

COOPERATIVE WIRELESS RELAY NETWORKS AND THE IMPACT OF FADE
DURATION

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DOCTOR OF PHILOSOPHY

by
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DURATION

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University of Missouri–Kansas City, 2020

ABSTRACT

In wireless communication networks, the Key Performance Indicator (KPI) parameters are mostly based on the average signal-to-noise ratio (SNR). Other parameters such as site selection during call initiation, handoff, relay selection etc., are all SNR based. SNR has been commonly used as a benchmark and has masked the real picture of the wireless network. In some instances, it might be misleading. This is mainly due to the fact that rapid fluctuation of the signal (i.e., fading) is not taken into account in the selection criteria. Such rapid signal change may cause significant loss of information, degrade signal quality for voice or video connections, or could make the channel coding fail. An alternative method to using SNR in a wireless network is to consider fading. Such parameters include average fade duration (AFD) and fade duration outage probability (FDOP), which are based on time correlation statistics. Both the AFD and the FDOP are computed in reference to a threshold value for signal quality. The main purpose of this dissertation

work is to apply FDOP and AFD in broad wireless network applications and show that such methods need to be used in 5G and beyond wireless communication. The specific applications that are studied are cooperative relaying, neighbor cell list, and femtocell sleep mode activation. In all of those applications, the use of fade duration is novel. Because fade duration methods more accurately control the fading nature and the true quality of the signal, its application is vital to get the true nature of quality of service performance in wireless communication networks.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the Graduate Studies, have examined a dissertation titled “Cooperative Wireless Relay Networks and the Impact of Fade Duration,” presented by Aklilu Assefa Gebremichail, candidate for the Doctor of Philosophy degree, and hereby certify that in their opinion it is worthy of acceptance.

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DEDICATION

This dissertation/thesis is dedicated to my Dad who passed away in March 2019. He supported me in all aspects to reach to this level, but unfortunately, he was not able to witness this moment. Special gratitude to my Mom for her love and support all day every day. I would like to thank my two boys, Jonathan and Nathan Aklilu for their support and understanding during my study. Finally, I would like pay special tribute to my lovely family for their support and unconditional love throughout my study.

CHAPTER 1

INTRODUCTION

The wireless cellular communication system has evolved over the last few decades from less efficient, lower speed to a higher data rate, broadband network system. It appears that a new wireless system has emerged roughly every 10 years.

In the wireless network, the received signal is highly influenced by reflection, refraction, and scattering. Such phenomena create a variation in the phase and amplitude of the multipath signal. The relative movement of user equipment (UE) towards the base station (BS) creates a shift in the carrier frequency of the received signal which is called the Doppler shift. These two phenomena (multipath and Doppler shift) make the received signal unstable and fluctuate which leads to fading. Consider Figure 1 [9, Fig. 4.1]. This shows signal strength at different transmitter-receiver separations. The smoother curve shows how average signal strength and resulting signal-to-noise ratio (SNR) gradually changes with distance. The actual signal strength, however, is illustrated by the curve that rapidly fluctuates. If acceptable signal strength were required to be more than -50 dBm, we can see several locations of sharp signal drops and rebounds. Below such a level the signal would be considered unusable (an "outage"). While the dips look to be very short lived, they can actually be quite long relative to a high rate signal. Deep fading conditions are fairly brief, but from the perspective of high-speed data transmission even brief outage periods can cause loss of large amounts of data. They can also be quite long relative to

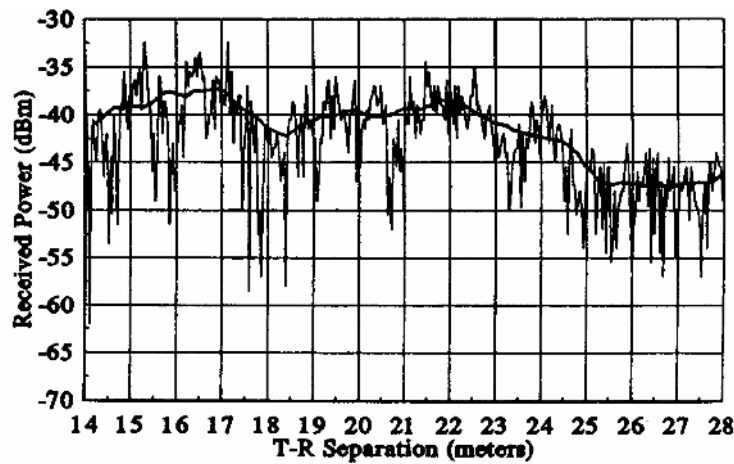


Figure 1: Small-scale and Large-scale Fading [9]

certain applications. For example, a 30 msec. fade duration is considered unacceptable for professional live audio productions [8]. The rapid signal fluctuations during fading may cause significant loss of information, substantially degrade voice or video coding, or could make error control coding fail.

Different models such as Rayleigh, Nakagami, and Rician could be used to analyze the multipath signal. In this research, the Rayleigh fading model is applied due to the assumption that commonly there is weak or no line-of-sight between the BS and the UE. The fundamental understanding of Rayleigh fading and channel variation characteristics was studied by Rice [10] of Bell Laboratory in the 1940s. His work provides the fundamental idea of Rayleigh fading and channel characteristics. Mandayam [11] [12] incorporated Rice's work from the data "outage" point of view, where during a deep fade the signal is in an outage condition and effectively no data is being transferred.

To overcome the bandwidth shortage and provide a reliable, low latency, high - speed mobile network, 5G started being deployed by major United States carriers in 2019

by focusing wireless communication networks onto "things". Evolved from 4G wireless systems, 5G provides high-speed broadband services. However, the main architecture of wireless cellular communication since its early generation remains base station centric. The UE always connects to the nearby BS inside the cell. The quality of service (QoS) inside the cell varies due to shadowing, rapid fluctuation of the signal (fading), or channel attenuation when approaching the cell boundaries.

In a situation where the direct link between BS and the UE is weak or obscured, the use of a cooperative wireless network connection in the form of a relay becomes very important. Such a method is a promising way of providing uninterruptible high-speed data service. Its application has been standardized since 3GPP Release 10. The relay station for relaying the incoming radio signal comes into main categories of amplify-and-forward (AF) and decode-and-forward (DF). The AF had widespread use mainly in 2G and 3G to extend coverage as a repeater, whereas the DF relays are deployed in 4G and beyond as a form of mini-macro cell, femtocell, picocell or magic box. The main advantage of using DF over AF is to suppress the noise by decoding the signal, then retransmitting and amplifying the main signal.

In cooperative relaying, the selection of relays could be based on different parameters. Most of the previous works [1] and [2] on the selection of relays were based on using the SNR as the main metric. Using SNR does not provide the overall picture of the channel behavior, however. Considering the rapid fluctuation of the received signal due to fading provides a better understanding of the channel behavior. An alternative method

of relay selection in a cooperative relay network is by considering fading. Fading metrics include average fade duration (AFD) and fade duration outage probability (FDOP), which are based on time correlation statistics. Both the AFD and the FDOP are computed in reference to a threshold value for signal quality. Because fade duration methods more accurately control the fading nature and true quality of the signals, such a relay selection method could be applicable in 4G and 5G.

In a dense femtocell network, beyond co-tier and cross-tier interference mitigation handover femtocell-femtocell and macrocell-femtocell is a major challenge. To perform successful handover, avoiding the scanning of a large neighbor list and shortening the handover period, FDOP based selection is a very promising method. It identifies the optimal number of neighbors and could apply for open and hybrid femtocells.

Current wireless technology is moving towards small and dense cells to provide high speed, low latency, and less prone to errors. One instance of such service is a dense femtocell network. It provides an efficient and low-cost solution to respond to high traffic demand. When a densely deployed femtocell network is underutilized during low traffic load this creates interference among registered and unregistered users. The FDOP could be used in sleep mode initiation during the times when the network is underutilized.

The main focus of this dissertation is to base the formation of cooperative relay and femtocell networks on considerations of outage conditions caused by fading. The main contributions of this dissertation work are as follows.

1. Formulation of Fade Duration Outage Probability (FDOP), average fade duration (AFD), and SNR-based relay selection.

2. Derivation of closed-form expressions of cooperative relay performance among relay pairs through one or two hop relay paths.
3. Derivation of optimal cooperative relay selection among relay pairs through one or two hop relay paths.
4. Comparison of the results by using comprehensive optimization and simulation.
5. Development and formulation of the use of relays in 4G and beyond to improve the QoS.
6. Application of FDOP on neighbor cell list selection.
7. Application of FDOP on power saving in dense femtocell networks.

CHAPTER 2

MULTI-HOP RELAY SELECTION BASED ON FADE DURATIONS

2.1 Introduction

The desire of mobile users for high quality wireless connections imposes tremendous pressure on a wireless service provider to improve the service quality. The traffic requirements of mobile users are also becoming prominent and the requirements of such users are increasing rapidly. To respond to such requirements and to satisfy users, different methods have been applied. One such method that has been studied quite frequently and can be applied for such applications is the use of the cooperative relay. From research that has been conducted in recent years and also from communication theory, the presence of a relay on a weak wireless link could improve quality of service (QoS) of the link. In typical circumstances, the relay overhears the source signal and forwards the data to the desired destination in case the direct link fails or to provide link diversity.

The cooperation among relays could use two, three or more hops and such cooperative relay protocol in effect establishes a virtual antenna array among geographically dispersed relays, even those that have been placed randomly. The selection of the best relay in cooperative wireless networks has been a topic of research for some time. Different relay selection methods have been proposed. For instance, in [1] the power and signal-to-noise ratio (SNR) auction method is proposed for power allocation and relay selection. In [2] it has been proved that a good channel condition determines the best selection of

dual hop relay. In [3] the relay selection problem using OFDM in a multi-access network for relay selection has been explored. The issue of fairness and data transmitting speed among relays is shown in [4]. In [5] a simplified form of single relay selection for decode and forward (DF) protocol has been studied. A two-stage strategy for relay selection to achieve the minimal outage probability was studied in [6]. In [7], a relay is selected to transfer an end to end signal only if it successfully decodes the source signal. Each relay stores information about the successfully decoded source signal.

The unpredictable behavior of the channel gain due to Rayleigh fading and its implications on the performance of the cooperative relay network needs to be more fully studied. Previous works on selection of relays have placed little emphasis on the fade duration as a relay selection criteria. This is unfortunate because fade duration may have the biggest effect on user experience and the performance of channel and source coding. Long fade durations can cause enough packet drops to noticeably degrade audio and video streaming. One study [8] has shown a duration of longer than 30 ms causes significant problems with professional live audio performances. Long fades can also cause channel coding schemes to fail, resulting in groups of dropped packets since channel coding cannot handle too long a burst of errors. Therefore, this chapter focuses on this issue to make use of fade duration to find the best relay selection decisions. In this chapter, relay selection based on the average fade duration (AFD) over Rayleigh faded channels is presented. Paths are found for two hop and three hop cooperative wireless relay networks. The selection method is based on the analysis of the second order statistics for level crossing rate (LCR) and AFD over multiple relay hops. We derive the closed form expression of

AFD over a DF cooperative network. We also consider the selection of relays and a relay path based on the fade duration outage probability (FDOP), which is the probability that a fade duration would exceed a given time duration threshold.

Some of the contributions of this chapter are as follows.

1. Proposal of cooperative relay techniques among source and destination pairs through one or two designated relays (i.e, two or three hop relay paths) to improve the received signal. The three hop path is more costly to the network (which we emulate through a cost penalty), but it can produce a better QoS.
2. Usage of the fade duration outage probability (FDOP) technique to analyze the quality of each end-to-end path and to apply the optimization method to select a designated relay.
3. Proposal of relay selection based on the average fade duration (AFD) method.
4. Simulation study for comparing relay selection with the traditional SNR method versus our fade duration methods. SNR based optimization frequently chooses different relay paths, as low as only 63% of the same relay paths as FDOP or AFD optimizations. Since the fade duration approach more accurately reflects the true quality of a signal, this work shows the value of moving away from SNR methods to fade duration methods.

The article is presented in four parts. In Section 2.2, the system model is presented. Section 2.3 discusses threshold based relay selection for two and three hop cooperative relay networks. Section 2.4 provides validation through optimization, simulation, and

numerical analysis. Section 2.5 provides real-world practical application of the concepts of this chapter. Section 2.6 provides final conclusions.

2.2 System Model

Cellular wireless networks allocate orthogonal divided channels to transmitting terminals. Due to insufficient isolation between TX and RX, a full-duplex system is not considered in this chapter, but rather a half-duplex allocation.

The channel model for the cooperative relay network is characterized by using time division notation where S_t , R_t and D_t represent the source, the relay, and the destination terminals. In this chapter, we study the up/down communication among the source/destination pairs through the designated relay. As depicted in Figure 2, we consider that relays are deployed randomly between the source and destination. The main purpose of the relay is to enhance source nodes' capacity through source-relay cooperation.

At a given time, relay cooperation is possible if there exists a relay that is capable of retransmitting data from the source and able to transfer to the final destination. The designated relay will be able to help receive the source signal. As shown, the system model is composed of a two hop and three hop cooperative relay system that consists of the source (S), relay (R), and the destination (D). The network contains S sources and R relays. The model is based on the DF protocol over the half-duplex sub-channel of S-R-D for two hop and S- R_x - R_y -D for a three hop relay cooperative network. There is an assumption that the direct link between the source and the destination is weak and

each sub-channel experiences independent, flat, frequency non-selective Rayleigh fading. The fading is assumed to have the same stochastic characteristics within each time slot. For a two hop network, the time slot is subdivided into two sub-time slots. In the first time sub-slot, S transmits while R and D listen, and in the second sub-slot R transmits and D listens. An important part of this work is consideration of the three hop relay network. A simple example illustrates. Suppose there are two sources, S_1 and S_2 , and two relays, R_1 and R_2 . Moreover, suppose the link from R_1 to the destination is very poor. In a two hop relay network, the sources would send to the relays in the first sub-time slot and then each relay would send to the destination in the second sub-time slot. The data from R_1 to destination would be severely degraded or lost. In a three hop case, however, relay R_2 could send data from one source in the second sub-time slot, say using the path S_1-R_2-D . Moreover, in the third sub-time slot would send data from the other source using path $S_2-R_1-R_2-D$. The three hop path option provides more opportunity for good communication. It does, however, require the network to use the third sub-time slot, which is a cost to the network; this cost is incorporated into the models in this work.

