Wireless communication is broadcast in nature where the transmitted signal undergoes reflection, refraction or diffraction and different copies of this transmitted signal reach the receiver in different paths. These are referred to as multipath signals. The receiver antenna detects these multipath signals, combines them to decode and regenerate the transmitted signal generally in a destructive way. This phenomenon is referred to as multipath induced fading. Fading caused due to obstacles in the path is referred to as

shadowing. As time evolved, techniques which could mitigate fading were developed and one of it is diversity. If there are two or more radio channels that are orthogonal, the fading seen by the signal through each channel is more or less independent. This inherent broadcast property of wireless communication systems can be used for our advantage where several received signals can be combined to improve Signal to Noise Ratio (SNR) and is referred to as Diversity.

Spatial diversity is an older technique but it is still commonly used. The fact that if physically separated multiple antennas are used at the receiver, then each could receive a statistically independent multipath signal and upon diversity combining could mitigate multipath induced fading. This is termed as diversity reception. On the other hand, we have the transmit diversity that is analogous to diversity reception. To combine statistically independent signals at the receiver, the linear combining techniques that came into field in 1950 were employed [4]. These techniques were extensively used in multi-antenna array setups at the transceivers in order to exploit spatial diversity gains at the cost of an extra set of antennas. Antenna diversity mitigates the small scale fading that is especially observed in urban environments and significantly employed in cellular systems. Having a multiple antenna array system on the receiver handset has its own disadvantages such as the size of the handset, power requirements, etc. For example, a GSM receiver (at 900MHz) with a required $\lambda/4$ antenna spacing for diversity gains, is required to have at least 8cm of antenna spacing that becomes inefficient with an increase in the number of antennas in the mobile handset [5]. But having this multiple antenna array setup is absolutely possible at the base station considering its resource availability, especially in both size and power.

Relays earlier operated as electrical switches were extensively used in telephone exchanges for receiving signals from one end and re-transmitting to the other end. This whole mechanism has exactly the same meaning when we talk about relaying in cellular systems. The relays act as the nodes in between the source and destination having capabilities to retransmit the signals they receive from source to destination. Given a channel, it would always be attenuated because of its medium of operation which makes long distance point to point communication less feasible. The same long link can be substituted with smaller hops with relay acting as a repeater at each hop to enhance received signal quality at MS. Cooperative communication relaying is a mechanism that virtually emulates the multiple antenna system to mitigate fading and achieves transmit antenna diversity. Both transmitter and receiver employ just one antenna and relay the signals to each other thereby achieving diversity reception. As they are also widely separated in space, this technique combats both the small and large scale fading (due to obstacles or path distance).

1.2 Principle of Relaying

Cellular systems involved communicating data with only two nodes, namely the BS and MS, but could not achieve the desired quality of service with increasing demand for capacity and higher data rates. The current cellular architecture performance is mainly affected by large communication distances between the BS and MS. If there is 3rd node such as relay which could be a dedicated node not acting either as source or destination, it could facilitate information exchange between nodes. The other type of relay nodes could be peer nodes where their roles could be changed based upon the requirement to act as a source or destination or a simple forwarding node.

A relay node in a cellular system would act as a peer node that could receive the signal sent from the BS during a time slot and process the signal (amplify or decode) and then re-transmit it to the destination. With the relay node operating at the physical layer (PHY mode), it could also be considered a small scale BS. The typical coverage range of a relay node is around 500m and need not be on the mast as high as the BS that reduces the operational expenses. Generally, a relay node is placed in the line of sight of the BS with a goal for the ubiquitous provision of improved coverage and high data rates.

1.3 Motivation

If we consider an emergency services context, reliability of communication is the primary goal; the majority of research studies have only targeted this goal by using the mesh or ad-hoc networks with relays being used as simple forwarding nodes for improving the performance and capacity of the network. On the downside, and because of two major reasons, the ad-hoc network topology suffers tremendously in trying to provide the quality of service or reliability. First, self-sustaining property is one of the major problems with ad-hoc network topology as there is no fixed infrastructure and therefore, providing reliability for emergency models becomes complex. Second, ad-hoc networks need complex routing solutions and cause additional signaling overhead in power constrained devices. Hence, fulfilling the reliability of communication service becomes expensive in ad-hoc networks.

In this thesis, we propose the usage of relays acting as peer nodes in a cellular system which by itself is a self-sustaining system, where the relay nodes don't directly communicate with each other but with the base stations (BS) and mobile stations (MS). The conventional cellular systems have already been optimized to achieve the best results

in high fading environments. Our goal to integrate the relay nodes into such a system would be to provide reliable and improved communications both within the cell and at the cell edge. We do not consider any specific emergency service model in a cellular system for evaluation to prove the hypothesis. However, relay assisted cellular system would highly match the requirements of an emergency system model and could provide seamless communication services especially for users at the cell edge or other deep fade regions within the cell. The objective of this thesis is to model a conventional cellular system with and without relay nodes and evaluate their BER performance by computing the outage probabilities at the destination. We also model the system for computing the possible cell range extension with relays while still providing acceptable coverage.

1.4 Thesis Organization

The work we present is organized as follows. In Chapter 2, we provide a brief background on the research work accomplished in the areas of cooperative communications, diversity combining techniques, relay assisted cellular systems and cell range extension models. In Chapter 3, we describe the conventional cellular System Model and briefly discuss the needs for methods to combat fading to achieve required results and throw light on using the methods of diversity. In Chapter 4, we describe the cellular system model assisted with relays and provide key receiver diversity combining results to measure the performance of the system compared to the conventional cellular system described in Chapter 3. We also demonstrate how it could possibly meet the set requirements. In Chapter 5, we extend the model described in Chapter 4 to compute the possible cell range extension possibilities with relays by keeping received signal power

within the acceptable threshold requirements. In Chapter 6, we conclude the work and provide directions for future work in this field.

CHAPTER 2

LITERATURE SURVEY

2.1 Cooperative Communication

Cooperative communication is likely the key technology for efficient use of the frequency spectrum with the idea of resource sharing among the nodes forming the network. In the recent years, Laneman, J.N. in [2], opened up the research space by exploiting space diversity with cooperative terminals relaying signals for one another. In the model presented, cooperative relaying was achieved by combining the signal at the receiver from both the relayed and direct path between source and destination in a wireless multihop network. Hence cooperative relaying can be defined as a form of space diversity.   In [3], it is shown how multi-antenna array systems were used to exploit the space diversity and also shows how the cooperative communication systems can emulate the same. Ad-hoc networks provide an enormous application space for diversity strategies to be employed especially in providing emergency services where the nodes are willing to share the limited resources available. Different variations of the relay network have been given in studied by Schein and Gallager [4] apart from famous 3 node relay model. Schein and Gallager studied a system with parallel relay networks having no direct path from source to destination. J.N. Laneman, G.W. Wornell, and D.N.C. Tse in [5], also showed the performance of the cooperative relaying protocols like amplitude and forward (AAF), decode and forward (DAF) in fading environments. AAF is the simplest technique where the replay amplifies the received original signal and forwards to the destination. DAF is a technique where the relay decodes the received original signal and forwards after re-encoding. These methods achieve full 2nd order diversity results

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(BER $\propto {}^1\!/_{\text{SNR}^2}$) at the cost of double the bandwidth as the source transmits the original signal twice on the direct path to destination and to relay. Other hybrid schemes were also suggested by like Selection Relaying (SR) and Incremental Relaying (IR) as a variation to AAF and DAF where the relay either decides to forward the signal based on the threshold (SR) or feedback (IR) from the destination.

We have implemented the amplitude and forward relaying (AAF) technique in this thesis, because it is efficient in fading environments where the cost of decoding (DAF) the signal would be expensive. The only drawback with the AAF technique is that if the relay picks up noise along with the signal sent from source, then it would amplify both and forward them to destination. But this can always be avoided by implementing selective relaying where the signal would be forwarded only if it's received above a certain threshold. But this assumption changes as the relay is moved in between the source and destination; a conclusion is made in this thesis on this scenario.

2.2 Receiver Combining Techniques

Diversity methods implemented at the receiver are effective in combating the effects of multipath and there are numerous ways of achieving this. References [6-7] and [8, pg. 263-267] summarize implementation details of popular combining techniques like the equal gain combiner, signal to noise ratio combiner, maximum ratio combiner and other variations of these. The equal gain combiner (EGC) is where the signals received on the antenna array at the receiver are just combined with unit gain at each array element. EGC ignores the fluctuations caused due to small scale fading, which is a major drawback. The signal to noise ratio combiner (SNRC) is where the signals combined at the receiver have a weight equal to the signal to noise ratio seen at each array element.

SNRC definitely will work better than ERC because it considers the small scales fluctuations and weights those signals less (low SNR) while combining.

Measurement of the signal to noise ratio at the receiver doesn't exactly give the measure of the channel conditions, however. It is very necessary to measure the channel conditions to get the best out of the diversity combining techniques and the maximal ratio combiner (MRC) does the same. On its downside, it is very difficult to have the exact knowledge of the channel response at the receiver and MRC suffers when the channel estimations are wrong. These diversity combining techniques have existed since 1950 and are majorly implemented in multi array antenna system at the transceivers. Usage of these techniques, however, must be accomplished for cooperative relaying networks to understand their unique characteristics and challenges. In this thesis, we have implemented and evaluated a few of these techniques in a cooperative relaying network system which emulates the space diversity similar to that achieved by multi-array antenna system but with the signal intentionally allowed to travel on diverse paths and combined at the receiver.

2.3 Relays in Cellular Networks

Multi-hop relaying has found its major applications in the context of ad-hoc and peer-peer networks but received limited attention cellular networks. References [9-13] show the major work in implementing the cooperative relaying strategies in wireless ad-hoc networks; they cover the relay selection strategies, routing algorithms, power allocation strategies and range extensions methods.

With the advent of 4G and its requirements of very high data rates and quality of service, research space has opened up in the search for new technologies and is currently

making space for the relay implementation strategies to supply the needs. With large cell areas, it is not feasible to achieve the 4G requirements with the conventional cellular architecture mainly because of the high power requirements and non-line of sight conditions in the assigned 4G spectrum well above 2GHz. The obvious solutions of increasing the transmit power at the base station (BS) or having more BS's to mitigate the non-line of sight conditions is definitely not reasonable considering the cost of such implementation. Hence, this required a major modification in the conventional cellular architecture and seamlessly, multihop relaying technology fit into the cellular architecture which had been already proved to provide high data rates and quality of service in ad-hoc networks [14] and is easily extendible to any wireless network. In [15], the ac-hoc relay systems were integrated into the cellular systems to reduce the call blocking probabilities by diverting traffic away from congested areas but with the signaling overhead. A different approach is taken in [16] where any terminal like a viewphone, computer or telephone considered a mobile, irrespective of motion, is connected to local access points to form micro cellular structures in specific geographical areas. These small cells are integrated and utilized as relay networks for achieving high data rates in the cellular systems. The relaying systems have also been integrated into GSM networks to increase capacity and improve coverage [18]. Recently, research work, implementation details, and protocol specifications were provided for integration of the relaying technologies into WiMax and LTE-Advanced Mobile Systems [19].

In this thesis, we have considered the typical 3-node model with source (BS), destination (MS) with relay integrated into the cellular system. We provide the performance analysis of the overall system by computing outage probabilities with and

without the relay assistance. We also show the performance of the cellular system when the relay is placed at arbitrary positions between the source and destination. As shown in Figure 2.1, we are mainly interested in studying the system where the destination is in a deep shadow region or at the cell edges where the coverage probability is low; similar or worse is the case under emergency requirements.
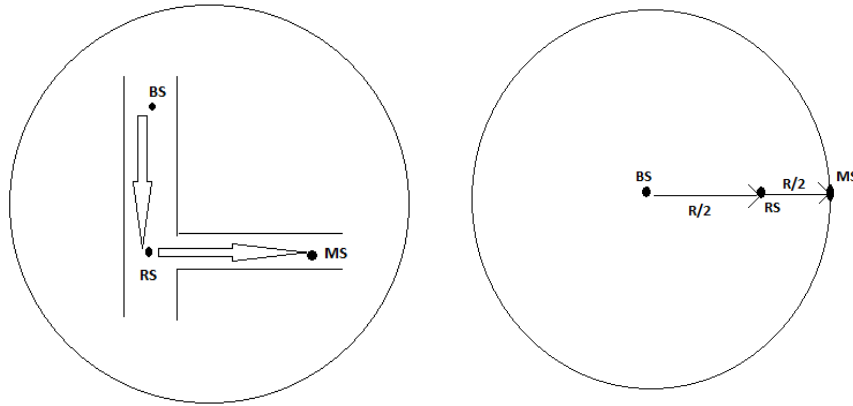
Fig 2.1. Left: A relay deployment in a cellular environment where the MS is in a non-line of sight zone or in a deep fade region. Right: A relay deployment where the MS is at the cell edge of BS where the coverage area probability is low.

2.4 Cell Range Extension with Relays

We have already highlighted the reasons for falling short of meeting 4G requirements with large cell sizes in the conventional cellular systems. If these large point-to-point links can be replaced with smaller multi-hop links, then the relay system capabilities can be used to either extend the range of the source or provide improved coverage within. The earlier approaches of estimating the cell range in cellular networks were inaccurate as pointed out in [19-20]. Wrong estimation in the cell range can lead to incorrect computation of area or the cell coverage probabilities. Also given in [19-20] are improved methods of estimating the cell range and area/coverage reliability. The closed form expression presented in those works that relates the cell radius and area coverage

probability is used in this thesis to compute the cell radius with relay system as shown in

the right part of Figure 2.1.

CHAPTER 3

LEGACY CELLULAR SYSTEM MODEL AND PROBLEM DESCRIPTION

In this chapter we will discuss the wireless channel communication model for the direct link between the source and the destination. This will include modeling of the modulation technique considered, path loss model, receiver model and definitions of other system parameters which set the platform for its performance comparison with that relay link.

3.1 Communication Channel Model

Wireless communication channel modeling is of paramount importance when it comes to getting best performance out of the system. The modulations schemes are chosen based on the assumed channel model to get greater power and bandwidth efficiency. It is thus essential to know and understand the wireless channel to push the limits of performance.

3.1.1 Additive White Gaussian Noise (AWGN)

An ideal wireless communication channel would be a channel with no noise, meaning that whatever signal was input to the system is perfectly decoded at the receiver. In short, the bit error probability with such a channel is zero. This is impractical in the real world with the receiver always adding up the both the received signal and the thermal noise; this work assumes the channel is AWGN which is best suited for performance analysis.

AWGN is the simplest channel system which just adds white Gaussian noise to the signal propagating through it. This compensates for the thermal noise present at the

receiver. This also implies that there is no amplitude or phase distortions introduced by an AWGN channel. AWGN can be represented as below,

$$y(t) = x(t) + n(t); \qquad (3.1)$$

Where, y(t) is the output of the AWGN channel with input being x(t) and white Gaussian noise being n(t).

AWGN is ever present in any communication channel, but alongside we also consider fading and multipath distortions to be more practical in the approach. The following sections explain about the other distortions considered in the system.

3.1.2 Path Loss

Path loss causes attenuation of the signal when it propagates through the channel. This could be due to many environmental effects but mainly happens due the distance factor between transmitter and receiver.

Given any radio propagation model, for example in [21, pg. 127], the average path loss decreases logarithmically with the increase in distance from the base station (BS). The average path loss at an arbitrary distance from the BS is given in decibels (dB) as follows.

$$PL = PL(d_o) + 10 n \log(\frac{d}{d_o}) + X \qquad (3.2)$$

Where $PL(d_o)$ represents average path loss at a reference distance d_o from BS, n represents the path loss exponent. X is a Gaussian random variable with zero mean and σ^2 variance which represents the probability that an MS will be in of shadowing conditions, following therefore the typical log-normal model for shadowing conditions where the variance σ^2 differs by the environment. The value 'd' represents any point from the BS

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where $d > d_o$. Equation (3.2) at the cell edge of the source with radius "R" can be rewritten as,

$$PL = PL(d_o) + 10n\log(\frac{R}{d_o}) + 10n\log(\frac{d}{R}) + X \tag{3.3}$$

The path loss (dB) at the reference distance (d_o) can be calculated using the free space equation,

$$PL(d_o) = 32.44 + 20*\log(F) + 20*\log(d_o) - G_{tx} - G_{rx} \tag{3.4}$$

Where F is the frequency of operation, G_{tx}(dBi) and G_{rx}(dBi) are the transmitter and the receiver gain respectively. Other cable and system losses are neglected.

3.1.3 Rayleigh Fading

Fading mainly occurs due to multipath components of the same input signal received at the receiver. These multipath components arise due reflection, deflection or diffraction. If these multipath components are received outside the symbol period, then they are considered as different signals and when combined cause amplitude and phase fluctuations.

As we are interested in modeling communication channels under emergency situations where there is no dominating line of sight component, the Rayleigh fading model suits the best. Mathematically, Rayleigh fading has been modeled as a time-varying random change in the amplitude and phase of the transmitted signal. It is represented as the sum of two uncorrelated Gaussian random variables in our simulations. An independent and identically distributed complex random variable exhibits this process where real and imaginary part represents the gain and phase and is shown below,

$$h(t) = r_{I(t)} + i \cdot r_{Q(t)} \tag{3.5}$$

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Where $r_I(t)$ and $r_Q(t)$ represent Gaussian processes with zero mean and variance of σ^2.

h(t) has a Rayleigh distribution and the angle of h(t) is uniformly distributed on $(0, 2\pi)$.

The probability density function of "h(t)" is given by,

$$P_R(h) \; = \; \frac{2h}{\Omega} e^{\frac{-h^2}{\Omega}} \qquad ; h \geq 0 \qquad\qquad (3.6)$$

Where, R is the random variable and $\Omega = E(R^2)$ where $E(x)$ represents the expected value.

3.1.4 Signal Modulation

Digital modulation is a process of mapping data bits to signal waveforms that can be transmitted over an (analog) channel. However the wireless channel being analog, for long distance transmission in case of cellular communications, bandpass modulation schemes are used where the input data modifies a high frequency sinusoidal carrier in phase, frequency or amplitude. In this thesis, the input data is randomly generated bits of 1's and 0's which is converted to a bipolar sequence to make it resistant to certain signal loses during transmission. This is considered an advantage especially when used with repeaters on the transmission link.

Phase shift keying (PSK) is a digital modulation scheme where the input data modifies the carrier wave in phase. Binary phase shift keying (BPSK) is a PSK where it uses two phases $+ \pi/2$ or $- \pi/2$ to represent the input data on the carrier. The input to a BPSK modulator in our thesis is the bipolar sequence explained above. As it's a phase modulation, the phase of the transmitted signal of a BPSK modulator will be $+ \pi/2$ or $- \pi/2$ for input 1 and 0 respectively or in simple words, 180 degrees apart. The criterion for choosing a good signal modulation scheme would depend on the factors namely power efficiency, bandwidth efficiency and system complexity. Certainly based on these factors,

there are numerous other modulation techniques that perform better than BPSK in achieving diversity but the work presented in this thesis doesn't consider this in the scope.

3.1.5 Receiver Model

In this thesis, the BPSK modulation technique is used which maps only 1 bit per transmitted symbol unlike QPSK (2 bits per symbol), and the receiver also detects the signal in the similar way. The input signal undergoes both phase and amplitude variations but assuming that the phase of the signal can be corrected by having proper feedback of the channel conditions, we only detect the signal at receiver based on received signal strength. Clearly we have assumed a system where the estimation of the channel quality is poor or unknown. As the real and imaginary part of the channel impulse response represent the gain (amplitude) and phase, the average value of the real part of the symbol received will be used for detection.

Consider a single user system where the received signal can be represented as given below,

$$y(t) = h(t)x(t) + n(t); \qquad (3.7)$$

where $h(t)$ represents the channel having Rayleigh fading with $x(t)$ being the input transmitted signal and $n(t)$ being additive Gaussian noise at the receiver system. The receiver model used in this thesis is given below

$$y(n) = \begin{cases} +1 & Real\{y_d[n]\} \geq 0 \\ -1 & Real\{y_d[n]\} < 0 \end{cases} \qquad (3.8)$$

Where $y_d[n]$ represents the nth symbol received.

From the received bipolar sequence of +1 and -1's the original data bits of 0's and 1's is obtained by applying the bipolar decoding as described in Section 3.1.4.

3.1.6 Bit Error Rate (BER) Performance of BPSK Modulation

For BPSK modulation, the BER performance in AWGN channel with Rayleigh fading is given by

$$P_{b|h} = \frac{1}{2}\left\{1 - \sqrt{\left[\frac{\lambda b}{1+\lambda b}\right]}\right\} \tag{3.9}$$

Where,

λ_b = Average signal to noise ratio.

$P_{b|h}$ = Probability of bit error in a Rayleigh channel.

The above equation has been computed in MATLAB and the results are shown in the Figure 3.1.
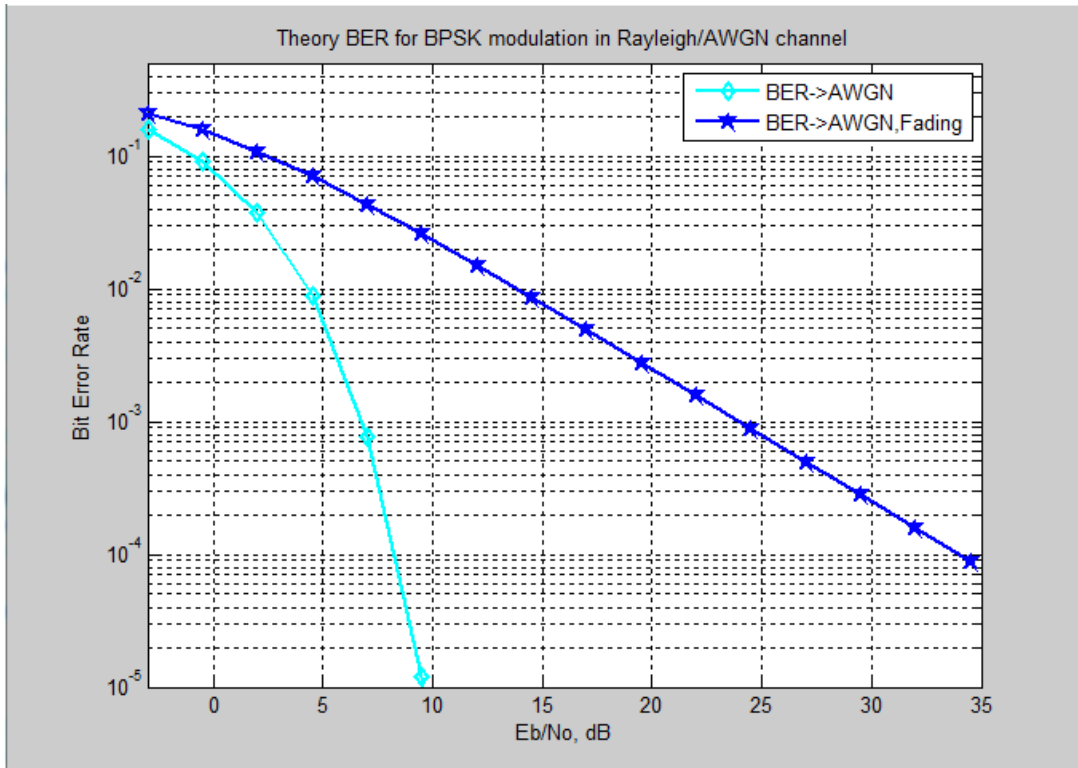
Fig 3.1. Plot showing the BER performance of BPSK modulation in AWGN and
Rayleigh fading channel.