In this chapter the signal transfer can be chosen to either use a single relay or multiple relays, based on the optimum path that is found, based on AFD, FDOP, or SNR. These include the paths which minimize the sum of total path AFDs, maximize the sum of total path SNRs, minimize the sum of total path FDOPs, minimize the maximum link AFDs on a path, maximize the minimum link SNRs on a path, or minimize the maximum link FDOPs on a path.

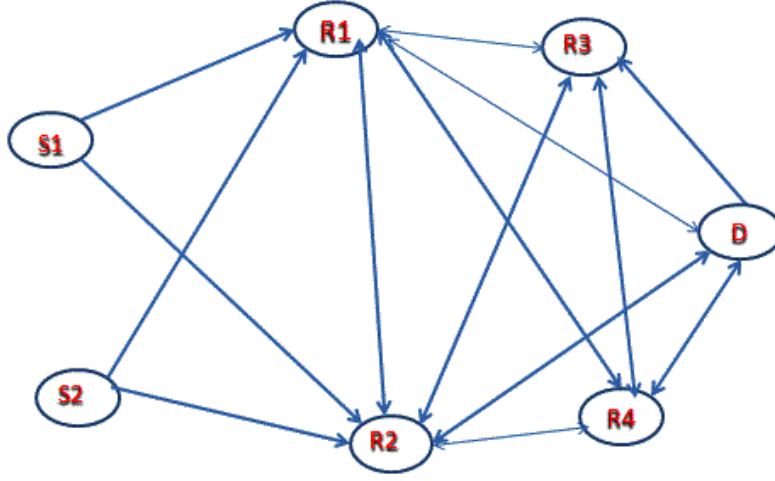


Figure 2: Two and three hop relay model

2.2.1 Direct Transmission

For direct transmission the channel can be modeled as

$$D_r[n] = h_{s,d}X_s[n] + n_d[n] \quad (2.1)$$

The mutual information for the direct transmission by independent identical distribution zero mean Gaussian distributions is described as

$$R = I_{DT} = \log_2 (1 + SNR|h_{s,d}|^2) \quad (2.2)$$

where $|h_{s,d}|$ is the channel gain on the source-destination link. In terms of $|h_{s,d}|$ and the fading coefficient for spectral efficiency R , the outage event occurs when $I_{DT} \leq R_{thr}$, for the direct transmission the outage in terms of channel gain is given as

Replacing SNR with the received signal and noise powers; the above equation can be represented as:

$$|h_{s,d}|^2 \leq (2^R - 1) \left(\frac{P_n}{P_s} \right) \quad (2.3)$$

For outage probability in Rayleigh fading, $|h_{s,d}|^2$ follows an exponential distribution with parameter $\sigma_{s,d}^2 = P_{s,d,avg}$ given by

$$P((I_{DT}) \leq I_0) = P((SNR) \leq (SNR_{th}) = 1 - \exp\left(-\frac{SNR_{th}P_n}{2\sigma_{s,d}^2}\right) \quad (2.4)$$

2.2.2 Two Hop Relay Network

In a single hop system, a relay is selected to transfer the received signal to the destination. The information per bit of the received signal is denoted by

$$I(t) = \frac{1}{2} \log_2(1 + SNR|H|^2) \quad (2.5)$$

where SNR and H represent signal to noise ratio and channel gain, respectively. Due to Rayleigh fading, the mutual information $I(t)$ may drop below a certain level. Assuming the minimum acceptable spectral efficiency to be I_o then

$$I(t) = \frac{1}{2} \log_2(1 + SNR|H|^2) \geq I_o \quad (2.6)$$

The received signal will be decoded successfully as the mutual information exceeds I_o . The channel amplitude can be represented in terms of $I_o(R_o)$ as

$$|H| = \sqrt{\frac{2^{2I_o} - 1}{SNR}} \quad (2.7)$$

2.2.2.1 AFD Based Analysis

An outage occurs with probability $P_r(R \leq R_o)$. During such event the received signal amplitude R crosses the threshold value R_o and the number of times the crossing occurs per unit time determines the level crossing rate (LCR) . The average fade duration

(AFD) depends on the LCR value. The channel gain $H(t)$ is a random process and the probability a going and staying below the threshold value of R_o is determined by the time correlation as captured by the LCR and the AFD. The AFD is the average time the received signal remains below R_o and is defined as [9]

$$AFD = \frac{P_r(R \leq R_o)}{LCR} \quad (2.8)$$

where LCR as a function of R_o is determined by the Rice equation as given by [10], equation (2.5):

$$LCR = L(R_o) = \int_0^\infty \dot{r}p(R_o, \dot{r})d\dot{r} = \int_0^\infty \dot{r}K_{R_o r}(R_o, \dot{r})d\dot{r} \quad (2.9)$$

Now we derive the fade duration equation for multiple links. The two links between source to relay and relay to destination are represented as $Q(t)$ and $S(t)$, respectively, are each distributed according to the Rayleigh PDF as

$$f_a(r) = \frac{2r}{\Omega_a} \exp\left(-\frac{r^2}{\Omega_a}\right) \quad (2.10)$$

The cumulative distribution function CDF for $P_r(a \leq r)$ is obtained as $1 - \exp(-\frac{r^2}{\Omega_a})$ where for link $Q(t)$. The value of Ω_q could be obtained as

$$\Omega_q = E[q^2] = \int_0^\infty r^2 p(r) dr = 2\sigma_q^2 \quad (2.11)$$

and $\Omega_s = E[s^2]$ where Ω_s is denoted as the average squared amplitude or the average power. In terms of R_o , the probability that one of the links is below the threshold value (hence the two hop amplitude R is below R_o) is given by

$$P_r(R \leq R_o) = 1 - P_r(Q \geq R_o)P_r(S \geq R_o) \quad (2.12)$$

From the Rayleigh fading calculation

$$P_r(Q \geq R_o) = \exp\left(\frac{-R_o^2}{\Omega_Q}\right) \quad (2.13)$$

and also

$$P_r(S \geq R_o) = \exp\left(\frac{-R_o^2}{\Omega_S}\right) \quad (2.14)$$

then

$$P_r(R \leq R_o) = 1 - \exp\left(\frac{-R_o^2}{\Omega_Q} + \frac{-R_o^2}{\Omega_S}\right) \quad (2.15)$$

If $\Omega_Q = \Omega_S$ happens to be true, Equation (2.16) can be simplified as

$$P_r(R \leq R_o) = 1 - \exp\left(\frac{-2R_o^2}{\Omega_s}\right) \quad (2.16)$$

From the Rice equation, the joint probability of R and \dot{r} is expressed as

$$K_{R_o\dot{r}}(R_o, \dot{r}) = K_{Q_o\dot{q}}P_r(Q(t) \geq R_o) + K_{S_o\dot{s}}P_r(S(t) \geq R_o) \quad (2.17)$$

where $K_{R_o\dot{r}}$ denotes the PDF of \dot{r} when \dot{r} is a time differentiation of R when it crosses the threshold value of R_o . Then applying Equation (2.17) to the Rice equation for the entire two hop relay network we obtain the LCR $L(R_o)$.

$$L(R_o) = L_Q(R_o)P_r(q(t) \geq R_o) + L_S(R_o)P_r(s(t) \geq R_o) \quad (2.18)$$

The LCR for individual links in terms of $R_o = Q_o = S_o$ as their respective thresholds is represented as

$$L(Q_o) = 2\pi f_q \rho \exp(-\rho^2) \quad (2.19)$$

$$L(S_o) = 2\pi f_s \rho \exp(-\rho^2) \quad (2.20)$$

where f_q and f_s denote the Doppler shift values for each link and ρ represents the value of R normalized to the RMS. $L_Q(R_o)$ is expressed in terms of the received signal as

$$L_Q(R_o) = 2\pi f_m \rho e^{-\rho^2} = \frac{R_o}{\Omega_Q} \sqrt{\frac{2\sigma_Q^2}{\pi}} \exp\left(\frac{-R_o^2}{\Omega_Q}\right) \quad (2.21)$$

Similarly, $L_S(R_o)$ can be expressed as

$$L_S(R_o) = 2\pi f_m \rho e^{-\rho^2} = \frac{R_o}{\Omega_S} \sqrt{\frac{2\sigma_S^2}{\pi}} \exp\left(\frac{-R_o^2}{\Omega_S}\right) \quad (2.22)$$

Rearranging Equation (2.19) using the above two equations where q and s links are identical yields

$$L(R_o) = \frac{R_o}{\Omega_Q} \exp\left(\frac{-2R_o^2}{\Omega_Q}\right) 2\sqrt{\frac{\Omega_Q}{\pi}} \quad (2.23)$$

Using Equations (22) and (23) and applying them to Equation (2.19), the AFD in Equation (2.9) can be formulated as

$$\frac{1 - \exp\left(\frac{-R_o^2}{\Omega_Q} + \frac{-R_o^2}{\Omega_S}\right)}{L(S_o)\exp\left(\frac{-R_o^2}{\Omega_S}\right) + L(Q_o)\exp\left(\frac{-R_o^2}{\Omega_Q}\right)}. \quad (2.24)$$

Thus Equation (2.25) represents the closed form of the average fade duration for path k over links q and s in a two hop cooperative relay network. The selection of the best relay easily relies on the value of the AFD value observed during the selection period.

If Ω_Q and Ω_S have similar values, the AFD in equation (2.25) can be simplified as

$$AFD_k = \frac{\sqrt{\Omega_Q \pi}}{2R_o} \left[\exp\left(\frac{2R_o^2}{\Omega_Q}\right) - 1 \right]. \quad (2.25)$$

2.2.2.2 SNR Based Analysis

The outage probability for Rayleigh fading occurs when the probability of the mutual information is below a certain rate I_0 .

$$P((I_{df}) \leq R_0) = P((SNR) \leq SNR_{th}) = P_r(|h_{s,d}|^2 \cap |h_{r,d}|^2) \leq F(SNR) \cap P_r|h_{s,r}|^2 \leq \frac{(2^{2R} - 1)}{SNR_{th}} \quad (2.26)$$

where

$$F(SNR) = \frac{(2^{2R} - 1)}{SNR} \quad (2.27)$$

In terms of SNR, the outage probability can be equally shown as

$$\min(SNR_{s,d}, SNR_{s,r}, SNR_{r,d}) \leq \frac{(2^{2R} - 1)}{|H^*|^2} \quad (2.28)$$

Assuming that on the S-D link there is no direct line of sight $SNR_{s,d} = 0$. Then for Rayleigh fading from equation (2.17)

$$P_r(R \leq R_o) = P_r(|h_{s,r}|^2) \leq \left(\frac{2^{2R} - 1}{SNR} \right) = 1 - \exp \left[\left(\frac{2^{2R} - 1}{SNR} \right) \left(\frac{1}{\Omega_s} \right) \right] \quad (2.29)$$

and also

$$P_r(R \leq R_o) = P_r(|h_{r,d}|^2) \leq \left(\frac{2^{2R} - 1}{SNR} \right) = 1 - \exp \left[\left(\frac{2^{2R} - 1}{SNR} \right) \left(\frac{1}{\Omega_r} \right) \right] \quad (2.30)$$

resolving the above equations for the two hop relay path yields

$$P_r(R \leq R_o) = P_r(|h_{r,d}|^2) \leq \left(\frac{2^{2R} - 1}{SNR} \right) = 1 - \exp \left[\left(\frac{2^{2R} - 1}{SNR} \right) \left(\frac{1}{\Omega_r \Omega_s} \right) \right] \quad (2.31)$$

2.2.3 Three Hop Relay Network

2.2.3.1 AFD Based Analysis

Referring to Figure 2, the three hop relay path has three links in order to reach the final destination. If two relays are involved, the time slots to get from the source to the destination consists of three sub-time slots. In the first sub-time slot, the source sends the data to the relay and destination, and in the remaining two sub-time slots the selected two relays use those sub-time slots to reach to the destination. Therefore the information is expressed as $|H| = \sqrt{\frac{2^{3I_o}-1}{SNR}}$. The probability that R on any given link will be less than the threshold value, R_o , is given by

$$P_r(R \leq R_o) = 1 - P_r(P \geq R_o)P_r(Q \geq R_o)P_r(S \geq R_o) \quad (2.32)$$

If $\Omega_Q = \Omega_S = \Omega_P$, similar to equation (2.17), Equation (2.33) simplifies as

$$P_r(R \leq R_o) = 1 - \exp\left(\frac{-3R_o^2}{\Omega_s}\right) \quad (2.33)$$

The LCR for $L_Q(R_o)$, $L_R(R_o)$ $L_S(R_o)$ is expressed as

$$L_P(R_o) = 2\pi f_m \rho \cdot e^{-\rho^2} = \frac{R_o}{\Omega_P} \sqrt{\frac{2\sigma_P^2}{\pi}} \exp\left(\frac{-R_o^2}{\Omega_P}\right) \quad (2.34)$$

$$L_Q(R_o) = 2\pi f_m \rho \cdot e^{-\rho^2} = \frac{R_o}{\Omega_Q} \sqrt{\frac{2\sigma_Q^2}{\pi}} \exp\left(\frac{-R_o^2}{\Omega_Q}\right) \quad (2.35)$$

$$L_S(R_o) = 2\pi f_m \rho \cdot e^{-\rho^2} = \frac{R_o}{\Omega_S} \sqrt{\frac{2\sigma_S^2}{\pi}} \exp\left(\frac{-R_o^2}{\Omega_S}\right) \quad (2.36)$$

From there the three hop relay AFD can be formulated as

$$\frac{1 - \exp\left(\frac{-R_o^2}{\Omega_P} + \frac{-R_o^2}{\Omega_Q} + \frac{-R_o^2}{\Omega_S}\right)}{L(P_o)\exp\left(\frac{-R_o^2}{\Omega_P}\right) + L(Q_o)\exp\left(\frac{-R_o^2}{\Omega_Q}\right) + L(S_o)\exp\left(\frac{-R_o^2}{\Omega_S}\right)} \quad (2.37)$$

To select the best relay for a three hop cooperative network, the closed-form of Equation (2.38) could be applied.

If $\Omega_P = \Omega_Q = \Omega_S$, and applying equation (2.19) for the three hop relay, yields

$$L(R_o) = \frac{R_o}{\Omega_Q} 3 \sqrt{\frac{2\sigma_Q^2}{\pi}} \exp\left(\frac{-3R_o^2}{\Omega_Q}\right) \quad (2.38)$$

$$\Omega_Q = \int_0^\infty r^2 p(r) dr = 2\sigma_Q^2 \quad (2.39)$$

In this case, the closed form of AFD can be simplified as

$$AFD_k = \frac{\sqrt{\Omega_Q \pi}}{3R_o} \left[\exp\left(\frac{3R_o^2}{\Omega_Q}\right) - 1 \right] \quad (2.40)$$

2.2.3.2 SNR Based Analysis

In a three hop relay network as shown in Figure 2, the data received from the source can be represented in terms of the channel gain as

$$r[n] = h_{s,r} X_s[n] + n_d[n] \quad (2.41)$$

$$d[n] = h_{s,d} X_s[n] + n_d[n] \quad (2.42)$$

whereas in the second time slot the data received at the second relay and the destination can be denoted as

$$d[n] = h_{r,d} r[n] + n_d[n] \quad (2.43)$$

In the third time slot the relay that detects the signal from the other relay transmits to the destination. Then

$$I_D = \frac{1}{3} \min[\log_2(1+SNR|h_{s,r}|^2), \log_2(1+SNR|h_{r_x}, h_{r_y}|^2), \log_2(1+SNR|h_{r_y}, d|^2+|h_{s,d}|^2)] \quad (2.44)$$

The outage occurs when

$$P(I_{df} \leq I_0) = P((SNR) \leq SNR_{th}) = (P_r|h_{r,d}|^2 \leq F_{SNR}) \cap (P_r|h_{s,r}|^2 \geq F_{SNR}) \quad (2.45)$$

Here , we are assuming that S-D link unreachable and no direct line of sight. Then the outage can be computed as

$$P\{\min(|h_{s,r}|^2, |h_{r_x,r_x}|^2, |h_{r_y,d}|^2 + |h_{s,d}|^2) \leq R_0\} \quad (2.46)$$

since there is no direct link then $SNR_{s,d} = 0$. For the source–relay link

$$P_r(R \leq R_o) = P_r(|h_{s,r}|^2) \leq \left(\frac{2^{2R} - 1}{SNR}\right) = 1 - \exp\left[\left(\frac{2^{2R} - 1}{SNR}\right) \left(\frac{1}{\Omega_s}\right)\right] \quad (2.47)$$

for r_x, r_y link

$$P_r(R \leq R_o) = P_r(|h_{r_x,r_x}|^2) \leq \left(\frac{2^{2R} - 1}{SNR}\right) = 1 - \exp\left[\left(\frac{2^{2R} - 1}{SNR}\right) \left(\frac{1}{\Omega_x}\right)\right] \quad (2.48)$$

and to the destination

$$P_r(R \leq R_o) = P_r(|h_{r,d}|^2) \leq \left(\frac{2^{2R} - 1}{SNR}\right) = 1 - \exp\left[\left(\frac{2^{2R} - 1}{SNR}\right) \left(\frac{1}{\Omega_r}\right)\right] \quad (2.49)$$

Considering three hop relay for the equation above and resolving for link S-R1, R1-R2, R2-D yields

$$= 1 - \exp\left[\left(\frac{2^{2R} - 1}{SNR}\right) \left(\frac{1}{\Omega_r} \frac{1}{\Omega_s} \frac{1}{\Omega_z}\right)\right] \quad (2.50)$$

2.2.4 Fade Duration Outage Probability

Due to Rayleigh fading, the received signal is usually affected by how long it remains in a fading dip. While the received signal remains in a fading dip, an ‘outage’

occurs. To select a relay based on the frequency of dips and to minimize outages, it is important to compute fade duration outage probability (FDOP), and ensure the FDOP \leq $FDOP_{thr}$. The amount of time the signal remains in a fading dip characterizes its quality. The longer it remains in a fading dip the more distorted the signal will be.

The fade duration outage probability (FDOP) is based on several works including the initial work on the fade duration distribution (FDD) by Rice in [10]. Subsequent efforts extended this work include [11], where Mandayam, Chen, Holtzman derived asymptotic approximations for FDD to determine what they call the minimum duration outage. We believe the term fade duration outage probability is a better understood name. This was extended by Lai and Mandayam [12] and simplified by Nadarajah and Kotz [13]. More recently, Ohmann and Fettweis showed interest in fade duration outages in [14] by approximating FDD models using an exponential model, making it tractable and manageable to include multiple links. References [15–23] provide other foundational contributions in cooperative relaying.

The probability that the amplitude of a received signal remains below the threshold value R_0 for more than τ_m is denoted by Rice's asymptotic approximation in [10]

$$P_{\tau_f}(\tau_m \geq \tau) = \frac{2}{x} I_1 \left(\frac{2}{\pi x^2} \right) \exp \left(-\frac{2}{\pi x^2} \right) \quad (2.51)$$

where I_1 is a modified Bessel function order one. The PDF of the fade duration can be obtained as shown in ([12], Equation (18)) as:

$$= -\frac{1}{\tau_f} \frac{d}{dx} \left[\frac{2}{x} I_1 \left(\frac{2}{\pi x^2} \right) \exp \left(-\frac{2}{\pi x^2} \right) \right] \quad (2.52)$$

where $x = \tau_m / AFD$, the PDF of the outage duration can be denoted for $(\tau_{out} \geq \tau_m)$.

As shown in [12] Equation (19)

$$f_{\tau_{\text{out}}}(\tau_{\text{out}}) = \frac{f_{\tau_f}(\tau_{\text{out}})}{P_{\tau_f}(\tau_f \geq \tau_m)} \quad (2.53)$$

The fade duration outage probability is computed as

$$FDOP = R_{\text{out}} \cdot T_{\text{out}} \quad (2.54)$$

where as R_{out} is the outage rate. After putting all the components together and simplifying, the FDOP can be finally denoted as (this is from [13], Equation (6), and our own simplifications)

$$(L)(A) \left\{ \exp\left(-\frac{2}{\pi x^2}\right) \left[I_1\left(\frac{2}{\pi x^2}\right) - I_0\left(-\frac{2}{\pi x^2}\right) \right] + 1 \right\} \quad (2.55)$$

where

$$L = LCR = \sqrt{2\pi} f_m \rho e^{-\rho^2} \quad (2.56)$$

$$A = AFD = \frac{e^{\rho^2} - 1}{\sqrt{2\pi} f_m \rho} \quad (2.57)$$

To determine the relay path with minimum fade duration outage probability for a particular source relay path, it is important to compute the fade duration outage probability of each relay path and select the minimum FDOP for each source relay path. The issue gets more challenging and complicated as the number of involved relays and sources gets bigger. To deal with such challenging issue and to obtain an optimal solution, we propose two optimization methods of relay selection based on FDOP. The analysis and the selection criteria along with AFD and SNR methods is shown in Section 2.3.

2.3 Optimal AFD/SNR/FDOP Threshold Based Relay Selection

In an effort to study the value and comparisons between fade duration based (either AFD or FDOP) and SNR based selection methods, we have conducted the following research. First of all, we devise several optimization approaches that would choose the best sets of relays. These are link-by-link and path based approaches that use SNR, AFD, and FDOP. Then we conduct extensive simulations to see when and where AFD, FDOP, and SNR optimizations choose the best paths. Of particular interest are cases when relay path choices are different. Since we assert that fade duration approaches approximate user expectations more effectively, we see that SNR approaches fail to choose the same paths as FDOP and AFD methods in several situations, resulting in lower performance. Such optimizations, however, would likely only be used in limited situations due to their computational complexity. As we conclude the chapter, we present methodologies for implementation of relay selection in today's coming 5G networks. In real situations, the number of available relays would not be very large. Individual sources would seek out possible macro cell and relays path using fade duration based metrics.

The traffic demand and the maximum allowable data loss that can be tolerable during wireless communication differs from one application to the other. For instance, a video signal will lose the picture synchronization if the data loss is more than a certain number of frames. During deep Rayleigh fading, as the length of the fade duration becomes longer and deeper, the more data gets lost before reaching the BS. Such loss will be hard to recover. To avoid such issues, relay selection based on the AFD and FDOP is proposed. To better correlate with quality of service for real applications, we also compare

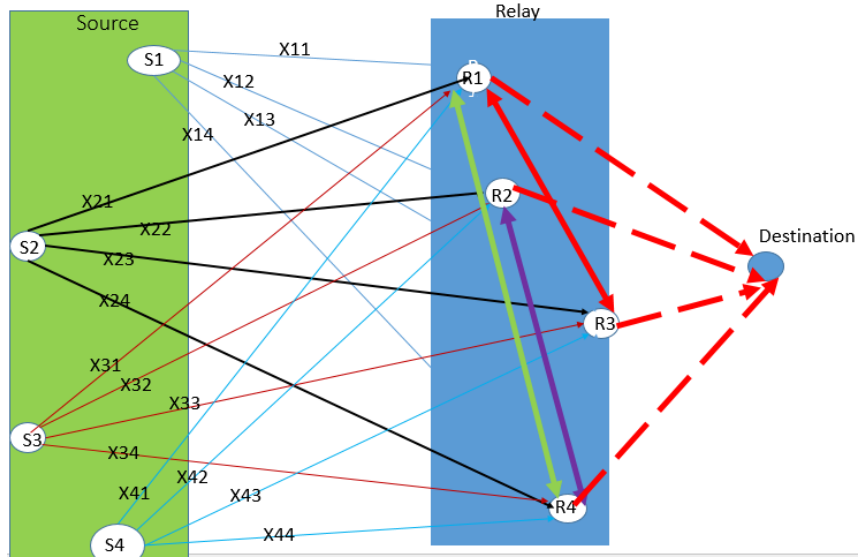


Figure 3: Two and three hop optimization network model.

with SNR based relay selection to see where SNR based relay selection would choose relay paths with worse AFD and FDOP performance.

As seen in Figure 3, the selection process needs to determine which relay path performs better in order to satisfy the selection criteria. The cooperative relay selection problem has been formulated to facilitate the best relay selection among R available relays for S number of sources. To determine the best relay choices, two different path selection methods are formulated, which are path-by-path (total path) and link-by-link optimization. In the former, we compute the total path metrics and find the best combination of paths. In the latter, we compute metrics for each link and then use max–min or min–max formulations to find the best paths.

2.3.1 Path-by-Path (Total Path) Optimization

2.3.1.1 AFD Based Optimization

The AFD based optimization method selects the best path on the basis of the AFD value. The path with the least AFD value exhibits less loss of data and a strong source signal reaches the final destination. In this type of optimization, the end-to-end optimization computes the path with the least sum of the AFD values for all of the paths to be the best paths for end to end connections.

To determine the AFD value, we apply the derived closed forms of AFD as shown in Equations (2.25) and (2.38). AFD_{jil} represents AFD for source j , first relay i , and last relay l . If $i = l$, only one relay is used. P_l represents the penalty value to the three hop path network for using an extra time slot in comparison to the two hop relay network. No penalty is imposed on a two hop relay. Penalty values are examined extensively in the simulations.

The optimization can be formulated as

$$\min\left(\sum_{j=1}^S \sum_{i=1}^R \sum_{l=1}^R AFD_{jil} X_{jil} P_l\right) \quad (2.58)$$

subject to

$$\sum_{i=1}^R \sum_{l=1}^R X_{jil} = 1 \quad \forall j = 1, 2, 3 \dots S \quad (2.59)$$

$$\sum_{j=1}^S \sum_{l=1}^R X_{jil} \leq 1 \quad \forall i = 1, 2, 3 \dots R \quad (2.60)$$

$$\sum_{l=1, l \neq i}^R X_{jil} + X_{jii} = 1 \quad \forall i = 1, 2, \dots, R \quad (2.61)$$

$$X_{jil} + X_{jli} \leq 1 \quad \forall j, \forall i, \forall l, i \neq l \quad (2.62)$$

$$AFD_{jil} < AFD_{threshold} \quad (2.63)$$

where X_{jil} is a binary variable that indicates the path chosen. If $i = l$, then the path is from source j to relay i and then straight to the destination. Otherwise, l is the second relay. AFD_{jil} is computed from Equations (2.25) and (2.38).

Equation (2.58) is a linear programming optimization. Equation (2.59) states that one and only one source must be associated with only one relay. Equation (2.60) ensures the first relay i can only be used at most once. The relay selected could not be used by any other source in that particular time slot. Equation (2.61) ensures that a path goes from one relay to another relay or goes direct to the destination. A relay link is bidirectional and can only be used in one direction at a time, which is enforced by Equation (2.62). Equation (2.63) enforces that each link AFD value remain below the threshold value.