3.2 Problem Description

From Figure 3.1, it is observed that the signal quality is significantly worse under
fading conditions. For instance, the BPSK signal in AWGN is 5dB better (i.e., it needs 5
dB less signal energy) than the BPSK signal in fading for a BER of 10^{-2}, and this
difference grows to about 18 dB at 10^{-3}. It is true that there are many other modulation
techniques would perform better in given fading conditions but cause other overheads.
The objective here is not to highlight the performances of the different modulation
techniques but to investigate techniques to mitigate fading and hence diversity becomes
the main focus of this thesis. Cooperative relays are the tools for taking advantage of
diversity.

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In [20], it is shown that the reliability of cell coverage area decreases with increase in cell radius. For example in Figure 3.2 [20, pg. 1218], with a 75% boundary coverage requirement (75% of the time the signal at cell edge is greater than threshold), the area coverage is 94% for σ=8 and n=4. The values provided in the Figure 3.2 are used as standard reference to compute the effective cell radius for a given cell edge probability later in the thesis. In [20], the relation between the cell radius (R) and area reliability for a fixed transmit power is given by Equation 3.10,

$$Fu = Q(a + b * lnR) + e^{\left(\frac{-2a}{b} + \frac{2}{b^2}\right)}\left[1 - Q(a + b * lnR - \frac{2}{b})\right] \quad (3.10)$$

Where,

$$a = \frac{Pmin - P_t - A}{\sigma} \quad and \quad b = \frac{Blog_{10}e}{\sigma} \quad (3.10)$$

The plot of the Equation 3.10 with A=120 dB, B=40 dB/decade, P_t=50 dBm and σ=8 dB has been shown in the Figure 3.3.
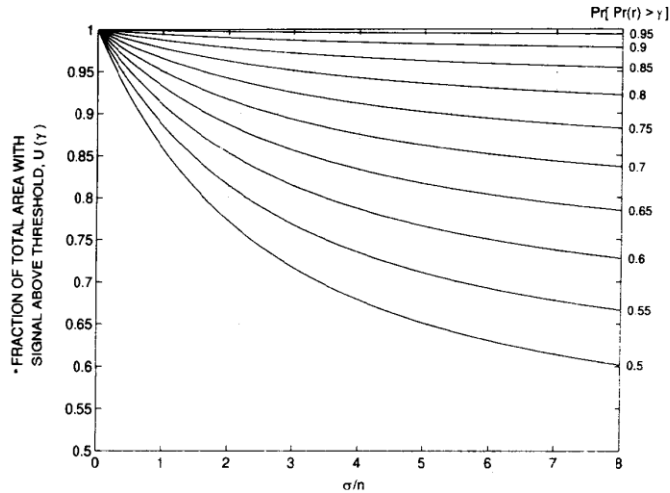
Fig 3.2. Family of curves relating fraction of total area with signal above threshold, as a function of probability of signal above threshold on the cell boundary [20].
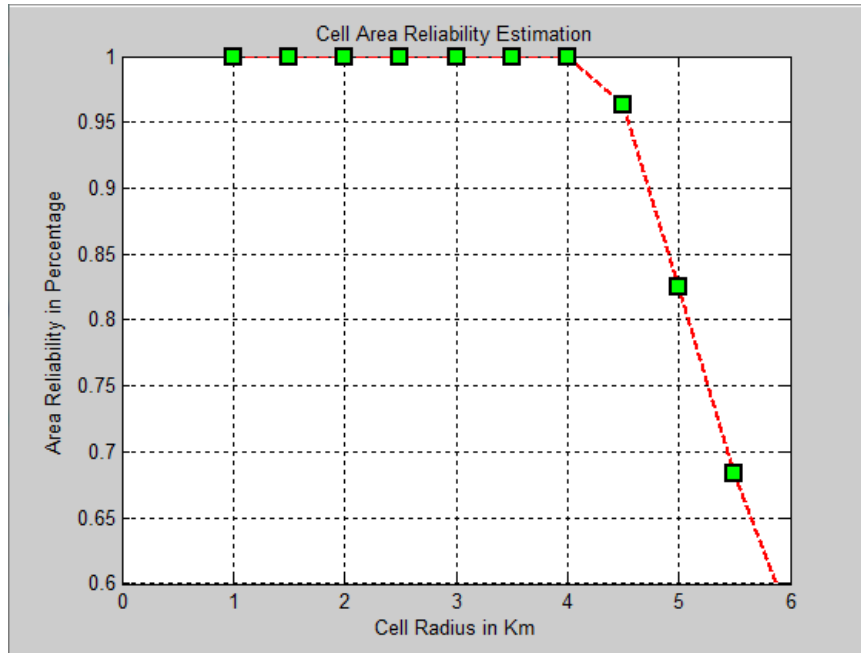
Fig 3.3. Showing relation between cell area reliability and cell radius

for A=120dB, B=40dB/decade, P_t=50dBm and σ=8dB.

It clearly depicts that as the cell radius increases, the area coverage reliability decreases, limiting the QOS. With maximum transmit power limited at the BS, the extension of the cellular coverage has to be traded off with the decrease in the coverage area reliability. Generally under an emergency situation, the user mobile trapped under rocks or other deep fade areas receives the same QOS as at the cell edge or sometimes even worse where there is absolutely no signal reception. This situation can be improved considerably with relays placed at the appropriate locations within the cell radius for coverage extension, reliable signal quality to users even at the cell edge, and increased QOS to the users closer to the BS also with decreased cost.

CHAPTER - 4

RELAY SYSTEM MODEL FOR IMPROVED SIGNAL QUALITY

In this chapter, we present a multi-hop cooperative relaying model assisting a cellular system to provide improved signal quality. We evaluate the performance of existing receiver combining techniques like equal ratio combining, fixed ratio combining, signal to noise ratio combining and maximum ratio combining with the Amplitude and Forward relaying protocol at the relay. Then we present diversity results (improved signal to noise ratio) at the receiver with relaying but also show that output SNR significantly varies with the position of the relay in the cellular system.

4.1 Relay Arrangement in Cellular System

A vast proportion of the research on cooperative communications has been dedicated to study the 3 node model. Technically it is possible to have "n" number of relays contributing to the diversity reception as shown in Figure 4.1 but in this thesis, we have considered only one relay contributing to diversity reception at the mobile receiver and the arrangement is shown in Figure 4.2.
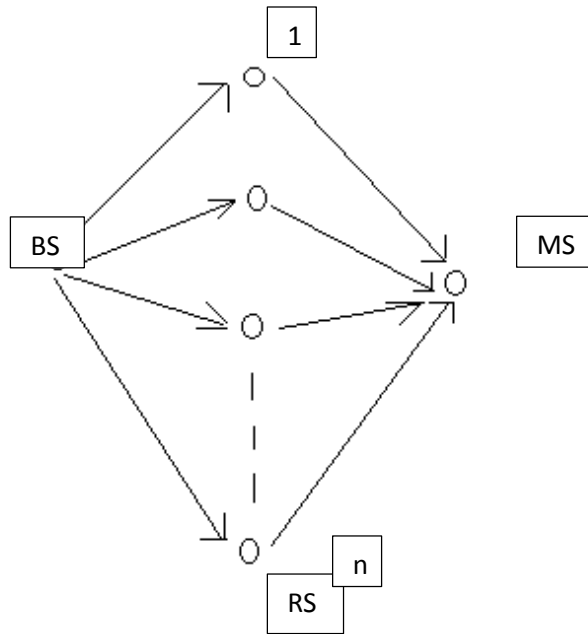
Fig 4.1 Arrangement of "n" relays (RS) in a cellular system contributing to diversity reception at Mobile Station (MS) with source as Base Station (BS).
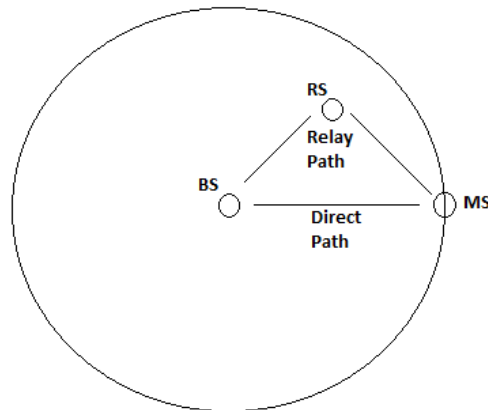
Fig 4.2 Cellular system with one relay (RS) providing 2 diversity paths for combining at mobile station (MS) with source as base station (BS).

4.2 Relay System Model and Parameters

We consider a circular cell assisted with a relay deployed as shown in Figure 4.3. This model and relay placement is best assumed to understand the diversity gains with

multi-hop between source and destination. The model shows a source BS, destination MS and a relay RS which for an instance forms an adhoc-like system but in a controlled manner. We consider relay assistance only in the downlink transmission. Hence we have a multi-hop system where the signal at the receiver can propagate to the destination either from source directly or via the relay.
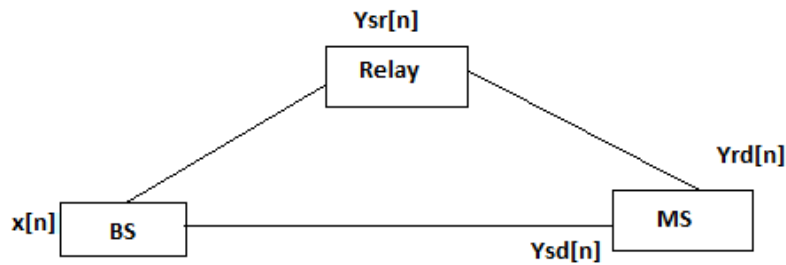
Fig 4.3 Relay assisted cellular system model.

As wireless transmissions are broadcast by nature, the signal sent by the source to the destination could also be heard by any receiver placed in close proximity to the path. This wireless phenomenon is used where during the phase one for a specific time interval, the source sends the signal to the relay, and during the second phase the source sends the signal to the destination on the direct path. These two radio channels on the direct and relay path respectively are considered to be orthogonal and half duplex. As the source send the same signal twice, this setup requires twice the usual bandwidth required than usual but this can be overcome by using the QPSK modulation technique on one of the link, even though has not been covered in this thesis. We consider orthogonal time division transmitting as shown in the Figure 4.4. The synchronization and its effects on the results are out of scope for this thesis.