2.3.1.2 SNR based Optimization

This method the selection of relay to transfer the data from source to destination is based on the path with possible higher SNR than the remaining paths. The objective is to find the maximum sum of the SNRs for the chosen paths. This method is similar to the AFD selection method except in this method the highest sum of SNR values is selected whereas in the AFD selection method the path with minimum AFD value is preferred.

$$\max\left(\sum_{j=1}^N \sum_{i=1}^K \sum_{l=1}^K SNR_{jil} X_{jil} P_l\right) \quad (2.64)$$

subject to

$$SNR_{jil} > SNR_{threshold} \quad (2.65)$$

and equations (2.59) through (2.62). SNR_{jil} comes from equations (2.32) and (2.51).

2.3.1.3 FDOP Based Optimization

The main task of this optimization is to locate those relays that minimize the total sum of fade duration outage probabilities based on the following

$$\min\left(\sum_{j=1}^S \sum_{i=1}^R \sum_{l=1}^R FDOP_{jil} X_{jil} P_l\right) \quad (2.66)$$

subject to

$$FDOP_{jil} < FDOP_{thr} \quad (2.67)$$

and Equations (2.59) through (2.62). The total path FDOP is computed as follows for two or three relays.

$$FDOP_{jil} = 1 - (1 - FDOP_1)(1 - FDOP_2)(1 - FDOP_3) \approx FDOP_1 + FDOP_2 + FDOP_3 \quad (2.68)$$

The optimization shown above is a simple LP optimization where Equation (2.67) states that the FDOP also needs to be less than the threshold value $FDOP_{thr}$. The selection of a relay based on this criteria will minimize the outage rate and increase the performance of the cooperative relay network.

2.3.2 Link-by-Link Optimization

In these methods, the metrics are computed for each link and optimization occurs to find the best combinations of links.

2.3.2.1 AFD Based Optimization

In this method the AFD value of link by link (source–relay, relay–relay, relay–destination) is optimized and the min–max method is applied to select the best relay. In each scenario, the AFD value of each link should be below the threshold value to be considered as a potential path.

The objective is first to select the link with the maximum average fade duration from the source to the destination through each two hop or three hop relay path. Then select the min of the selected values to find the best path. The optimum solution

$$\min\{max[\sum_{j=1}^S \sum_{i=1}^R AFD_{ji}X_{ji}, \sum_{i=1}^R \sum_{l=1}^R AFD_{il}Y_{il}P_i, \sum_{i=1}^R \sum_{l=1}^R (AFD_{ld}Z_{il})]\} \quad (2.69)$$

subject to

$$\sum_{i=1}^R X_{ji} = 1 \quad \forall j = 1, 2, \dots, S \quad (2.70)$$

$$\sum_{j=1}^S X_{ji} \leq 1 \quad \forall i = 1, 2, \dots, R \quad (2.71)$$

$$\sum_{l=1, l \neq i}^R Y_{il} + Z_{ii} = 1 \quad \forall i = 1, 2, \dots, R \quad (2.72)$$

$$Y_{il} + Y_{li} \leq 1 \quad \forall i, \forall l, i \neq l \quad (2.73)$$

$$Y_{il} - Z_{il} = 0 \quad \forall i, \forall l, i \neq l \quad (2.74)$$

$$AFD_{ji}, AFD_{il}, AFD_{ld} < AFD_{threshold} \quad (2.75)$$

where X_{ji} is a binary variable that indicates the link from source j to relay i ; Y_{il} is a binary variable that indicates the link from relay i to relay l . If such a link is chosen, a penalty P_i is multiplied to that link AFD. Z_{il} is a binary variable that can

indicate either a link from relay i to relay l and then to the destination, or if $i = l$ a link directly from the relay to the destination without going to the second relay. Each AFD is computed from equation (2.9), AFD_{ji} from source to relay, AFD_{il} relay–relay, and AFD_{ld} to the destination.

In this linear programming optimization, Equations (2.71) and (2.72) state that each source will be served at least by one relay and each relay will be served from at most one source. From the relay, the packet must then go directly to the destination or to another relay, as enforced by Equation (2.72). A relay link is bidirectional and can only be used in one direction at a time, as in Equation (2.73). In Equation (2.74), once a relay–relay link is used then the packet goes to the destination. Equation (2.75) enforces that each link AFD value remain below the threshold value.

2.3.2.2 SNR Based Optimization

The SNR based optimization is similar to the above method with the exception of the objective function and the threshold value.

$$\max\left\{\min\left[\sum_{j=1}^S \sum_{i=1}^R SNR_{ji}X_{ji}, \sum_{i=1}^R \sum_{l=1}^R SNR_{il}Y_{il}P_i, \sum_{i=1}^R \sum_{l=1}^R SNR_{ld}Z_{il}\right]\right\} \quad (2.76)$$

subject to

$$SNR_{ji}, SNR_{il}, SNR_{ld} > SNR_{threshold} \quad (2.77)$$

and the same Equations (2.71) through (2.75). SNR optimization is a max–min optimization in this case.

2.3.2.3 FDOP Optimization Method

In case of FDOP based optimization, we use the following

$$\min\{\max[\sum_{j=1}^S \sum_{i=1}^R FDOP_{ji}X_{ji}, \sum_{i=1}^R \sum_{l=1}^R FDOP_{il}Y_{il}P_i, \sum_{l=1}^R \sum_{l=1}^R FDOP_{ld}Z_{jl}]\} \quad (2.78)$$

subject to

$$FDOP_{ji}, FDOP_{il}, FDOP_{ld} < FDOP_{threshold} \quad (2.79)$$

and again the same Equations (2.70) through (2.74). FDOP optimization is a min–max optimization.

2.4 Simulation Results

A series of simulations were conducted regarding the link-by-link min–max (AFD and FDOP) and max–min (SNR) optimizations. A 1000 by 1000 m area was used. The source nodes were uniformly randomly placed in the leftmost 400 by 1000 m area, relays in next 400 to 700 by 1000 m, and a single destination in the rightmost 700 to 1000 by 1000 m area. A Friis' pathloss model was used with pathloss exponent 3.0, carrier frequency 1.8 GHz, transmit power 40 dBm, omnidirectional transmit and receive antennas, and background noise of -90 dBm. AFD and FDOP simulations used maximum Doppler shift $f_m = 20$ Hz, minimum received power $R_0 = -90$ dBm (min SNR of 0 dB), and for FDOP maximum fade duration $\tau_m = 10$ ms.

2.4.1 Verification

The first step was to verify the correctness of the optimizations and simulations. Table 1 shows details of a two source and two relay simulation. The separate AFD, FDOP, and SNR tables show each parameter from source nodes to relays, between relay nodes, and from relays to the destination. The penalty parameters used were $P = 1.5$ for AFD and FDOP, and $P = 1/1.5 = 0.667$ for SNR. The logic of using these penalty choices was that a relay–relay transmission would add an extra timeslot to transmit to the destination, increasing from two to three slots.

The results show that all cases make use of a relay to relay transmission. Looking first at the AFD results, the maximum AFD for all links was the R1–D AFD of 0.001647. Therefore, both paths chose to use the R2–D link, with the S1–R1–R2–D path including a link between R1 and R2. Now let’s consider the effect of the penalty value. Since the relay–relay link had an AFD of 0.000673, the adjusted AFD including the penalty would be $1.5 \times 0.000673 = 0.001010$, less than the 0.001647. If however, a penalty of $P > 2.45$ were used, then the adjusted AFD would be $2.45 \times 0.000673 = 0.001648$, making the relay–relay link increase the objective of the min–max optimization. The optimization would then chose to use paths S1–R1–D and S2–R2–D, avoiding use of the relay–relay link. The FDOP results also avoided the R1–D link when using $P = 1.5$. For the FDOP case, for $P > 29.55$, the optimization avoids the relay–relay link, since the ratio between the R1–D link and the R1–R2 link is $0.003486/0.000118 = 29.55$. Only when the penalty for FDOP is much larger than the AFD penalty (29.55 compared to 2.45) would FDOP avoid the use of relays. We investigate this effect further in the next subsection.

AFD Path Selection				
	R1	R2	D	Route
S1	0.000748	0.000502		S1-R1-R2-D
S2	0.00066	0.000152		S2-R2-D
R1		0.000673	0.001647	
R2	0.000673		0.000441	

FDOP Path Selection				
	R1	R2	D	Route
S1	0.000178	0.000037		S1-R2-D
S2	0.000109	0.000000		S2-R1-R2-D
R1		0.000118	0.003486	
R2	0.000118		0.000022	

SNR Path Selection				
	R1	R2	D	Route
S1	29.4	64.2		S1-R2-D
S2	37.5	693.2		S2-R1-R2-D
R1		36.2	6.8	
R2	36.2		82.9	

Table 1: Examples with Two Sources and Two Relays

The SNR optimization is a max–min optimization, so the penalty value needs to reduce the adjusted SNR of the relay–relay link to possibly make that link undesirable. If at first using the 1.5 penalty value for AFD and FDOP, but in this case using $P = 1/1.5 = 0.667$, the results are seen in Table 1. Again the worst link is R1-D, here with the lowest SNR of 6.8 (not in dB). Here a lower penalty value of $P < 0.187$ would make the routes become S1-R1-D and S2-R2-D, where the P value threshold comes from $6.8/36.2 = 0.188$.

Table 2 provides some results for four scenarios with four sources and four relays. Table 2 shows four scenarios where the results are different between the AFD, FDOP,

and SNR methods. Those routes which are highlighted are different from the other two methods, and for scenarios 3 and 4, the three methods produce three different results. As we will see in the next section, with the P values equal to 1.5 and 0.667 as above, FDOP and AFD use different sets of paths 70.0% of the time, FDOP and SNR methods use different paths 75.7% of the time, and SNR vs. AFD are different 72.1% of the time.

2.4.2 Penalty Value Comparisons

This subsection provides a comparison of the effects of varying the penalty parameters. As seen above for the two-by-two cases, penalty values can be quite different to cause the avoidance of using a relay–relay path, such as $P > 2.45$ for AFD and $P > 29.55$ in those examples. The goal here is to vary penalty values in the range of values over which we see the full effects of the penalty value. Greater than some large penalty values for AFD and FDOP and less than small penalty values for SNR, relay–relay hops would stop being used completely.

Before finding optimizations with relays, we first determined the maximum and minimum values of AFD, FDOP, and SNR that were found in the simulations, then determined the maximum values of P that were needed. These were found to be $P_{max,AFD} = 10^4$, $P_{max,FDOP} = 10^{17}$, and $P_{min,SNR} = 10^{-5}$. When conducting the simulations, we varied P_{AFD} from 1 to 10^4 on a linear log scale, then varied P_{FDOP} and P_{SNR} along linear log scales from 1 to their maximums or minimums. For example, $P_{FDOP} = 10^{(\log_{10}(P_{AFD}) \times 17/4)}$.

Figure 4 shows the results of variations compared with penalty values. The three

AFD Path Selection

	Scenario 1					Scenario 2			
From Src	S1,R4	S2,R2	S3,R1	S4,R3		S1,R4	S2,R3	S3,R2	S4,R1
Btw Relays			R1,R4						
To Dest	R4,D	R2,D	R4,D	R3,D		R4,D	R3,D	R2,D	R1,D

	Scenario 3					Scenario 4			
From Src	S1,R4	S2,R2	S3,R1	S4,R3		S1,R1	S2,R2	S3,R3	S4,R4
Btw Relays			R1,R4						R4,R3
To Dest	R4,D	R2,D	R4,D	R3,D		R1,D	R2,D	R3,D	R3,D

FDOP Path Selection

	Scenario 1					Scenario 2			
From Src	S1,R4	S2,R2	S3,R1	S4,R3		S1,R2	S2,R3	S3,R4	S4,R1
Btw Relays		R2,R4	R1,R2				R3,R4		
To Dest	R4,D	R4,D	R2,D	R3,D		R2,D	R4,D	R4,D	R1,D

	Scenario 3					Scenario 4			
From src	S1,R4	S2,R2	S3,R1	S4,R3		S1,R2	S2,R1	S3,R3	S4,R4
Btw Relays		R2,R4	R1,R2					R3,R2	R4,R1
To Dest	R4,D	R4,D	R2,D	R3,D		R2,D	R1,D	R2,D	R1,D

SNR Path Selection

	Scenario 1					Scenario 2			
From Src	S1,R4	S2,R2	S3,R1	S4,R3		S1,R4	S2,R3	S3,R2	S4,R1
Btw Relays			R1,R4				R3,R4		
To Dest	R4,D	R2,D	R4,D	R3,D		R4,D	R4,D	R2,D	R1,D

	Scenario 3					Scenario 4			
From Src	S1,R4	S2,R2	S3,R1	S4,R3		S1,R1	S2,R2	S3,R3	S4,R4
Btw Relays			R1,R2						R4,R1
To Dest	R4,D	R2,D	R2,D	R3,D		R1,D	R2,D	R3,D	R1,D

Table 2: Examples with Four Sources and Four Relays

curves provide pairwise comparisons between the three optimization criteria. Each sample point is the result of randomly generating 2000 scenarios and determining when the simulation results were the same or different. Optimizations were conducted using the AMPL tool using the CPLEX solver.

These results are most useful if a particular parameter is chosen to be the most relevant. For ultra-reliable ultra-low latency (URLLC) traffic, the FDOP metric might be most important. FDOP might also be most important for other types of critical traffic. AFD might be most useful for voice and video streaming, since this would help find the proportion of the streaming signals that might be degraded and SNR would be useful for more traditional uses. In 5G and beyond be a machine to machine communication or any other form of communication, the most important point is reliable and error free network. The communication network should provide closer to 100% reliability. Such type of communication could not be achieved just by adjusting the SNR value, but instead by providing a tool that creates a conducive environment for reliable and error free network. FDOP could be useful tool for such mission. We believe SNR will be the least useful for emerging 5G and machine-to-machine traffic types.

Regardless of the choice, the extent to which that choice is better than other choices can be pronounced. Take the traditional use of the SNR metric. When $P_{AFD} = 8$ as seen in Figure 4, this corresponds to $P_{FDOP} = 689$ and $P_{SNR} = 0.074$. In this case, the similarity in routes between FDOP and SNR is only 70% and similarity between AFD and SNR is only 63%. So the SNR choice can frequently produce routes that are not as

useful for FDOP. The most important observation is that the AFD and FDOP optimizations share the same routes much more often than FDOP vs. SNR or AFD vs. SNR. Since we believe fade duration based metrics are most important, this shows that it is very important to actually use fade duration metrics instead of SNR when choosing one or two relays.

Figure 5 provides some insight into how often relays are used. Again the AFD penalty is used for the x-axis, but the other metrics also range from their minimum to maximum accordingly. When all penalty values are 1 (i.e., no penalty), all three methods used relays in 78% of the scenarios. Then as the impact of penalty values increases, Figure 5 shows how the use of relays diminishes. Penalty values cause AFD and FDOP to limit uses of relays much sooner than SNR as the penalty values increase.

2.4.3 Doppler Spreading

A parameter that has a significant impact on AFD and FDOP equations is the maximum Doppler shift, f_m . The amount of time in a fade is certainly dependent on the rate of change of the fading effects. Figure 6 shows the differences in choices of relay routes as f_m varies from 2 to 200 Hz. It is anticipated that the differences in relay routes would exist between SNR and either FDOP or AFD. This is confirmed with the AFD vs. SNR curve, although it is interesting to see that the proportion is always around 79%. Differences in relay routing for either metric compared to FDOP do indeed vary significantly versus f_m . However, above approximately 60 Hz, there are no additional significant changes in those differences.

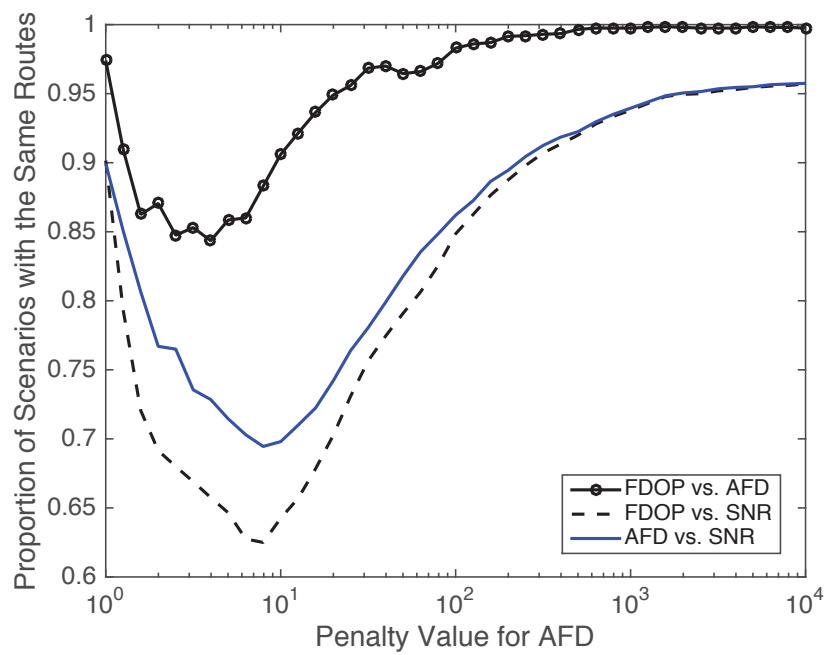


Figure 4: Variation of penalty for four sources and four Rrelays.

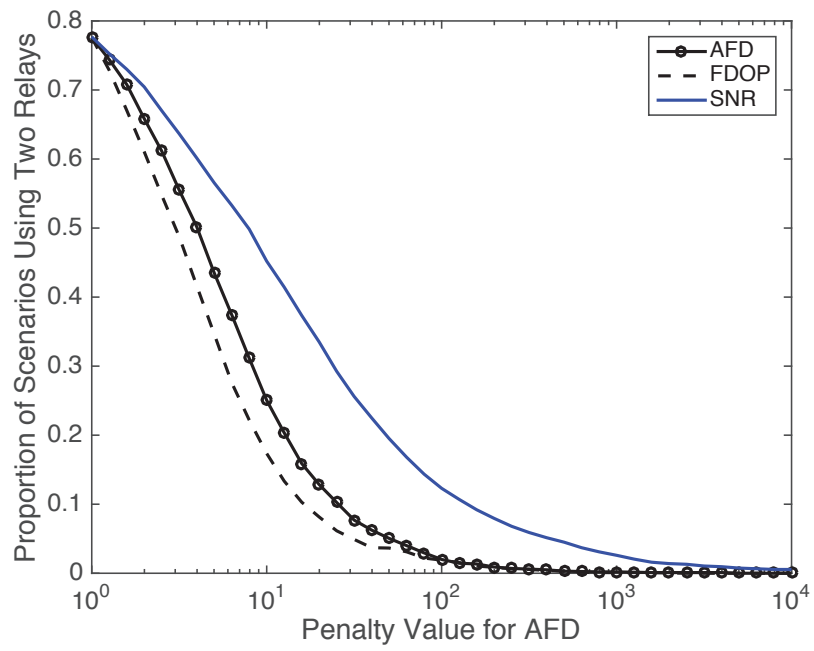


Figure 5: Use of two relays with four sources and four relays.

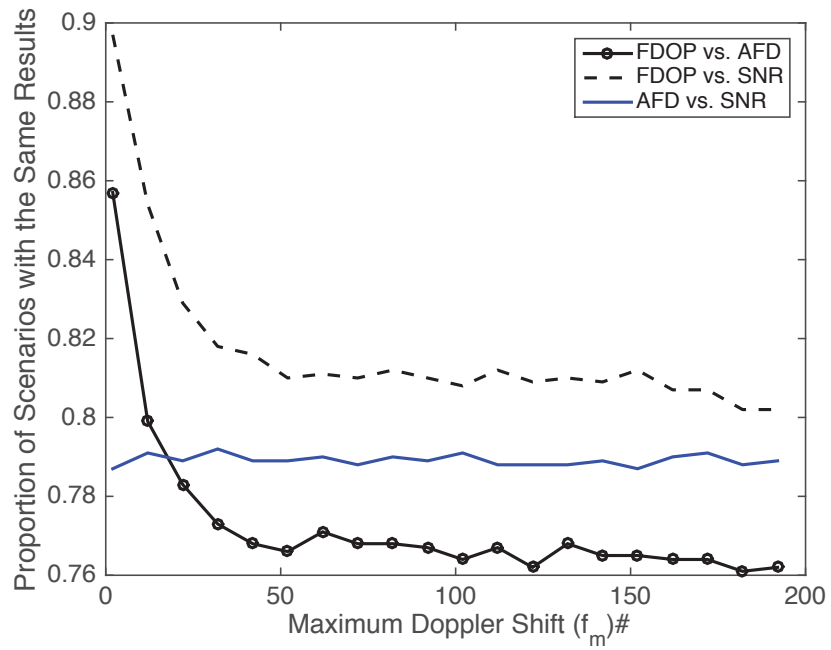


Figure 6: Variation of doppler spread.

2.5 Practical Implementation

In real-world practical application of the concepts of this chapter, it is important to understand deployment issues of relays in today's and future networks. Today's real-world practical application of relay deployment is extensive and varies based on the cellular operator's available resources, users' demands for better service, traffic analysis, and collected key performance indicators such as drop call rates, data rates, low data rate thresholds, etc. The geographical landscape of the area where a macro station is intended to cover is also another factor to consider for the use of a relay. These factors may compel an operator to deploy a relay to facilitate users' traffic in a seamless way and to improve the coverage.

We do not suggest always deploying the optimizations in Sections 2.3 and 2.4 due to the computational complexity of the optimizations when there are many sources and relays. The purpose of those sections was to compare and show the benefits of AFD and FDOP relay path selection compared with SNR based selection. Rather we suggest that source nodes work individually to find best paths. Cellular networks help sources find the best relays when communication is requested. We have shown in previous sections that fade duration (AFD or FDOP) based methods have the best correlation with the performance expected by end users. During relay selection, throughput and reliable link selection becomes the main focus in selection of the best relay or multihop relay path. Throughput on some occasions could be compromised due to relay placement and the distance between relay and the macro station. When choosing relay paths, a source would need to query the network about the relays available, relay locations, link quality between

relays and macro stations, and link quality between relays. From our analysis, these link quality metrics should be related to AFD and FDOP computations.

Various cellular operators apply the relay concept in various forms using labels such as "UE relay," "repeater," "magic box," etc. Such equipment can handle more than one user at a time, so we are not limited to one user per relay as we used in the optimizations. The user also has a choice to connect either to the nearby macro cell or to the relay. The focus in our case was on situations where there is a bad link between the user and the macro site, so the user needs to connect to one of the nearby relays. We assume the main purpose of the relay is to provide coverage to the badly covered area that is away from or in an obstructed location from the macro site. The placement of relays should have minimal overlap of each other's coverage areas to avoid possible interference and to provide the best use of resources such as available bandwidth.

There are cases, however, when our optimization frameworks may be useful, when the number of relays available for a single user at a time is limited. This is usually the case in today's networks, but more relays are being deployed over time. In our case we assumed only four sources and four relays, this took very little computation time to find a solution. However, even if there is a case of 100 sources and 100 relays, we completed the computation on a general purpose computer that took 5.3 sec. This was accomplished using AMPL with the CPLEX solver.

Figure 7 shows an instance of relay deployments from a cellular carrier where UE relays connect to macro sites and provide coverage for users not reachable by the macro station. The red labeled symbol is a macro station with a capability of three bands in

800, 1800, and 2500 MHz. The ones with the green labels are UE relays with different capacities of user connections than the macro stations. The furthest relay is located about 800 m from the main station and the distance between each UE relay is between 150 and 400 m. The one labeled in gray is a non- active relay. The purpose of Figure 7 is just to show one typical example of relay deployment in a practical environment, but not necessarily every relay deployment should follow this type of deployment. The user that is located far from the macro station may have a maximum of four UE relays to choose from. Based on our suggestion in this chapter the user may connect to the one with a better FDOP for the best customer experience, and multihop relay paths may provide even better benefit.

2.6 Conclusions

Several unique as well as reliable relay selection methods have been proposed which can achieve the best performance for wireless networks. Depending on service requirements, fade duration outage probability, average fade duration, or SNR can be used to determine the best wireless channels and relay links. We have argued that fade duration metrics are increasingly important for today's streaming and IoT URLLC traffic. We have also shown that simply using SNR metrics to choose relay paths would frequently result in different paths than would have been chosen if fade duration metrics were used directly. Moreover, we have shown how to use those metrics. Future work could be to extend routes to allow more than two relays, but we posit that diminishing benefits would be gained from more relay hops, especially considering the penalty values. Relay networks



Figure 7: Example of real world relay deployment.

keep being more widely deployed, and this work takes advantage of them, especially with more substantial possibilities for connections between relays. Fade duration metrics will best serve the traffic that is emerging.

CHAPTER 3

FADE DURATION BASED NEIGHBOR CELL LIST OPTIMIZATION FOR HANDOVER IN FEMTOCELL NETWORKS

3.1 Introduction

The main goal of wireless operators is to provide higher speed communication with minimum interference. Users within macrocell require high data rate, reliable hand over with no failure. Fulfilling such requirements with a single macrocell is very challenging, use of low powered short range femtocell placement to enhance indoor coverage is important. Femtocell traffic uses back hauling over IP network. It is a promising technology that provides higher data rate for indoor users, improves the quality of service and minimizes interference.

One of the main challenges for dense femtocell networks is handover between macrocell-femtocell, femtocell-femtocell and selection of the optimal neighbor list. Traditional macrocell networks use a central RNC to manage the radio resource of several macrobase stations and femtocell that have deployed within the macrocell. But, however such systems are very challenging to deploy, instead the femtocell network need to equipped with The SON(self organized networking) capability and Femtocell access point management.

The neighboring list selection in femtocell networks is not studied throughly. Few papers have been published in this area. For instance Soldani and Ore proposed NCR

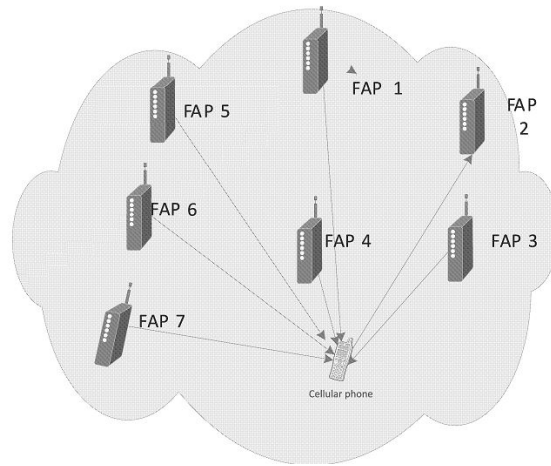


Figure 8: Femtocell deployment in a dense femtocell network

list using DSR for UTRA FDD network. In [4], Zhang et al proposed UE's mobility based handover optimization algorithm. None of these proposals include the SON and management feature of the femtocell network.