Source Transmit Length $\left(\frac{N}{2}\right)$	Relay Transmit Length $\left(\frac{N}{2}\right)$
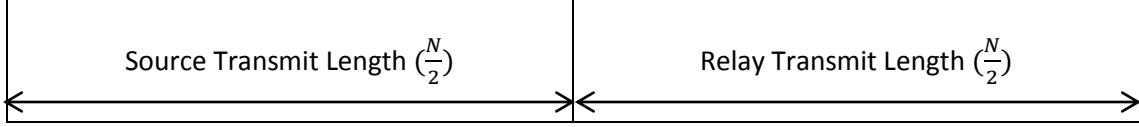
Fig 4.4 Time division transmission in a relay assisted cell.

Considering the Equation 3.7 defined for single user receiver system, we rewrite it for the direct path between source and destination as below,

$$y_{sd}(t) = h_{sd}(t)x_s(t) + n_{sd}(t) \qquad (4.1)$$

where, $h_{sd}(t)$ represents the Rayleigh fading channel, $x_s(t)$ represents transmitted input signal, $n_{sd}(t)$ represents the noise at the receiver.

The power of the received signal $y_{sd}(t)$ is given by,

$$P_{sd} = \frac{1}{T_s} \int_0^{T_s} |h_{sd}(t)|^2 |x_s(t)|^2 dt \qquad (4.2)$$

as $h_{sd}(t)$ will remain fairly constant over a small period of input symbol time, T_s, and let power of the input signal be,

$$p_s = \frac{1}{T_s} \int_0^{T_s} |x_s(t)|^2 dt \qquad (4.3)$$

Hence, the Equation 4.2 can be written as,

$$P_{sd} = |h_{sd}|^2 * p_s \qquad (4.4)$$

The noise power for the given received signal in Equation 4.1 is given by,

$$E[|n_{sd}|^2] = N_0 = 2\sigma_{sd}^2 \qquad (4.5)$$

Where, N_0 is two sided noise power spectral density for bandpass noise and σ_{sd}^2 is noise variance.

Using Equation 4.4 and 4.5, the instantaneous output SNR of the direct path between source and destination is given by,

$$\gamma_{sd} = \frac{P_{sd}}{E[|n_{sd}|^2]} = \frac{|h_{sd}|^2 * p_s}{2\sigma_{sd}^2} \qquad (4.6)$$

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4.3 Amplitude and Forward Relay Protocol

This is the simplest relaying protocol technique where the relay amplifies the signal it receives from the source and forwards it to the destination. The computing time and power capabilities with the replay employing such a protocol are limited. The major drawback of the AAF technique is that it also amplifies the noise along with the original signal and causes instability at the destination. The gain introduced by the relay [2], is given by,

$$\beta = \sqrt{\frac{P_r}{[\,|h|^2 P_r + N_o]}} \tag{4.7}$$

Where, P_r is the relay power, N_o is the noise power spectral density at the relay and $|h|^2$ is the Rayleigh fading coefficient.

The relay amplifies the received signal with a gain defined in the Equation 4.7. Clearly the relay node also amplifies the noise along with the received signal and this is the major disadvantage of this approach. The alternative approach would be to decode the received signal at the relay and then forward, avoiding unwanted noise introduction; this approach is called as decode and forward relaying. Decode and forward relaying is out of scope for this thesis as we have considered a system for modeling where channel estimation is poor or unknown and decoding the signal with improper channel knowledge is impossible.

Considering Equation 3.7 defined for single user receiver system, we rewrite it for the relay path with source as transmitter and relay as destination given below,

$$y_{sr}(t) = h_{sr}(t)x_s(t) + n_{sr}(t) \tag{4.8}$$

where, $h_{sr}(t)$ represents the Rayleigh fading channel of the relay path, $x_s(t)$ represents transmitted input signal, and $n_{sr}(t)$ represents the noise picked up at the relay.

Using Equation 4.6, the instantaneous output SNR of the path between source and relay is given by,

$$\gamma_{sr} = \frac{P_{sr}}{E[|n_{sr}|^2]} = \frac{|h_{sr}|^2 * p_r}{2\sigma_{sr}^2} \qquad (4.9)$$

where h_{sr} is the channel between source and relay having Rayleigh fading, p_r is the transmit power of the relay, σ_{sr}^2 is the noise variance. The signal received from the relay path at the destination is given by the following equation,

$$y_{rd}(t) = \beta h_{rd}(t)y_{sr}(t) + n_{rd}(t) \qquad (4.10)$$

Using Equation 4.8, we have

$$y_{rd}(t) = \beta h_{rd}(t)[h_{sr}(t)x_s(t) + n_{sr}(t)] + n_{rd}(t) \qquad (4.11)$$

where, β is the relay gain, $h_{rd}(t)$ is the Rayleigh fading channel of the path from relay to destination, $y_{sr}(t)$ represents transmitted signal at relay and $n_{rd}(t)$ is the noise picked up at the destination on the relay path. The power of the received signal $y_{rd}(t)$ is given by,

$$P_{rd} = \beta |h_{rd}|^2 |h_{sr}|^2 * p_s \qquad (4.12)$$

The two-sided noise power spectral density (N_0) for the received signal P_r is given by,

$$N_0 = \beta|h_{rd}|^2 E[|n_{sr}|^2] + E[|n_{rd}|^2] = 2\beta|h_{rd}|^2\sigma_{sr}^2 + 2\sigma_{rd}^2 \qquad (4.13)$$

Where, σ_{sr}^2 and σ_{rd}^2 are noise variance.

Using Equation 4.10 and 4.11, the instantaneous output SNR (γ_{rd}) of the relay (multi-hop) path is given by,

$$\gamma_{rd} = \frac{P_{rd}}{N_0} = \frac{\beta |h_{rd}|^2 |h_{sr}|^2 * p_s}{2\beta|h_{rd}|^2\sigma_{sr}^2 + 2\sigma_{rd}^2} \qquad (4.14)$$

4.4 Receiver Combining Techniques

We are looking at a system where the transmit diversity is formed for a single receiver by deliberate transmission of the source signal in two paths, i.e., direct path between source-destination and another path via the relay. This is different from conventional transmit diversity where there are series of antennas at the source using beamforming to serve multiple receivers. In an urban environment, the fading on each radio channel (direct and replay path) is independent and these two components of the same signal add up differently at the receiver to increase SNR and reduce BER.

Combining techniques are mainly intended to mitigate small scale fading and we use Rayleigh fading for modeling. The goal is to set the weight on each communication channel to minimize the impact of fading. In our thesis, we have considered 4 receiver combining techniques for performance evaluation under the cooperative relaying technique [4]. One of our goals was to develop a MATLAB simulator that could be used by subsequent students to consider more advanced relaying approaches.

4.4.1 Equal Ratio Combining (ERC)

This is the simplest diversity technique where it is assumed that all channel gains are equal and hence, simply combining the signal copies received on these channels can give equal diversity gains [4]. This technique can be used where the channel quality information is not known. In our thesis, we have considered only two channels, namely the direct path and relay path. If $y_{sd}[n]$ is the sequence of symbols received from the direct path and $y_{rd}[n]$ is obtained on the relay path and as we are assuming the channel gains are equal, the combined signal can be generated by using the following equation,

$$y_{d}[n] = y_{sd}[n] + y_{rd}[n] \qquad\qquad (4.15)$$

4.4.2 Fixed Ratio Combining (FRC)

If channel gains can be approximated to have a fixed ratio on the multi-path channels based on little knowledge of channel quality, then the equal gain diversity can be converted to fixed ratio combining [4]. In our thesis, different channel gain ratios (fixed weight on each channel) have been simulated to show the variation in fixed gain combining results. Practically this combining technique is less used as the ratio cannot be determined without estimating the channel quality (and if one knows the channel quality, better approaches exist) but it gives an idea about how significant it is to estimate the channel quality for better diversity. The following equation has been used for simulation in our thesis where w_{sd} and w_{rd} determine the fixed channel weights (or gain) applied to the respective direct and relay paths,

$$y_d[n] = w_{sd} * y_{sd}[n] + w_{rd} * y_{rd}[n] \qquad (4.16)$$

4.4.3 Signal to Noise Ratio Combining (SNRC)

The channel quality is generally measured in terms of signal to interference noise ratio (SINR) for the transmission of the signal over a fading channel. In our thesis, the output SNR at each channel is used to form the weight of the channel, and the interference from the co-channels is ignored. For instance, if the output SNR on the direct path is better than the output SNR on the relay path, then the weight of the direct path is greater than the relay and vice versa is also true. The following equation has been used for simulation,

$$y_d[n] = \gamma_{sd} * y_{sd}[n] + \gamma_{rd} * y_{rd}[n] \qquad (4.17)$$

where, γ_{sd} represents output SNR on direct path and γ_{rd} represents SNR on relay path given by the Equation 4.9 and 4.12 respectively.

4.4.4 Estimated SNR Combining (ESNRC)

This technique is a variation of the SNR combining technique where only that symbol sequence is considered whose output SNR is better than another by a factor while combining. This factor can generally be varied depending on the threshold set at the receiver. The accurate computation of the required threshold at the destination is beyond the scope of this thesis. If the two channel's output SNR is more or less the same, then gains are equally considered and signals are just summed up. This technique can also be referred as sort of a selection diversity but more sophisticated as estimation of the channel quality is considered. The following equation gives the model used in the simulation to extract the original signal from the received,

$$y_d[n] = \begin{cases} y_{sd}[n] & (\frac{\gamma_{sd}}{\gamma_{rd}} > 10) \\ y_{sd}[n] + y_{rd}[n] & (0.1 \leq \frac{\gamma_{sd}}{\gamma_{rd}} \leq 10) \\ y_{rd}[n] & (\frac{\gamma_{sd}}{\gamma_{rd}} \leq 0.1) \end{cases} \qquad (4.18)$$

4.4.5 Maximum Ratio Combining (MRC)

In MRC, each radio channel is weighted with the complex conjugate of the respective channel gain. In [4], with maximal ratio system, the maximum power (P) realized by the linear combination is the sum of individual power ratios (p_j),

$$P = \sum_{j=1}^{N} p_j \qquad (4.19)$$

For this to be true, each channel gain must be proportional to the rms signal level and inversely proportional to the noise level in the channel. This means that the weights

multiplied with the signal level for a good channel will amplify and will attenuate the signals on the poor channel upon linear combination.

In other words, the following equation considered in our thesis shows that the weights used are the conjugate of channel gains h_{sr} and h_{rd} respectively,

$$y_d[n] = h_{sd}^* * y_{sd}[n] + h_{rd}^* * y_{rd}[n] \qquad (4.20)$$

The signals considered for linear combination above are the ones received from the source and relay only and hence only those channels are considered. It is clear that the relay has to re-generate a perfect signal copy of the original source signal to avoid decode errors propagating to destination as MRC doesn't consider the channel between the source and destination. MRC is ineffective with the amplitude and forward technique as there is poor channel estimation. In our thesis, MRC simulations have still been considered to show its results compared to AAF and its performance under poor channel estimations.