The rapid fluctuation of the receive signal due to the Rayleigh fading and its implication on the selection of NCR list needs to be exploited fully. However, previous works on NCR list selection have placed no emphasis on this topic and the subject has hardly been addressed at all. Since, the fade duration plays an important role on the performance of each femtocell, our NCR list selection is based on the Fade duration instead of the average received signal. The method increases user and cell-edge data rate, reduces delay, and guarantees seamless mobility. The proposal also includes the SON and management features of the femtocell network.

3.2 System Description

Due to the dense deployment of the femtocell and the movement of the MS, the femtocell network suffers a lot of challenges during handover. Determining the right number of neighboring FAPs from the list of many possible neighbors during femtocell to femtocell or macrocell to femtocell handover is a huge task. The MS usually moves within or away from the serving FAP. The receiving signal level and the fade duration may suffer due to this movement. The MS also detects a large number of neighboring femtocells from a densely deployed network. It is highly important to select the right neighbor list during handover from serving femtocell. Large time can spent just formulation the list. Such handover needs to be joint coordination among femtocells and serving macrocell. If MS is allowed to scan large amount of FAP, it will require more power, the MAC overhead becomes large and it slows down the overall femtocell network performance. However, using an efficient optimization, it is possible to minimize the list of neighbors. The main point of neighbor list is to select minimum number of neighbors list, so that the MS will select from such list during handover.

In our proposal three main factors have been considered to select the neighbor list from densely placed femtocell network. Those selection criteria are discussed in the preceding subsections.

3.2.1 Fade Duration Probability

The duration of fade below acceptable threshold (i.e. in a "dip") can be more important than SNR and other factors. Long fades cause packets to be lost and channel coding

to fail. The initial list for a femtocell to be labeled as a neighbor femtocell is based on the fade duration probability. It can be expressed as a group A:

$$R = \{ \dots FAP_k(FD_k) \dots : 1 \leq k, FD_k \leq FD_{thr} \} \quad (3.1)$$

Due to Rayleigh fading, the signal received by the MS is usually affected by the time it remains in a fade. The longer the received signal remains in a fading dip, the less likely the femtocell will be selected in the neighbor list. To check if a femtocell is part of neighbor the list or not, fade duration probability need to be more then the threshold value as:

$P_r(dip > FD_{thr})$. To ensure a condition where $P_r(dip < FD_{thr})$ is acceptable, the following conditions need to be satisfied.

Let D_t be the time in a dip, FD_{thr} be a threshold value and D_r dip rate.

$$FD_k = P_r(D_t > FD_{thr1}) \quad (3.2)$$

$$FD_k = P_r(D_t > FD_{thr2}) \quad (3.3)$$

$$= P_r(dip)P_r(D_t > FD_{thr1}) = P_r(dip)P_r(D_d < \frac{1}{FD_{thr1}}) \quad (3.4)$$

or

$$= P_r(dip)P_r(D_t > FD_{thr2}) = P_r(dip)P_r(D_d < \frac{1}{FD_{thr2}}) \quad (3.5)$$

Where FD_{thr1} and FD_{thr2} designates the threshold value of unhidden (in normal scenario) and hidden femtocell cases respectively.

The first part of equation (4) and (5) designates that the signal is in dip or the receive signal is less than the threshold value R_0 . From the Rayleigh fading equation, this can be represented as

$$P_r(R \geq R_o) = \exp\left(\frac{-R_o^2}{\Omega_Q}\right) \quad (3.6)$$

then

$$P_r(R \leq R_o) = 1 - \exp\left(\frac{-R_o^2}{\Omega_R}\right) \quad (3.7)$$

the second part of equation (4) and (5) can be represented as:

$$P_r(D_t > FD_{thr}) = P_r(rate \leq \frac{1}{T_{sec}}) \quad (3.8)$$

refer to [5.88] for PDF function, equation (7) can be simplified using the PDF function as

$$\int_0^{\frac{1}{T}} r \text{pdf}(r, \dot{r}) dr \quad (3.9)$$

after simplification of equation (8) finally it yields

$$(2\rho e^{-\rho^2})\left(\frac{1}{2} - Q\left(\frac{1}{T_{thr}\sqrt{\Omega_2}}\right)\right) \quad (3.10)$$

by Putting all the components together equation [4] can be finally simplified as:

$$FDk = P_r(D_t > FD_{thr}) = (1 - e^{-\rho^2})(2\rho e^{-\rho^2})\left(\frac{1}{2} - Q\left(\frac{1}{T_{thr}\sqrt{\Omega_2}}\right)\right) \quad (3.11)$$

where $\Omega_2 = \frac{1}{2}\Omega_0(2\pi f_m)^2$

In equation (1) where $FAP_k(FD_k)$ represents the fade duration of the k^{th} neighbor FAP. For a femtocell to be qualified in a neighbor list, fade duration outage probability need to be less than the threshold value. The proposed algorithm takes the upper fade duration threshold to be considerably low for any femtocell to be considered in the neighboring list.

In comparison to our proposal Senyat, Chowdhury et al [1,2,3] proposal takes the RSSI level as an indication for femtocell neighbor list selection. Where as, in this proposal Fade duration probability is taken as a selection criteria

3.2.2 Neighbor List Elimination Based On Frequency

To avoid frequency interference among neighbors, it is important not to use of similar frequency for neighbor which are closer to each other. In this method the neighboring FAP uses the same frequency as the serving FAP is eliminated from the list. Those femtocells in this group expressed as :

$$S = \{ \dots FAP_k(FD_k) \dots : 1 \leq k, S \in R, F_k \cap F_s = F_s \} \quad (3.12)$$

where F_k is frequency of the target femtocell and F_s the frequency of the serving femtocell. Such group of femtocell included in this group first needs to fulfill the criteria introduced under equation.(1)

3.2.3 Hidden FAP

The FAP that are included in this category are those FAPs that are located less than the predefined maximum distance from the serving femtocell D_{max} . The location of the

hidden femtocell which is closer to serving FAP obtained from the neighboring femtocell by the joint coordination of the serving FAP and the neighboring femtocell. The femtocell in this category shows higher value of fade duration value than the predefined FD_{thr1} and it is denoted by FD_{thr2} where $FD_{thr1} < FD_{thr2}$

The group of femtocell in this category is expressed as

$$T = \{ \dots FAP_k(FD_k) \dots : 1 \leq k, (FD_k \leq FD_{thr2}) \} \quad (3.13)$$

or

$$F_k \cup F_s = F_s \quad (3.14)$$

and

$$D_k < D_{max} \quad (3.15)$$

Where D_k is the distance between the K^{th} femtocell and the MS with the frequency of F_k and $< D_{max}$ is the predefined Max. distance allowed for the femtocell location to be considered as a neighbor.

By putting the above mentioned benchmarks for neighbor list selection together (Fade duration, frequency and distance), we can conclude that the neighbors included in this list can be stated as: $P = (R - S) \cup T$

3.3 Neighbor List Optimization Method

To determine the femtocell neighbor list in a dense femtocell network is a very challenging issue. To deal with such issue we proposed Optimization method for the femtocell neighboring list. The list contains both the hidden and reachable target femtocells.

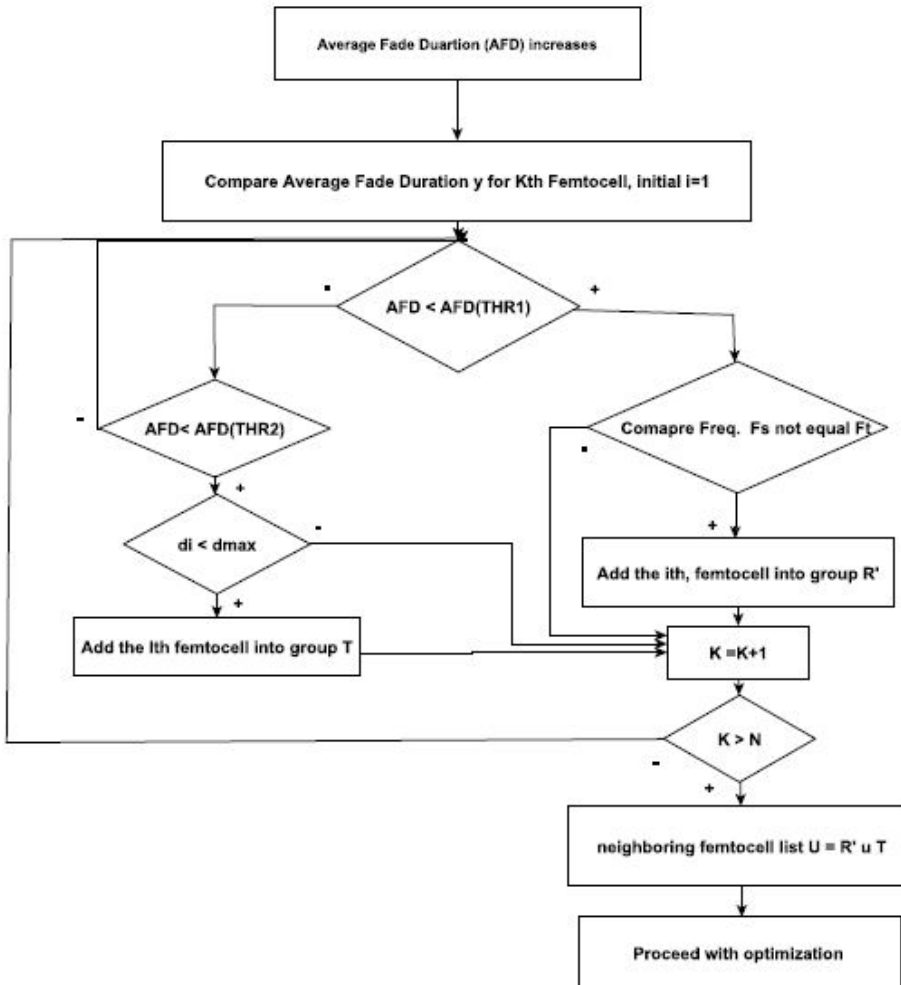


Figure 9: Flow chart for selection of neighbor cell list

The initial assumption for both cases is expressed as:

Let

$$= P_r(dip)P_r(D_t < FD_{thr1}) \quad (3.16)$$

or

$$= P_r(dip)P_r(D_t < FD_{thr2}) \quad (3.17)$$

where equation (8) express the fade duration probability for the target femtocell to be less than the threshold Thr1. where as equation (9) sets a condition of the fade duration probability for hidden femtocell to be less than the threshold value Thr2 .

let $P_i = P_1, P_2, \dots, P_i$ be the computed FDOP (fade duration outage probability) as shown in equation (4) and (5), then the task of the optimization is then to locate those femtocells that satisfy equation (8,9). The femtocell that satisfies these conditions will be considered as candidate for the neighbor list subjected to frequency similarity with the serving FAP and location of the target FAP. When the handover takes place, the coordination of the serving femtocell and the neighbor list FAP are required. The Objective of this Optimization scheme is to select the FAP with minimum fade duration based on (8,9) as

Objective

$$\sum_{k=1}^n (\min(FDOP_k)) \quad (3.18)$$

subject to:

$$(F_k u F_s = F_k) \quad (3.19)$$

$$FD_k < FD_{thr1}) \quad (3.20)$$

$$D_k < D_{max} \quad (3.21)$$

for hidden FAP , the neighbor list optimized as:

Objective

$$\sum_{k=1}^n (\min(FD_k)) \quad (3.22)$$

subject to:

$$FD_k < FD_{thr2}) \quad (3.23)$$

$$D_k < D_{max} \quad (3.24)$$

The optimization shown above is a simple LP optimization where constrain (13) states that the fade duration probability need to be less than the threshold value FD_{thr2} and (14) states that the distance of the target neighbor should be less than the predefined maximum distance D_{max} . The objective function function selectes a femtocell which is ready to handover from serving femtocell to the target femtocell from the selected neighbor list.

3.3.1 Neighbor List Selection Analysis

The proposed algorithm along the selection methods mentioned under A,B,C has been verified using a numerical method. The result is shown on Figure 6 the basic parameter for the numerical analysis is shown under table 1. In the analysis, the number/location

of the neighboring/hidden femtocell are generated randomly.

Table 3: Femtocell parameters

coverage area of Radius of femtocell	50 mt.
Transmit power of the FAP(maximum)	10mw
FAP carrier frequency	10GHz
FAP Height	2 mt
threshold value for hidden FAP	0.05sec

The numerical result of our optimization scheme shown on Figure 6. On figure 6 the number of FAP in the neighbor list Versus the number of femtocell available is shown. From the fig. we can see that, Our proposal performs better than the traditional scheme and also, the number of femtocell in the neighbor list remains linear regardless of the number of target femtocells. Compared to the traditional way our proposal includes hidden femtocell in neighbor list so that it reduces the probability of failure during handover. In our proposal instead RSSI the target femtocell, the fade duration probability is compared. Therefore the target FAP contains the neighbor FAP list with high throughput during handover. In a traditional scheme the hidden FAP is not included in neighbor list; so the handover failure rate is higher than our proposal.

The algorithm for neighbor list is shown under Table II

Neighbor list optimization Algorithm

1. Start
2. detection of Fade duration deterioration from serving Femtocell
3. Compare fade Duration for K number of femtocell

if $FD_k < FD_{thr1}$ and

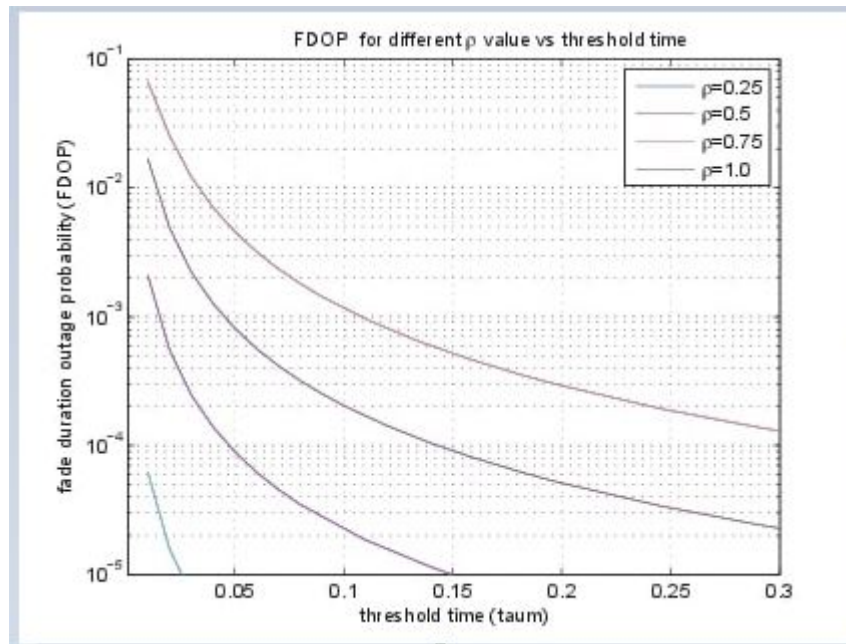


Figure 10: FDOP as the threshold value varies from 0.01msec to 1msec and ρ varies from 0.25 to 1, $f_m=90$ Hz

F_s notequal F_K include Kth into group R

else $FD_k < FD_{thr2}$ and $D_k < D_{max}$

include Kth into group T

4.combine group R and T to a neighbor list

5.Proceed with optimization:

subjected to $FD_{thr1}, FD_{thr2}, D_{max}, F_s$

END

3.4 Conclusion

In this paper an algorithm for neighboring cell list that plays a major role during handover in femtocell network has been proposed. The main contribution of this paper

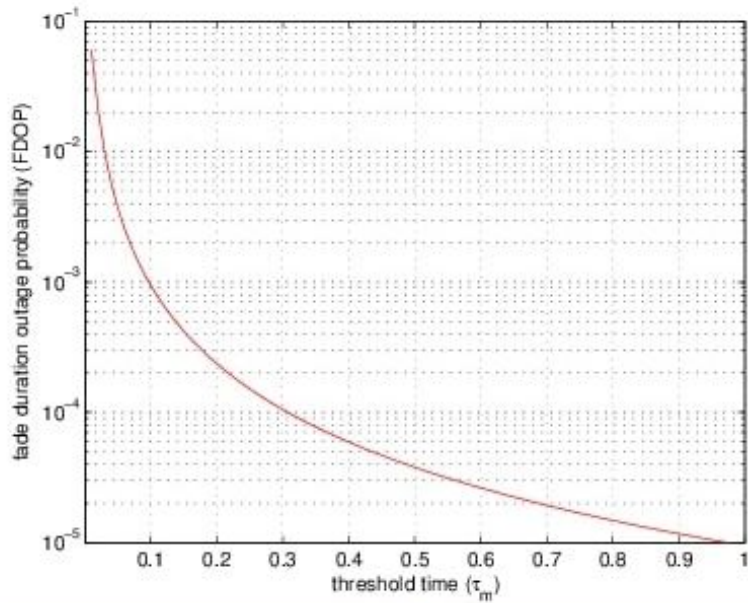


Figure 11: FDOP as the threshold value varies from 0.01 msec to 1 msec, $f_m = 50$ Hz

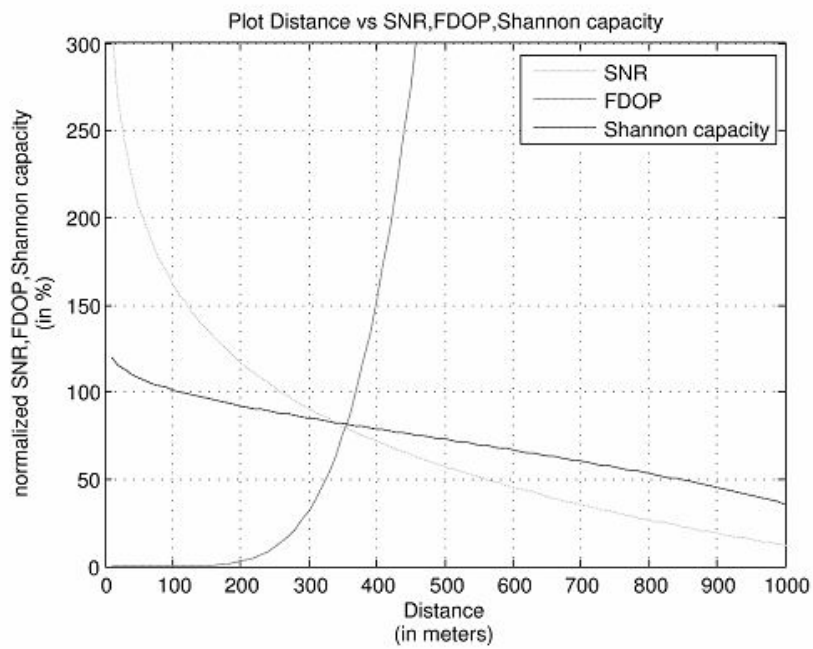


Figure 12: FDOP/SNR/channel capacity vs distance

is to include the effect of fading during neighboring list creation. In addition, the proposed algorithm put a mechanism in place to overcome the hidden femtocell problem. The reduction of the femtocell list will make the handover process more efficient,timely, and also reduces the MAC overhead. The result of the numerical analysis justifies our argument that Fade duration based neighboring cell selection is a better alternative than SNR or SINR based during neighboring list formulation.

CHAPTER 4

FADE DURATION BASED SLEEP MODE ACTIVATION IN DENSE FEMTOCELL CLUSTER NETWORKS

4.1 Introduction

The demand for mobile broadband wireless service shows exponential growth in recent years. Study also shows the demand for this service will grow to reach over 6 billion users globally by the end of 2018. As the mobile traffic increases users requirement such as high speed data for multimedia applications, service availability (any time, any where) is on the rise.

Due to the user mobility and presence of highly concentrated users in areas such as airports, subways, and arriving trains opens a door for temporary requirement mobile service to carry high volumes of traffic. To tackle the requirement of such traffic on the temporary basis the deployment of temporary wireless base station [25] seems a solution. Such an approach may be considered as an alternative solution for irregular occurrence of high concentrated users, but in areas where such users occur on regular basis, temporary deployment of base station is not the best alternative. On the other hand, deployment of dense femtocell serves a peak traffic of highly concentrated users.

Femtocell access point (FAP) was introduced in long term evolution (LTE). Femtocell is a small size wireless BS where their access policy varies among open, close and

hybrid. Open access policy usually applies for cost minimization and interference avoidance. Due to open subscribers access policy, an unlimited number of users share the same resource and the QOS may be compromised. The close access is serving only certain subscriber which are known as closed subscriber group (CSG). In this access policy the spectral efficiency is low whereas the QOS is guaranteed. In Hybrid access resource are shared among subscribers and non-subscriber. It is a compromise access policy between closed and open access policy.

To address the temporary high concentration of users, close femtocell deployment has been considered as an alternative solution. However, the disadvantage of a dense femtocell presence for every premises with a closed access femtocell is increment increase in interference to the users of neighboring femtocells. Such access does not reflect users' demand in service quality, but rather private accessibility of the service. To overcome the close dense femtocell deployment problem a hybrid dense femtocell deployment is the best alternative.

Currently, sleep mode activation is regarded as an active research. In [26], the use of the opportunistic base station cluster as a sleep awake-switching proposed. Its main idea is to balance between energy efficiency and delay. It was pointed out that such a method results a gain of 23% load and 40% energy consumption. On [24], a virtual clustering algorithm proposed. In the proposal, a mechanism to relate the logical cluster with relative FAP position was shown. Also the the provision of intelligent spectrum allocation based on user priority and network congestion is proposed. In [27], the paper exploits the way to improve energy efficiency along with improving interference mitigation. Energy

efficiency algorithm in small cell base station by turning off some of them to sleep mode is mentioned in [9]. Various types of sleep mode in dense small cell has been discussed in [25]. The paper shows turning small cell into a sleep mode created a room for energy efficiency. Most of the papers published on this topic primarily more focus on the sleep mode mechanism of energy efficiency and few papers mentioned interference mitigation based on SNR.

In our paper, we proposed cluster based sleep mode technique for dense hybrid femtocell deployment. The aim of the proposal is to reduce interference among dense femtocell neighbors and improve power efficiency by turning some of the femtocell into sleep mode based on FDOP of femtocell users in a cluster. Previous works on the use of FDOP(Fade duration Outage Probability) on dense femtocell and sleep mode selection have placed little emphasis and the topic has hardly been addressed. Since the fade duration plays an important role on the performance of each femtocell, our proposal on sleep mode activation is based on the FDOP instead of the Signal to noise ratio (SNR) or signal to interference noise ratio (SINR).

Turning some femtocell into sleep mode will improve interference, excess power usage, and service quality. A femtocell in a sleep mode uses a minimum amount of power and easily transit to normal state with the full power usage when the need arises.

The rest of the paper organized as follows: Section II describes the system model. The Proposed Sleep mode optimization method and performance analysis discussed in III. and The final conclusion described in .

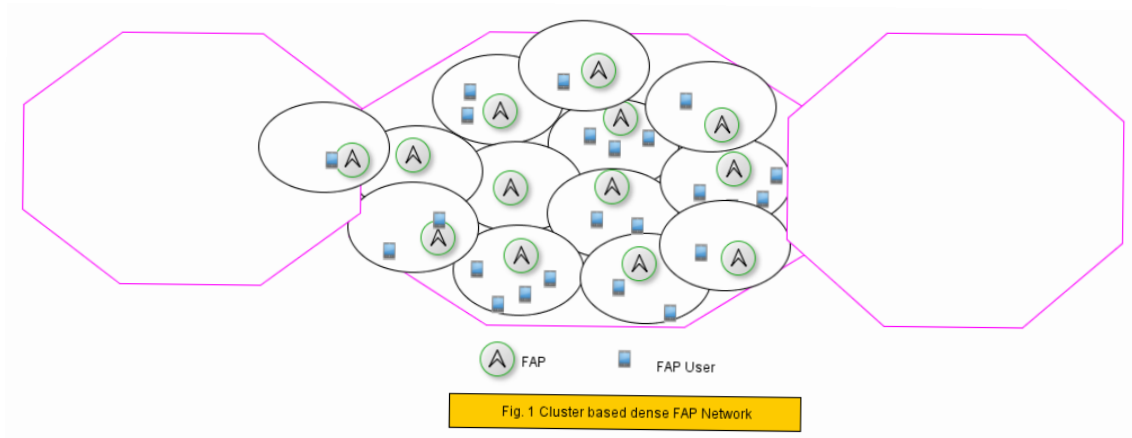


Figure 13: Cluster based dense femtocell Network

4.2 System Model

The system model considers a propagation model in a joint femtocell to femtocell configuration and an orthogonal frequency division multiple access (OFDMA) approach. Users in the FAP network are randomly distributed with non significant interference from the macrocell. Each FAP belongs to a cluster and connected to each other through X2 interface. The FAPs and the core network are connected through S1 interface. The system model is shown in Figure 13.

The System model in Figure 13 referred to a propagation model in a joint femtocell - femtocell network in a hybrid mode. The FAP referred to be in sleep mode when it transit from active state using to low-powered in the hardware component. The FAP may exhibit two main scenario which is sleep mood (SL) and ready mode (RE). as all the hard ware parts in FAP are ready including $RF_{tx/rx}$ then the FAP is considered in ready mode. Where as the major components of the FAP either in low powered or switched off the it

is considered in sleep mode.

Control of the sleep mode may occur by three different methods. The first one is by the FAP itself. In this mode the FAP turned to active mode when the call initiated by the UE in its coverage area not able to be handled by any other FAP then the turned itself on. The remaining control methods are core control and UE control. In our case FAP controlled sleep mode is considered.

The femtocell transmission power is mainly depend on the location of users where the FAP serves and the area it covers. The power consumption [25] does not depend on the number of users the FAP serving. Power consumption of the FAP varies between 100 - 250 mw [28]. As shown in [26] the power control algorithm is denoted by

$$P(k + 1) = \frac{P(k) * SINR_t}{SINR_c} \quad (4.1)$$

Our approach differs from the above in that it is based on the FDOP value.

4.2.1 Fade Duration Outage Probability

The duration of fade below an acceptable threshold (i.e in a "fading dip") can be more an important factor. Packet loss and failure of channel coding may be caused due to long fades. Due to Rayleigh fading, the signal received by the femtocell users is usually affected by the time it remains in a fade. The longer the received signal would remain in a fading dip, the less likely the femtocell user data rate and reliability could be maintained by serving FAP. To determine if the femtocell user will continue with the current serving FAP or to reallocate the user to neighboring FAP, FDOP needs to be computed. This is because the FDOP of the serving FAP could be maintained by the neighboring FAP in the

cluster. The users of serving FAP could be reallocated to the neighboring FAP and the serving FAP could be turn to sleep mode. The neighboring FAP need to fulfill the fade duration outage probability minimum requirement of the reallocated users. For the k^{th} user in the FAP $FDOP_k \leq FDOP_{min}$ and $FDOP_{min} < FDOP_{thr}$. To ensure a condition where $FDOP_{min} < FDOP_{thr}$ is in an acceptable range, the following conditions need to be satisfied.