4.5 Simulation Results

In this section we present numerous plots showing the performance of the receiver combining techniques under different channel conditions. We also present the results of the combining techniques when the relay is placed at arbitrary distances between the source and the destination. The figure of merit considered for showing the performance results is the plot of signal to noise ratio (SNR, dB) versus the bit error rate (BER) at the receiver for both the combined signals and also signals received on the direct path. The source (BS) sends the source signal once to the relay (RS) via the relay path and sends the same copy of the signal to the destination (MS) on the direct path using different antennas. The signal and channel modeling for the relay path has been implemented in

the same way as the direct path explained in the respective sections Chapter 3. The following sections show the plots between SNR and BER for each of the receiver combining technique and with relay placed in several positions with respect to the source or destination. We analyze the variation in performance of each receiver combining technique by changing the position and conclude that there is a need for finding the optimal position for the relay for better diversity results.

4.5.1 Equidistant Relay

The results in this section have been obtained with a relay placed at one of the edges of the equilateral triangle with the source (BS) and destination (MS) on the other edges. The path loss on each channel would be nearly the same as the path distances are equal, and they are assumed in an urban environment with path loss exponent (n) of 3.5 used in the simulations. The x-axis labeled as SNR (dB) gives the signal to noise ratio (in dB) and the y-axis labeled as BER gives the bit error rate of the considered diversity combining technique. The path distances between all the nodes are taken as unit distance 1.

Before the performance can be evaluated for all combining techniques, the best weights have to be computed for FRC and this has been done by simulating different ratios of weight on direct path to the relay path respectively. Weights of 2:1, 2.5:1, 3:1, 1:2 and 1:2.5 have been simulated as shown in the Figure 4.5. Figure 4.5 shows that the performance of FRC with weights of 2:1 is better than other weighted FRC combinations. As the 3 nodes are placed equidistant in space with respect to each other, the signal sent on the direct path is travelling less distance than the signal on the relay path which is double the distance than former. As a result, the signal quality achieved on the receiving

end of the direct path is much better than that of the relay path and using higher weight on the former (2:1) would achieve better results. As there is attenuation regardless of any channel and the same would also apply to the direct path in this case. If weight assigned to the direct channel is increased beyond a certain limit, it is expected to degrade in performance as the assigned weight multiplies with the noise component as well and this is evident from the plot in Figure 4.5 where the weights considered are 3:1 for direct and relay path respectively. On the other hand, when the channel with good channel response is assigned a less weight than the channel with bad response, like in the case of weights being 1:2 for direct and relay path, the combined signal quality is degraded as is also evident from the Figure 4.5

The computations for the optimal ratio for FRC are out of scope for this thesis. It is not the optimal ratio combiner anyway since it doesn't take the channel fluctuations into its computations while more realistic methods like SNRC and MRC are evaluated. From here in all the simulation results, we have considered to use the weights of ratio 2:1 with FRC when doing a comparison with other combining techniques.

Figure 4.6 shows the performance comparison of all the combining techniques. It is clear from the plot that the diversity combining achieved with AAF protocol has seamless benefits when compared to the BPSK modulated direct transmitted signal. For instance, to achieve a BER of 10^{-2}, the required SNR for ERC which is the simplest of combining techniques is nearly 4dB better when compared to the direct transmission link. As explained before, FRC (2:1) performs better than ERC but not when compared with SNRC or ESNRC. SNRC as explained before requires SNR computation of every block received at the destination whereas in case of ESNRC, the ratio of the SNR computed for

direct and relayed signal can be varied or can be flexible to accommodate estimation errors. So in the plot shown, this was an expected result because, both SNRC and ESNRC take the channel attenuation fluctuations into account by computing the weights equivalent to channel SNR but ERC or FRC don't make the channel estimations and hence perform better. Both SNRC or ESNRC show nearly same results but the SNR ratio in case of ESNRC can be even better estimated if the threshold at the receiver can be accurately calculated. Accurate channel estimation of each block especially in this case with AAF relaying protocol is pointless as DAF (Decode and Forward) relaying method would have been preferred otherwise. We have considered using AAF because of its simplicity in design and is also cost effective. Finally, maximum ratio combining which was predicted to produce best diversity results has shown poor performance when compared to other combining techniques. This is because the weights (gain) in case of MRC estimating the channel quality are the conjugate of the Rayleigh fading channel. As we have considered a system where the channel estimation is inaccurate, the MRC suffers with poor performance but nevertheless better than the direct link transmission only. MRC gives best results when there is accurate channel gain estimation and works better with DAF than AAF.
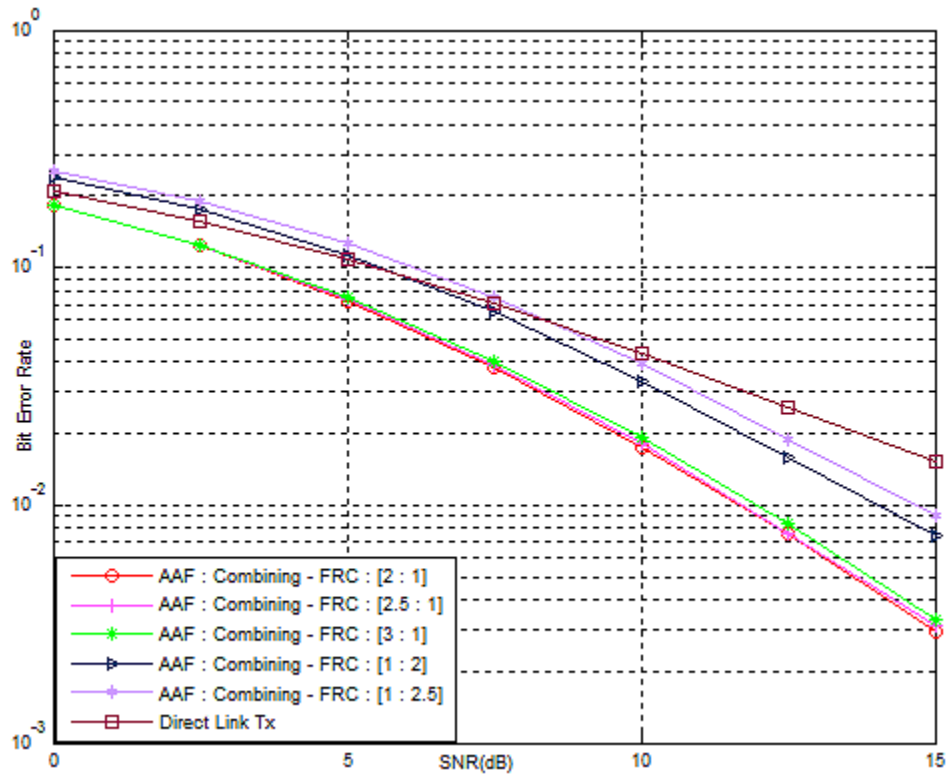
Fig 4.5 FRC with weights different weights on direct and relay path respectively. The path distances are in the ratio 1.0:1.0:1.0 [S-D:S-R:R-D]. FRC (2:1) outperforms other combinations.
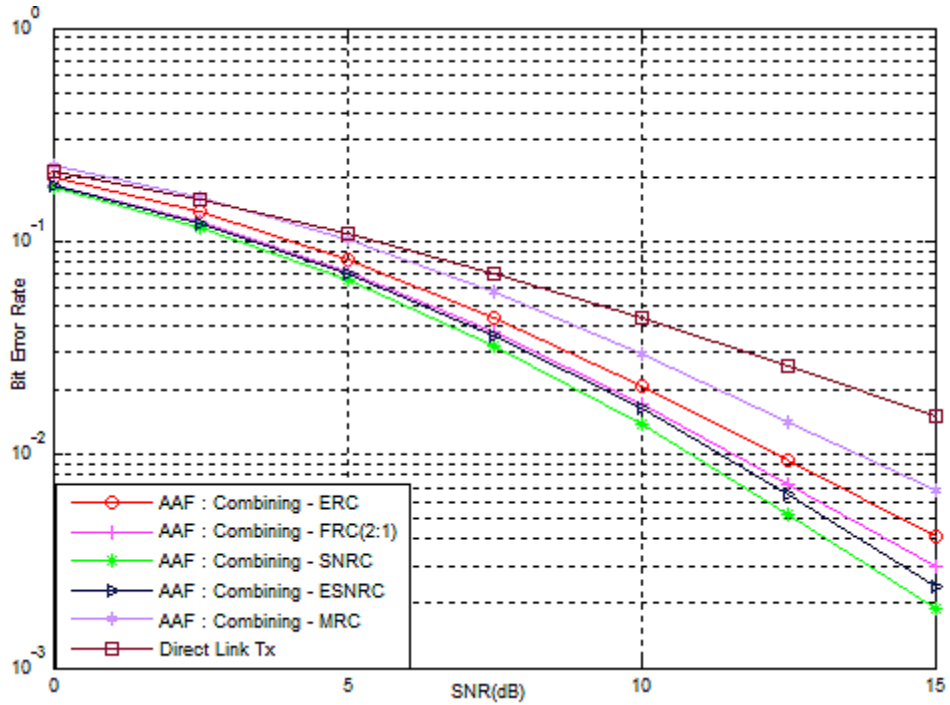
Fig 4.6 Performance comparison of all combining techniques with path distances in the ratio 1.0:1.0:1.0 [S-D: S-R: R-D]. SNRC/ESNRC outperforms other techniques.

4.5.2 Relay Close to BS

In earlier system modeling, the 3-nodes were placed at equidistance with respect to each other. Now the relay is moved between the source and destination and the BER performance of the all the receiver combining techniques have been evaluated in the following plots.

Figure 4.7 gives the performance of all the combining techniques when the relay is placed at 0.3 unit distance with respect to the base station or 0.7 unit distance with respect to the destination (MS). The distance between BS and MS remains the same which is 1 unit distance. Clearly all the combining techniques have better BER for a given SNR when compared to the direct link transmission only as expected. Interesting results are obtained in this case when compared to the results in Figure 4.6 when the