Let R_{out} be the fading rate, T_{out} be a average duration outage. The FDOP for FAP k can be denoted as

$$FDOP_k = R_{out} * T_{out} \quad (4.2)$$

Consideration of the FDOP involves three parameters:

- R_0 is the signal amplitude below which a fade occurs.
- T_{thr} is the maximum amount of time for a fade beyond which the fade is considered an outage.
- $FDOP_{thr}$ is the limit beyond which and probability of an outage is unacceptable.

The probability that the level of a received signal remains below the threshold value R_0 for more than T_{thr} is denoted by the Rice equation as in [9]

$$P_{\tau_f}(T_{thr} \geq \tau) = \frac{2}{x} I_1 \left(\frac{2}{\pi x^2} \right) \exp \left(-\frac{2}{\pi x^2} \right) \quad (4.3)$$

where $x = AFD/\tau_m$ and I_1 is a modified Bessel function order one. The pdf of the fade duration can be easily obtained from equation (4.5) as shown in [11] equation (4.18) as:

$$= -\frac{1}{\bar{\tau}_f} \frac{d}{dx} \left[\left(\frac{2}{x} I_1 \left(\frac{2}{\pi x^2} \right) \exp \left(-\frac{2}{\pi x^2} \right) \right) \right] \quad (4.4)$$

From (4.5) and (4.6), the pdf of the outage duration can be denoted for $(\tau_{out} \geq \tau_m)$ as shown on [11] equation (4.13) :

$$f_{\tau_{out}}(\tau_{out}) = \frac{f_{\tau_f}(\tau_{out})}{P_{\tau_f}(\tau_f \geq \tau_m)} \quad (4.5)$$

The above equation will be zero for all other values.

As shown in (4.2) and (4.3), the Fade duration outage probability computed as:

$$FDOP = R_{out} \cdot T_{out} \quad (4.6)$$

where as R_{out} is the outage rate

After putting all the components together and simplifying using [13] equation (4.5), fade duration outage probability $FDOP_k$ for (4.3) and (4.4) can be finally denoted as:

$$(L)(A) \left[\exp\left(-\frac{2}{\pi x^2}\right) \left(I_1\left(\frac{2}{\pi x^2}\right) - \left(I_0\left(\frac{-2}{\pi x^2}\right) \right) \right) + 1 \right] \quad (4.7)$$

where

$$LCR = L = \sqrt{2\pi} f_m \rho e^{-\rho^2} \quad (4.8)$$

$$AFD = A = \frac{e^{\rho^2} - 1}{\sqrt{2\pi} f_m \rho}. \quad (4.9)$$

for $\rho = r/r_{rms}$.

To determine if the FAP could be put on sleep mode, fade duration outage probability of its active users need to be maintained to the minimum required FDOP value in a cluster which is $FDOP_k \leq FDOP_{min}$. Then users of the serving FAP could be relocated to the neighboring FAP while satisfying the minimum FDOP required. In our case $FDOP_{min} \leq FDOP_{thr}$. The $FDOP_{thr}$ is the least value FDOP that triggers the hand off of users and distortion of data.

4.3 Sleep Mode Optimization Method

An exclusive use of a femtocell by private owners or high concentrated FAPs in a designated area such as the airport tends to create a negative effect on users' experience. The intended data rate of the private FAP would be compromised by the interference of the neighboring FAP users. The densely deployed FAPs may leads to unnecessary power usage due to lower traffic load. The main concept behind the optimization is to look for a way to avoid a FAP that is unnecessary in the cluster operation. This can be achieved by turning the FAP into sleep mode or allowing the private FAP users to share the same FAP with neighboring users for a better power utilization and interference mitigation.

The total out of cell interference I_{total} contributed by r^{th} neighbor on each FAP can be expressed as

$$\sum_{i=1}^r I_r = \sum_{i=1}^r \frac{O(2 * II * R_i)}{O(R_i^\alpha)} \quad (4.10)$$

In the above equation D is the average distance , α is the pathloss exponent and r is the total number of interfering FAP. as the number of sleeping FAP increases by "n" , the total interference decrease on each active FAP by n FAP (r-n), the it can be denoted as.

$$\sum_{i=1}^q I_r = \sum_{i=1}^q \frac{O(2 * II * D_i)}{O(D_i^\alpha)} \quad (4.11)$$

where $q = r - n$. As shown in equation (33) when the FAP turns to the sleeping mode in addition to power saving interference to the neighboring cell is also decreases.

The initial user connection to the FAP is mainly based on two methods.

4.3.1 Distance based on connection

In this method users are connected to the nearest by FAP at the initial stage. Then, the FAP with fewer users and an acceptable FDOP to the neighboring FAP could be turned to sleep mode.

4.3.2 Non restricted to distance

In this category user connection to the FAP is not bound to connection to the nearest FAP. As long as the FDOP is less than the $FDOP_{min}$, users are free to connect to any FAP in the cluster. As the coverage area of the FAP is limited, users placed at the border between FAPs will have more flexibility of choosing a FAP than users placed on the far end.

The operation of the FAP could be divided into three categories:

1. Sleep mode: when no user is served and the FAP is in sleep mode.
2. Active mode: when the FAP is active and serving users.

$$\begin{aligned} P_{FAP_i} &= \begin{cases} P_{SP} & \text{sleep mode} \\ P_{act} & \text{active mode} \\ P_{act}(1 + \Delta * P_{add}) & \text{added mode} \end{cases} \end{aligned}$$

where P_{add} represents the power required to extend the active FAP to enable of adding more user from the neighboring FAP or to load balance with neighboring user.

3. Added mode: When the FAP is active and serving more users from neighboring sleeping FAP or to load balance users of neighboring FAP. Power requirement of these three FAP mode could be denoted as:

$$\begin{aligned}
 P_{FAP_i} &= \{ P_{SP} && \text{sleep mode} \\
 P_{act} &&& \text{active mode} \\
 P_{act}(1 + \Delta * P_{add}) &&& \text{added mode}
 \end{aligned}$$

To determine the FAPs that need to be turned to sleep mode in a cluster, the FDOP of its users need to be determined. The outage occurs when the fade duration gets higher than the predefined threshold value $FDOP_{thr}$, but in order for the femtocell users to reallocate to the other FAP and to avoid the outage, the fade duration needs to be less than $FDOP_{min}$. Such a condition guarantees continued service to the users by the newly reallocated FAP. The sleep mode activation optimization is formulated in the preceding section. The sleep mode activation categorized FAPs into active and sleep mode, where the set of femtocell defined by $\bar{F} \equiv f_1, f_2, f_3, \dots, f_n$. The value of f_n is 1 if FAP_n is active and 0 otherwise. The main objective of the optimization is to minimize the total active femtocell by turning some FAP into sleep mode which is denoted by the formula below:

$$\min\left(\sum_{i=1}^N F_i\right) \tag{4.12}$$

Each FAP has a capacity of carrying certain traffic. In order for femtocell users to be allocated to the neighboring FAP in a cluster, availability of the resource is an important factor. Therefore, resource availability remains one of the constraints. The maximum

resource R_{max} per FAP along with resource block B_i for each user u_i can be denoted as

$$\sum_{i=1}^N u_i B_i \leq F_i R_{max} \quad (4.13)$$

When relocating users into active FAP so as the serving FAP could be turned into sleep mode, the active FAP resource available should be more than the resource block occupied by users. The other constraints are the distance between the sleep mode candidate FAP and the neighboring FAP in a cluster as $D_i < d_{max}$. The objective of this optimization scheme is to select the candidate FAP for sleep mode where users of the FAP reallocate to the neighboring FAP in a cluster as:

Objective

$$\min\left(\sum_{i=1}^N F_i\right) \quad (4.14)$$

Subject to

$$D_i \leq D_{max} \text{ for this case} \quad (4.15)$$

$$0 \leq N_j \leq X_i \quad (4.16)$$

$$FDOP_i \leq FDOP_{min} \quad (4.17)$$

$$\sum_{i=1}^N u_i B_i \leq F_i R_{max} \quad (4.18)$$

The optimization shown above is a simple LP optimization where constraints (4.17) state that the fade duration needs to be less or equal to the minimum value $FDOP_{min}$ and (4.14) states that the distance of the target neighbor should be less than the predefined maximum distance D_{max} . where as (4.16) states that each FAP serves at that most N_j UEs. The objective function minimize the total FAP in the cluster. The inactive FAP stay in the sleep mode until user request that could not fulfill by active FAP arise.

The two types of FAP modes that exist in the cluster are active and sleep mode. Sleep mode FAP stays inactive until reactivation request received. As the sleep mode FAP becomes active the resource taken by neighboring FAP will be reallocated back. The proportional expansion the neighboring cell returns to its regular covering size of the FAP.

4.3.3 Femtocell Coverage Extension

Femtocell initial power is estimated to provide coverage within a radius of R_f . However, Changing the femtocell power has a direct influence on the interference and coverage. Increasing the femtocell power makes the coverage wider, but also increase the interference on the near by macro user. As the femtocell goes to sleep mode, the closest neighbors increase the FAP power to provide coverage for some newly arriving users in the sleep mode FAP area. The power increase by the neighboring FAP to extend coverage is far less than the power required by the sleeping FAP to provide service when it is active. The coverage of the neighboring FAP expand by the $\Delta d = d_2 - d_1$ where d_1 and d_2 are the original and the final coverage P_{T1} and P_{T2} the original final power. There relationship can simply stated as.

$$\frac{P_{T2}}{P_{T1}} = \frac{d_2^2}{d_1^2}$$

4.3.4 Sleep Mode Performance Analysis

As the FAP stays in the sleep mode the major components of the hardware consumed very minimum power. The time where the FAP stays in the sleep mode considered as an Idle state. The average power reduction due to the FAP stays in a sleeping mode can be denoted as [45]:

$$\Omega = \frac{P_{sleep}}{P_{act}} * (\bar{\eta}) * 100 \quad (4.19)$$

where $(1 \leq \bar{\eta} \leq 1)$ [45] is the active duty cycle. P_{act} is the power consumed by FAP in [w] when it is in active mode and P_{sleep} is the power consumption by FAP in sleeping mode in [W]. The traffic model in [45] is used for the value of ω

Table I shows the parameter that was applied during system analysis. The minimum coverage of each FAP is at a range of 20 m. Each user initiates connection with the nearby FAP using FDOP. In each cluster a maximum of 9 FAP are deployed. The performance is evaluated by considering non-registered and registered users. The $FDOP_{min}$ is taken to be more than $FDOP_{thr}$ to avoid a possible hand off initiation by the serving FAP. Based on the combined analysis of the optimization and Algorithm discussed in section III , expansion factor of 10% to 20% was evaluated. Such expansion was chosen to cover the hole that may be created due to sleep mode initiation. The result of the analysis shown in table II.

Table II shows the energy efficiency for different sleep mode expansion factors and FDOP . It can be easily shown the power saving increase the expansion factor remains minimum. This is because the gain that has been obtained by turning the FAP off may be lost as additional power is required to cover an expanded area. In addition to power saving data rate and interference improves.

Table 4: Femtocell Parameters

coverage area of Radius of femtocell	50 m.
Transmit power of the FAP(maximum)	10mw
FAP carrier frequency	10GHz
FAP Height	2 m
threshold value for hidden FAP	0.05sec

Table 5: Performance Result

FDOP %	# of FAP to sleep mode	Expansion factor in %	Power saving in %
10	1	0	39.47
10	1	10	34.81
10	1	20	32.42
10	2	0	36.83
10	2	10	32.49
10	2	20	30.26
20	2	0	36.83
20	2	10	32.49
20	2	20	30.26
20	2	0	35.96
20	3	10	31.71
20	3	20	29.54

4.4 CONCLUSION

In this paper we propose optimization that plays a major role during sleep motivation in dense hybrid femtocell networks. The main contribution of this paper is to include the effect of fade durations outage probability(FDOP) during femtocell sleep mode selection. Turning the femtocell into sleep mode in a dense femtocell cluster will improve the interference, bandwidth utilization , and power efficiency among femtocell users. The result of the optimization along with the algorithm justifies our argument that fade duration based sleep cell activation is a better alternative than SNR or SINR .

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

This work has shown the importance of understanding the different components that attenuate and shift the frequency of the received signal. To devise a method to tackle such issues is very important. It was repeatedly shown in various research that the UE signal deteriorates randomly due to fading.

In the case of multi-hop relaying, we derived new formulas for two-hop and three hop relay paths, with three hop paths given a penalty cost. Then we derived optimization algorithms for each type of relay selection for total path and link-by-link. Simulation results provided optimal AFD and FDOP paths for various random network topologies. These paths were then compared to paths that would be found if SNR metrics were used instead. It was shown that SNR optimization results in much different performance. Our solution shows that using SNR metrics to choose relay paths would frequently result in different path selection than the FDOP selection method. The FDOP method is a better alternative than SNR.

For cases of four sources and four relays, SNR based optimization frequently chose different relay paths, as low as only 63% of the same relay paths as FDOP or AFD optimizations. Because fade duration methods more accurately control the fading nature and true quality of the signals, the results here provide significant improvements in a relay performance and allow two and three hop relay paths to be implemented effectively.

The current wireless technology (5G and beyond) is towards small and dense cells to provide high speed, low latency service. In our research, it was shown that on dense femtocell networks, the application of FDOP on neighboring cell and sleep mode selection is a better alternative than SNR or SINR.

In general, this dissertation illustrated a better understanding of the cooperative relay network and fade duration outage probability to improve the received signal. A future study could be done to assess the application of FDOP on wideband millimeter wave signals. FDOP could be applied for determining the level of packet duplication in dual or multiconnectivity cellular scenarios. Also future work could involve the application of the UE as a relay for URLLC traffic to improve user experience with and without using a BS. Because URLLC has such tight delay and loss requirements FDOP and AFD-based methods will become more and more important.

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