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nodes are placed at 1 unit distance with respect to each other. For instance, the BER of nearly 10^{-3} is achieved by SNRC, ESNRC combining techniques at SNR of 10dB in the former case which is 5≅6dB better than the latter case. One thing is clear from this case and can be concluded that the placement of the relay plays an important role in the performance of the diversity combining. This result can be explained based on the factor that if the relay is placed close to the source, the whole system essentially becomes a two sender system giving best results. As we used AAF at the relay node which amplifies noise that it picks up along with the original signal, it is desirable to keep the noise level low and this is only possible if the channel response between the source and relay is good ,i.e., relay placed closer to the source. In the Figure 4.7, as expected, SNRC and ESNRC perform much better than the other combining techniques as the reason will be the same as explained in the Section 4.5. It is also observed that the FRC (2:1) dint produce better results than ERC because higher weight is assigned to the direct path which has poor channel response. MRC as expected produces poor BER performance results as the system considered has inaccurate channel estimations.
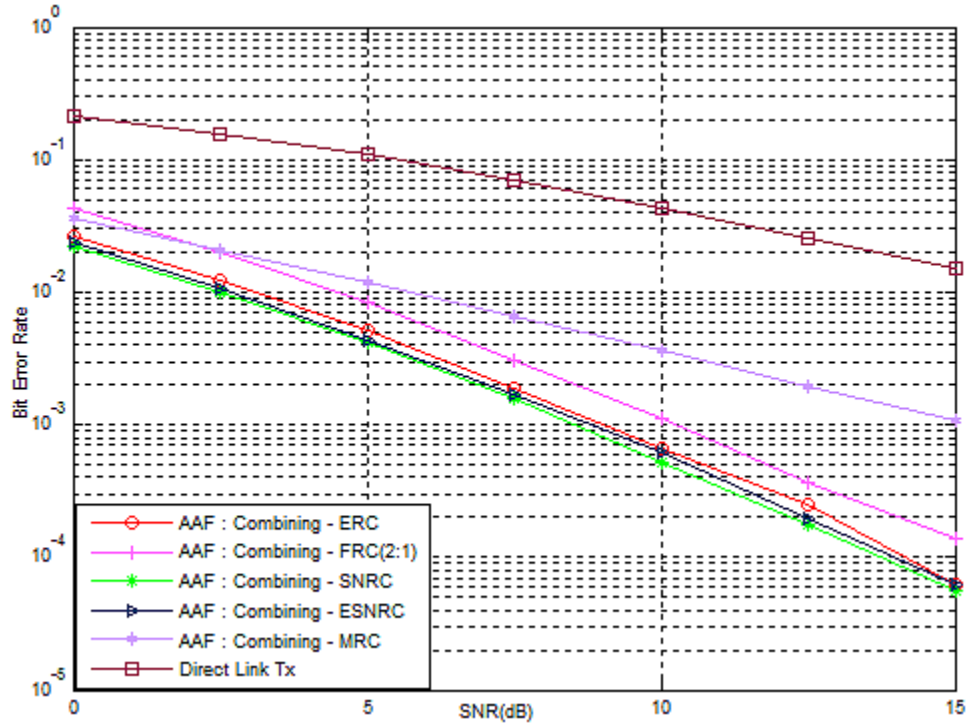
Fig 4.7 Performance comparison of all combining techniques. The path distances are in

the ratio 1.0:0.3:0.7 [S-D:S-R:R-D].

4.5.3 Relay close to MS

Ideally, the closer the relay is to source the better are the results but as the relay is moved away from source the performance of the diversity combining methods are expected to drop. This is evident from the plots shown in the Figure 4.8. These plots give the performance of all the combining techniques when the relay is placed at a 0.7 unit distance with respect to the base station or 0.3 unit distance with respect to the destination (MS). The distance between BS and MS remains the same which is 1 unit distance. Clearly all the combining techniques have better BER for a given SNR when compared to the direct link transmission only as expected. When the relay is placed close to destination or away from source, the path distance between the source and the relay is higher and causes more attenuation losses and AAF protocol at the relay in-turn causes

the noise level to go up and forwards the signal to destination. This produces poor results when combined with the signal on the direct link. Hence all the combined signals show poor performance when compared to the results when the relay is placed close to the source. It is very interesting to observe that the ERC, FRC and MRC combining methods definitely perform better than the system with only the direct transmission link but don't differ much when compared with each other. This is because of the inaccurate channel estimation in case of MRC and wrong weighting of the channels in case of FRC. SNRC and ESNRC perform much better than other combining methods due to the same reasons as explained in Section 4.5 but not when compared to system when the relay is placed close to source for the same reasons explained in Section 4.5.2.
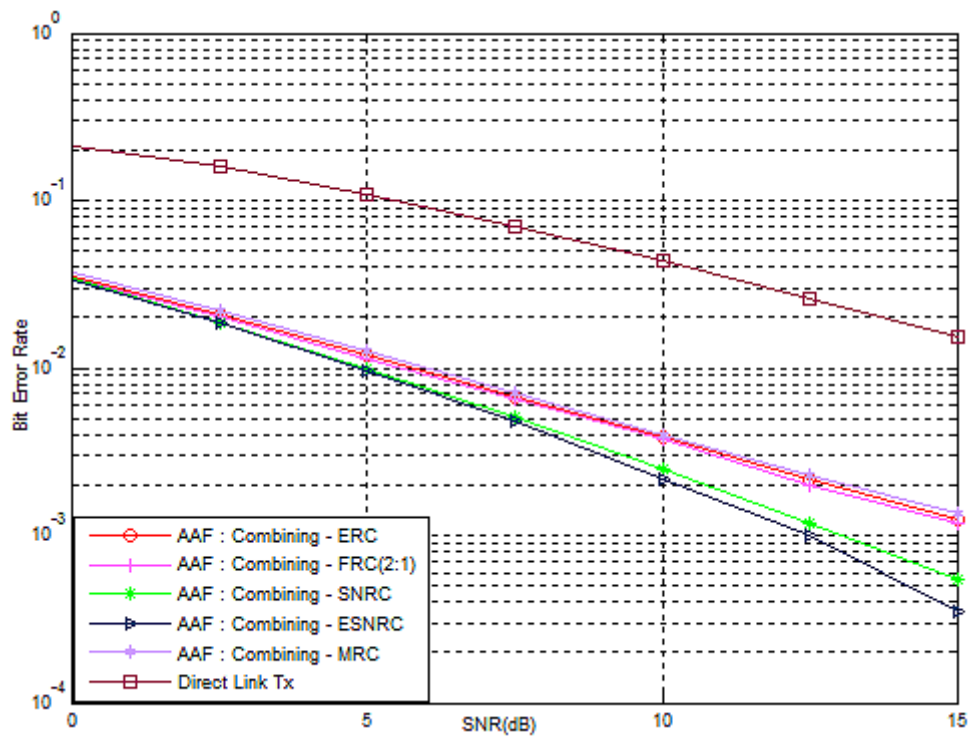

Fig 4.8 Performance comparison of all combining techniques. The path distances are in the ratio 1.0:0.3:0.7 [S-D:S-R:R-D].

4.5.4 Relay Placed in Between BS and MS

So far, we have presented the performance results of all the combining techniques when the relay is placed close or away from the destination and now present the results when the relay is arbitrarily placed between source and destination at the distances much greater than the direct path. Also this time we have just considered SNRC and ESNRC diversity combining methods for comparison as in all the earlier cases these two methods have outperformed. Figure 4.9 and 4.10 shows the results for ESNR and SNRC for various path distances also shown in the same plots. As expected, both these combining methods perform nearly with the same results. Interesting results to observe is under the case when the path distance between relay and source/destination is 3 where the performance of ESNRC or SNRC is nearly the same as the system with only direct link transmission. This clearly indicates that the with increased distance between the source and relay (S-R), the higher is the BER at the relay and there is definitely a S-R path distance boundary beyond which the system with or without the relay would produce the same BER results or could be even worse with wrong channel estimates or weighting. The plots clearly show that as the relay is moved close to the source, the performance is greatly improved.
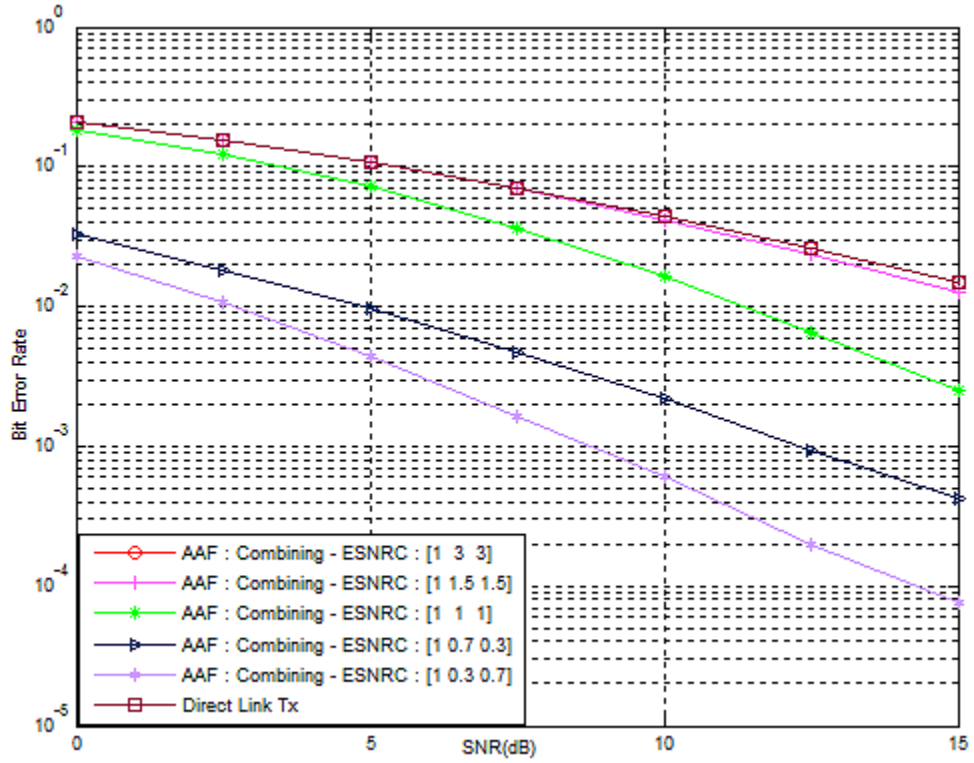
Fig 4.9 Performance comparison of ESNRC combining technique with relay arbitrarily
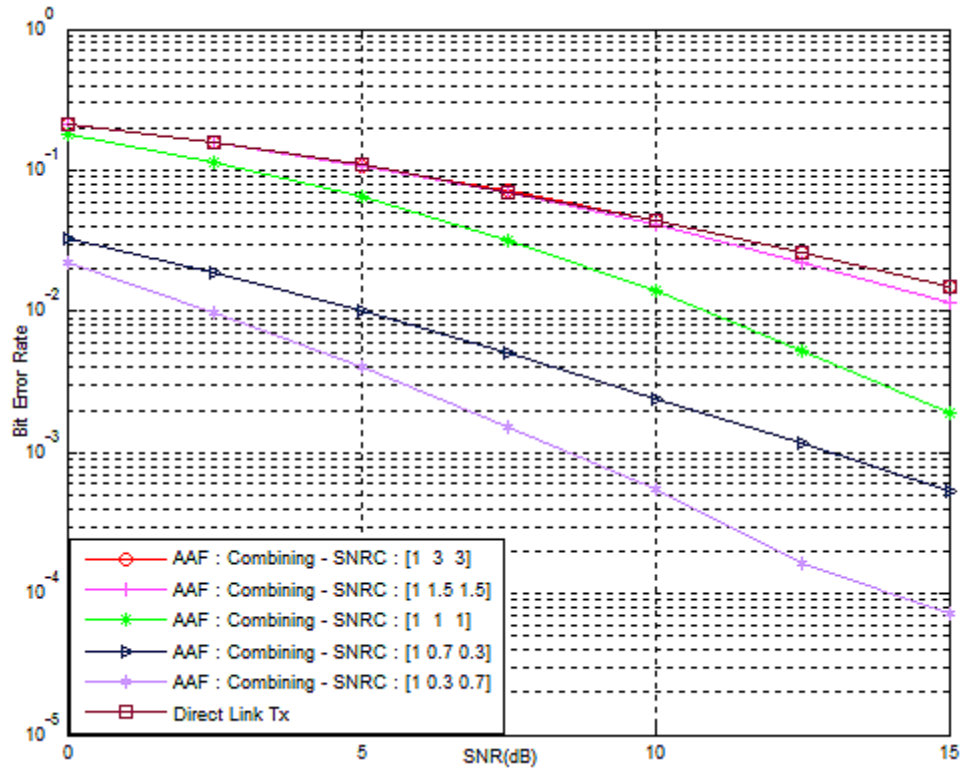
placed between BS and MS.

Fig 4.5.4.2 Performance comparison of SNRC combining technique with relay arbitrarily

placed between BS and MS.

CHAPTER 5

RELAY SYSTEM MODEL FOR COVERAGE EXTENSION

With the results of the previous chapter, the platform to understand the significance of the relay placement has been established for the improved BER performance of a relay assisted cellular system. By maintaining the received signal power under the threshold requirements at the destination, the relay can be moved away from the source to a maximum distance and using the coverage of the relay from that point, the range of the considered cell can be extended. In this chapter, we have presented a simple method where the cell radius can be extended in a relay assisted cellular system with the cell edge coverage probability forming the boundary conditions which is shown (Figure 3.3) the Chapter 3.

5.1 System Model

We have considered the relay assisted cellular system shown in the Figure 5.1, where the relay is placed at the cell edge of the source (BS). The cell radius of the source (BS) is R_1 and the cell radius for the relay system is R_2 respectively. We have assumed that the relay is placed on the cell edge of the source where the cell edge coverage probability is within the acceptable limits. Computing the accurate limit of the cell edge coverage probability is out of scope in this thesis but the coverage extension results have been simulated for cell edge probability of 0.5 or greater. For an instance, given the cell edge probability of 0.9 would mean that the average received power of the signal on the cell edge is 90% of the time greater than the threshold considered at the receiver.
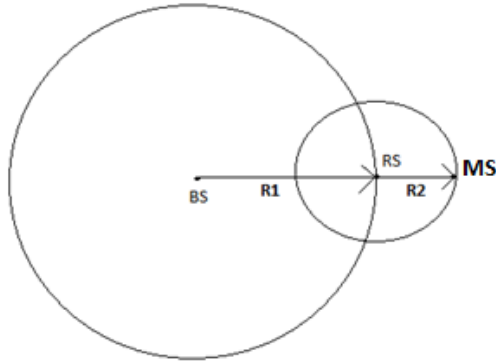
Fig 5.1 System model representing possible cell range extension with relay assistance.

Our focus is only on a two hop situation where the BS transmits the source signal to the MS only via the relay (RS) and is extendable to multiple hops but is out of scope for this thesis. When the source signal is transmitted to relay, the probability of the average received signal power signal being above the threshold at RS be P_1 and similarly, when the relay forwards the amplified signal (using AAF protocol), the probability at MS be P_2. These conditional probabilities P_1 and P_2 are defined as follows,

$$P_1 = P_r(P_{sr}(d) > P_{MIN}) \qquad (5.1)$$

$$P_2 = P_r(P_{rd}(d) > P_{MIN}) \qquad (5.2)$$

Where, $P_{sr}(d)$ and $P_{rd}(d)$ are the average received power at the RS and MS respectively and P_{MIN} is the threshold power and d is the distance of any point from BS.

Let's consider that the relay operates under selective relaying schema where it decides to forward the only when the received signal power is above the threshold or say probability of success that relay would forward the signal. In other words, if the relay (RS) is placed at the cell edge of source (BS) with the cell edge probability equivalent to P_1=0.5, the relay will forward the received signal only 50% of the time. This also means that if the relay is moved closer to the BS, P_1 gets closer to 1. This value of P_1 is inversely

proportional to R_1 which is the cell radius of BS. Similarly, at MS, let the probability of success (P_2) that the received power be greater than the threshold be above 0.5. As the probabilities P_1 and P_2 are mutually exclusive events, i.e., the MS would receive the signal from relay path only if $P_1 \geq 0.5$ and the MS will accept the received signal only if $P_2 \geq 0.5$ and hence the overall coverage probability of the extended cell is defined by the following equation,

$$P = P_1 * P_2 \geq 0.5 \tag{5.3}$$

It can be clearly depicted from the above equation that P_1 and P_2 are the functions of R_1 and R_2. As R_1 is increased, the value of P_1 goes down and P_2 bounded by Equation 5.3 causes R_2 to decrease and vice versa is also true.

Using the standard link budget on the path from BS to RS, the received power at the relay is given by,

$$P_{sr}(d) = P_{BS} - [PL(d)] \tag{5.4}$$

Where, P_{BS} is the transmit power at BS, $PL(d_o)$ is the average path loss at the distance "d_o", $PL(d)$ is the average path loss at the distance "d" from BS.

Using the path loss equation defined in (3.2) in 5.4, we have,

$$P_{sr}(d) = P_{BS} - \left[PL(d_o) + 10n\log(\tfrac{d}{d_o}) + X \right] \tag{5.5}$$

Therefore,

$$P_1 = P_r \left(P_{BS} - \left[PL(d_o) + 10n\log(\tfrac{d}{d_o}) + X \right] > P_{MIN} \right) \tag{5.6}$$

Re-writing in terms of Q-function, we have,

$$P_1 = Q\left(\frac{P_{MIN} - \left[P_{BS} - \left[PL(d_o) + 10n\log(\tfrac{d}{d_o}) \right] \right]}{\sigma_{sr}} \right) \tag{5.7}$$

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As the RS is placed at the cell edge of BS, the average path loss can be written as,

$$P_1 = Q\left(\frac{P_{MIN} - \left[P_{BS} - \left[PL(d_o) + 10nlog(\frac{R_1}{d_o}) + 10nlog(\frac{d}{R_1})\right]\right]}{\sigma_{sr}}\right) \qquad (5.8)$$

The Q-Function can also be written in the form as given below,

$$Q(x) = \frac{1}{2} - erf(\frac{x}{\sqrt{2}}) \qquad (5.9)$$

Re-writing eq. 5.8 in terms of eq. 5.9

$$P_1 = \frac{1}{2} - erf\left(\frac{P_{MIN} - \left[P_{BS} - \left[PL(d_o) + 10nlog(\frac{R}{d_o}) + 10nlog(\frac{d}{R})\right]\right]}{2\sigma_{sr}}\right) \qquad (5.10)$$

Applying the Reudinks solution defined in [21, pg. 107] to 5.10, we have

$$P_1 = \frac{1}{2} - \frac{1}{R^2}\int_0^R r * erf\left(a + bln\left(\frac{r}{R}\right)\right) dr \qquad (5.11)$$

Where,

$$a = \frac{P_{MIN} - \left[P_{BS} - PL(d_o) - 10nlog(\frac{R}{d_o})\right]}{\sqrt{2}\sigma_{sr}} \qquad (5.12)$$

$$b = \frac{10nlog_{10}e}{\sqrt{2}\sigma_{sr}} \qquad (5.13)$$

The solution of the integral given in Equation 5.11 is [21, pg. 107],

$$P_1 = \frac{1}{2}\left[1 - erf(a) + \left(exp\left[\frac{1-2ab}{b^2}\right]\right)\left(1 - erf\left[\frac{1-ab}{b}\right]\right)\right] \qquad (5.14)$$

At cell edge, we consider that the received signal strength is equal to the threshold P_{MIN}.

In other words, $P_{MIN} = P_{sr}(d)$ or a=0.

Substituting a=0 in Equation 5.11, P_1 reduces to,

$$P_1 = \frac{1}{2} - \frac{1}{R^2}\int_0^R r * erf\left(bln\left(\frac{r}{R}\right)\right) dr \qquad (5.15)$$

Solving the integral in (5.15) by substituting a=0 in Equation 5.14,

$$P_1 = \frac{1}{2}\left[1 + \left(\exp\left[\frac{1}{b^2}\right]\right)\left(1 - \operatorname{erf}\left[\frac{1}{b}\right]\right)\right] \qquad (5.16)$$

Similarly, writing the Equation 5.2 in terms of Q-function by considering MS placed at R_2, we have,

$$P_2 = Q\left(\frac{P_{MIN} - \left[P_{RD} - \left[PL(d_o) + 10n\log\left(\frac{R_2}{d_o}\right)\right]\right]}{\sigma_{rd}}\right) \qquad (5.17)$$

Where, d is any point between RS and MS with $d < R_2$, σ_{rd} is the standard deviation of the received signal power and n is the path loss exponent.

R_2 is evaluated from Equation 5.17 and is given by,

$$R_2 = d_o * 10^{\left\{\frac{\left[\sigma_{rd}Q^{-1}\left(\frac{0.5}{P_1}\right) - P_{MIN} + P_{RD} + PL(d_o)\right]}{10n}\right\}} \qquad (5.18)$$

Clearly we observe from (5.18) that R_2 is indirectly proportional to R_1 by being dependent on P_1. The value of R_1 can be obtained from (5.8) and the maximum value of R_1 (cell edge) is obtained of source BS where $P_1 = 0.5$ and is given by,

$$R_1^{max} = d_o * 10^{\left\{\frac{\left[\sigma_{rs}Q^{-1}(0.5) - P_{MIN} + P_{BS} + PL(d_o)\right]}{10n}\right\}} = d_o * 10^{\left\{\frac{\left[-P_{MIN} + P_{BS} + PL(d_o)\right]}{10n}\right\}} \qquad (5.19)$$

Knowing the maximum value of R_1 and using the bounds defined by the Equation 5.3, the effective cell radius is computed using the following,

$$R_{max} = R_1^* + R_2^* \qquad (5.20)$$

R_1^* is the effective position of the relay with respect to the BS where $P_1 \geq 0.5$ and R_2^* is the coverage radius of the relay (RS) when the relay is at its effective position. If the relay is placed beyond this point R_1^*, then $P_1 < 0.5$ would violate the Equation 5.3. We are only interested in the point where the relay would be at the maximum distance from the source (BS) but still achieves the acceptable signal power at the destination.

5.2 Simulation Results

For a given BS cell radius R_1, we intend to find the point R_1^* which would be the optimal position for the relay. For every computed value of P_1 at given value of R_1, R_2 is calculated given by the Equation 5.18. The simulation stops when the probability P_1 equals 0.5 to compute R_{max} as per the Equation 5.20 and then obtain R_1^*. We have assumed that when the relay is placed at the cell edge of BS, the value of $P_1 = 0.5$. To be more practical, the simulations were also run for P_1 values of $0.5 < P_1 < 1$ and the results have been presented showing the possible cell range extension achievable.

The maximum distance of RS from BS (R_1^{max}) is calculated using eq. 5.20 where its inputs are given in the table 5.1. For the given range of $R_1 < R_1^{max}$, the simulation is run to find the values of R_1^* and R_2^* using the bounds defined in the eq. 5.2. The path loss at the given reference distance is computed using the Equation 3.4. For more practical reasons, the path loss calculations at any point "d" in the simulations are computed using the okumura-hata model [8, pg. 127].

Table 5.1 System parameters used for computing the cell radius of BS (R_1^{max}).

Parameter	Value used in Simulation
P_{MIN}	87.3166 dBm
SNR	10 dB
Frequency (f)	700 MHz
Temperature	298K
Path loss exponent (n)	3
Bandwidth	9 MHz
Noise Floor (NF)	7
Noise Power	-163.0073 dBm
Reference Distance (d_o)	350 meters
G_{tx}	2.14 dBi
G_{rx}	2.14 dBi

Figure 5.2 shows the plot for the assumed cell edge probability (P_1=0.5). Given the value of P_1=0.5, the effective cell radius (R_{max}) given in Equation 5.20 is computed to 3671.208232m and the corresponding value of R_1^* is 2380m which is the effective position of the relay from the source BS. The value R_1^{max} was computed to 2943.408979m using the Equation 5.19. This is the simplest method of extending the cell radius where the relay is placed at approximately (2380/3671.208 = 0.6483) 64.83% of the effective cell radius with probability of success (P_1) still greater than 0.5. It is observed that as the BS cell radius (R_1) is increased the probability P_1 goes down and it's as expected because the path distance between the source and relay is increasing whereas R_2 increases with P_2 bounded by Equation 5.3. The effective cell radius is obtained at the (R_{max} = 3671.208232m) after which the R_{max} decreases. This is because any further increase in R_1, the relay (placed at that point) receives a highly attenuated signal from source to only amplify and forward a noisy signal to the destination which very closely follows with the receiver diversity combining results obtained in Section 4.5.2 and 4.5.3 of Chapter 5.
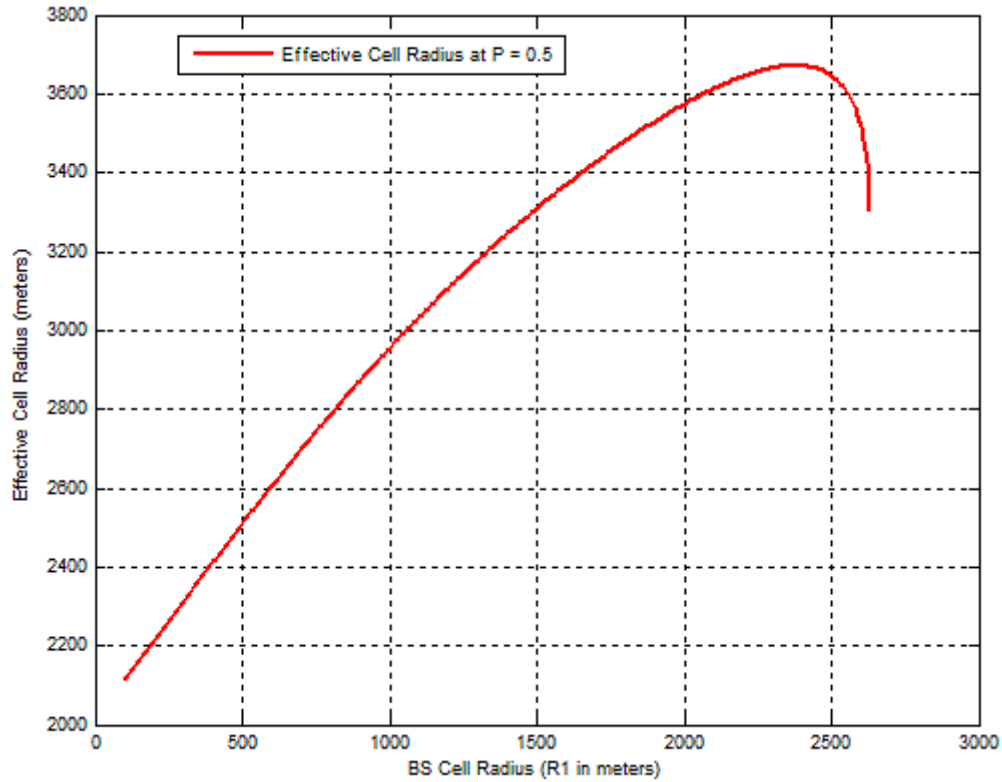
Fig 5.2 The Plot between effective cell radius ($R_{max} = 3671.208232$ m) with relay positioned at ($R_1^* = 2380$ m) and probability P_1 set to 0.5.

The table 5.2 summarizes the achievable effective cell radius of the cellular system considered given cell edge probability (P_1). The values obtained for R_1^* in the table 5.2 clearly show that for increased P_1 or QOS by the BS, the relay must be placed close to the BS.

Table 5.2 Effective cell radius (R_{max}) obtained for different Cell Edge Probability.

Effective Cell Radius (R_{max})	Optimal Relay Position (R_1^*)	Extended Radius (R_2^*)	Cell Edge Probability (P_1)	R_1/R_{max}
3671.208232	2380	1291.208232	0.5	0.64
3651.622303	2230	1421.622303	0.6	0.61
3515.507084	1870	1645.507084	0.7	0.53
3334.798832	1540	1794.798832	0.8	0.46
3086.167398	1170	1916.167398	0.9	0.37

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusion

In Chapter 4, we have shown how the relay terminal can be used in a cellular network to achieve improved performance in terms of the signal quality and the coverage extension. The BER vs. SNR plots show the improvement in the quality of signal received at the destination with relay exploiting the space diversity given any linear diversity combining method when compared to the cellular system with only the point to point link between the source and destination. We also show how the BER performance of the system varies by using different receiver combining techniques with relay fixed at a position and also when the relay is moved between the source and destination. The AAF protocol has been used at the relay system which proved very efficient in achieving 2nd order diversity assuming that the exact channel estimation is not known at the receiver. Among the different receiver combining techniques, SNRC and ESNRC methods gave the best results as they estimate the channel quality in terms of SNR of each block on the given channel at the receiver. Both ERC and FRC methods seemed very easy to implement with AAF and also proved efficient as their BER performance was comparable with SNRC or ESNRC considering the fact that the ERC/FRC don't compute the channel estimations. MRC as expected shows poor performance compared to others as the channel estimation is poor or unknown in the system. Given any receiver combining technique used in the analysis, there has been significant difference in the BER performance when the relay is moved between the source and destination. The best BER performance of any receiver combining technique is observed when relay is placed

close to the source than the destination. This particular result leads to an important conclusion that the in such a system architecture, the path and channel quality between the source and relay plays significant role which is defined by position of the relay. Also we see poor diversity results when the relay is placed at a much larger path distance with respect to source and destination in comparison to direct path. At such large path distances it becomes pointless to have a relay assisting the cellular system which is quite obvious as we are no longer using the capabilities of the relay terminal being in a poor coverage area of the source.

In Chapter 5, with simplest methods we showed that the cell range of the considered 3-node system model can be extended (R_{max}) well upto 1.5 times the cell radius of the source given the cell edge probability is 0.5. To achieve this we compute a point called the effective relay position (R_1^*) with respect to the source where if the relay is placed can extend the range of the source to R_{max} ($R_{max} > R_1$). As the cell edge probability is increased ($0.5 < P < 1$), which basically means higher threshold SNR values at the cell edge and not surprisingly causes the effective cell radius to drop but still extends the cell radius of the source.

6.2 Future Work

In this thesis we haven't considered quite a few areas which become a necessity when it comes to implementing the cooperative relaying methods in a cellular system. With the intention of serving the emergency service models, one of the open research area is the study of relay assisted cellular architecture when the relay terminal is on the move mounted on an emergency vehicle. Another important area for consideration in future work would be including the accurate channel estimations where relay protocols

like decode and forward (DAF) and receiver combining techniques like maximal ratio combining (MRC) could achieve higher diversity order. Other open research areas are using more relays for forwarding the signal to destination in a given cell and hence the requirement of an efficient routing algorithm, power allocation algorithms and scheduling algorithms.

REFERENCES

[1] Tse, D. and P. Viswanath Fundamentals of wireless communication. New York, NY, USA, Cambridge University Press, 2005.

[2] Laneman, J. N., D. N. C. Tse and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," IEEE Transactions on Information Theory, vol. 50, no. 12, pp. 3062-3080, December 2004.

[3] Abrar, M., X. Gui, A. Punchihewa, S. Khan and M. Iqbal, "Cooperative diversity versus antenna diversity in wireless communication systems", New Trends in Information Science and Service Science (NISS), 4th International Conference, pp. 260-263, May 2010.

[4] Schein, B. and R. Gallager, "The Gaussian parallel relay network," in Proceedings. IEEE International Symposium on Information Theory, Italy, p. 22, June 2000.

[5] Laneman, J. N., G. W. Wornell, and D. N. C. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in Proceedings. IEEE International Symposium on Information Theory, Washington, DC, p. 294, June 2001.

[6] Schwartz, M., W. R. Bennett, and S. Stein, Communications Systems and Techniques, New York, McGraw-Hill, 1966.

[7] Brennan, D. G., "Linear diversity combining techniques," Proceedings of the IRE , vol.47, no.6, pp.1075-1102, June 1959

[8] Andreas F. Molisch, Wireless Communications - 2nd Edition, Fellow, IEEE, University of Southern California, USA, 2010.

[9] Luo, J., R. S. Blum, L. J. Greenstein, L. J. Cimini and A. M. Haimovich, "New approaches for cooperative use of multiple antennas in ad hoc wireless

networks," Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th, vol.4, pp.2769-2773, 26-29 Sept. 2004

[10] Chu, S., X. Wang and Y. Yang , "Exploiting cooperative relay for high performance communications in MIMO ad hoc networks," Computers, IEEE Transactions on, vol.62, no.4, pp.716-729, April 2013

[11] Sharma, S., S. Yi, Y. T. Hou, and S. Kompella, "An optimal algorithm for relay node assignment in cooperative ad hoc networks," Networking, IEEE/ACM Transactions on, vol.19, no.3, pp.879-892, June 2011

[12] Xie, F., H. Tian, P. Zhang, N. Yang, "Cooperative routing strategies in ad hoc networks," Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st, vol.4, pp.2509-2512, 30 May-1 June 2005

[13] Yan, C., G. Ynu , P. Qiu and Z. Zhang, "Power-aware cooperative relay selection strategies in wireless ad hoc networks," Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on, pp.1-5, 11-14 Sept. 2006

[14] Yanikomeroglu, H., "Fixed and mobile relaying technologies for cellular networks," Second Workshop on Applications and Services in Wireless Networks, Paris, France, pp. 75-81, 3–5 July 2002.

[15] H. Wu et al., "Integrated cellular and ad hoc relaying systems: iCAR." IEEE JSAC, vol. 19, no. 10, pp. 2105–15, October 2001.

[16] Steele, R., "Towards a high-capacity digital cellular mobile radio system," Communications, Radar and Signal Processing, IEE Proceedings F , vol.132, no.5, pp.405-415, August 1985.

[17] Neonakis Agglou, G. and R. Tafazolli, "On the relaying capability of next-generation GSM cellular networks," IEEE Pers. Commun., vol. 8, no. 1, pp. 40-47, February 2001.

[18] Yang, Y., H. Hu, J. Xu and G. Mao, "Relay technologies for WiMAX and LTEAdvanced mobile systems," in IEEE Communications Magazine, vol. 47, pp. 100-105, October 2009.

[19] Bernardin, P., M. Yee and T. Ellis, "Estimating the range to cell edge from signal strength measurements", IEEE Vehicular Technology Conference, VTC-97, Phoenix, 1997.

[20] Bernardin, P., "Cell radius inaccuracy: A measure of coverage reliability", IEEE Transactions on Vehicular Technology, vol. 47, no. 4, pp. 1215-1226, November 1998.

[21] Rappaport, T. S., Wireless Communications: Principles and Practice, Prentice Hall Communications Engineering and Emerging Technologies Series, 1999.

[22] Liu, K., A. Sadek, W. Su and A. Kwasinski, Cooperative Communications and Networking, Cambridge University Press, 2009.

VITA

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