Positioning of a Wireless Relay Node for Useful Cooperative Communication

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Article Info	ABSTRACT

Given the exorbitant amount of data transmitted and the increasing demand for data connectivity in the 21st century, it has become imperative to search for pro-active and sustainable solutions to the effectively alleviate the overwhelming burden imposed on wireless networks. In this study a Decode and Forward cooperative relay channel is analyzed, with the employment of Maximal Ratio Combining at the destination node as the method of offering diversity combining. The system framework used is based on a three-node relay channel with a source node, relay node and a destination node. A model for the wireless communications channel is formulated in order for simulation to be carried out to investigate the impact on performance of relaying on a node placed at the edge of cell. Firstly, an AWGN channel is used before the effect of Rayleigh fading is taken into consideration. Result shows that performance of cooperative relaying performance is always superior or similar to conventional relaying. Additionally, relaying is beneficial when the relay is placed closer to the receiver.

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1.   INTRODUCTION

With ongoing progression of modern technology, new challenges and predicaments have emerged in order to cope with the networking demands of an increasing number of devices. Current technology provides wireless data connectivity for voice and video, through which human interaction and communications have been completely revolutionized. Mobile network traffic is constantly growing at an exponential rate. In order to combat this dilemma, one of the solutions that has been commonly researched in recent years is the use of cooperative communications, namely cooperative relaying. With cooperative relaying, in addition to the existing link between a user and a base station, dedicated relay nodes are also utilized in order to forward data. Conventional use of relay links include communication via satellites and microwave backhauling. Recently, relaying is also proposed for cellular networks and ad hoc networks. In particular, relaying is very useful when considering cooperative communication in wireless ad hoc networks [1].

The main advantage offered by cooperative relaying is spatial diversity [2]. In spatially diverse systems, antennas distributed in space through relay nodes so as to provide a different wireless channel as compared to a single transmission between a source and a receiver. Diversity schemes are used in order improve network reliability. This is achieved through the transmission of several independent versions of the same signal. These signals are then combined at the receiver. This improves reliability by reducing the bit error rate as well as offering increased throughput. Due to the fact that it offers superior performance and the fact that it is most commonly used it WCDMA and LTE relaying systems [3], during the course of this research, Maximal Ratio Combining will be implemented as the preferred method of diversity combining.

When transmitting signals through wireless media, various channel impairments exist that hinder the reliability of the transmission. Two of the major issues that present themselves with transmission over wireless channels are path loss and multipath fading. In this work simulation is carried out assuming Rayleigh fading. Rayleigh statistical model is more suitable for application with outdoor cellular networks [4]. One of the most commonly used models due to its simplicity and relative accuracy is the Lee model. Lee's model has been implemented throughout the cellular industry for radio propagation analysis with great success [5].

There are a number of cooperative relaying techniques that are used in modern celluar networks. These techniques can be classified according to the method in which data is forwarded at the relay node. For the purpose of this research, the decode-and-forward relaying is assumed. Decode-and-forward is populr due to overall performance in comparison to other protocols [6] with reasonable degree of complexity.

This study designed to scrutinize the effects of relay node placement on the capacity of a 3-node communications system. Principles of information theory will be applied in order to compare system capacity under various different positions. Factors involved in cooperative relaying such as relaying techniques and diversity combining methods will be chosen in order to accurately represented those used in modern WCDMA and LTE networks.

The remaining of this paper is organized as follows. Section 2 illustrates the methodology used in this work, including the model for the wireless link, performance criteria and system setup. Simulation results are given in Section 3 together with the discussion on these results. Finally conclusion is in Section 4.

2. SIMULATION OF RELAY CHANNEL PERFORMANCE

This study focuses on a 3-node relay channel with a source, dedicated relay and destination node. The relay node utilizes the decode-and-forward relaying protocol with a half-duplex constraint. Performance is analyzed based on the throughput which is represented by the channel capacity.

2.1. Modeling the Wireless Channel

The following equations presented for path loss, noise and fading are utilized to model the wireless channel. Both AWGN and Rayleigh fading channels are considered. Path loss is according to the Lee model:

$$PL_{Lee} = PL_0 + m \, log\left(\frac{d}{d_0}\right) - 15 \, log\left(\frac{h_t}{h_{tref}}\right) - 15 \, log\left(\frac{h_r}{h_{rref}}\right) + 20 \, log\left(\frac{f}{f_0}\right) \qquad (1)$$

Each of the variables in the equation presented above correlates to the following:

PL_0 - Path loss at reference distance (d_0) in [dB]
m - Slope in [dB/decade]
d - Transmitter-receiver separation in [km]
d_0 - Reference distance (1.609 km)
h_t - Transmitter antenna height in [m]
h_{tref} - Reference transmitter antenna height (30.48 m)
h_r - Receiver antenna height in [m]
h_{rref} - Reference receiver antenna height (3.048 m)
f - Signal frequency in [MHz]
f_0 - Reference signal frequency (900MHz)

For LTE and WCDMA networks, the standard outdoor base station antenna height is 80m, mobile receiver antenna height is assumed to be 1.5m and downlink transmission power is 62 dBm [7]. Also, the typical height for an LTE relay node is 10m [8]. The signal frequency is assumed to be 1800 MHz because it is the most commonly used frequency band for global LTE deployments [9]. In an outdoor urban environment, $PL_0 = 116$ dB and $m = 36.8$ dB/decade. For the AWGN channel the noise power is represented by Johnson's Equation, as shown Equation 2:

$$P_n = KTB \qquad (2)$$

where K is the Boltzmann's constant (1.3807×10^{-23} J·K⁻¹), T is the receiver temperature in Kelvin and B is the bandwidth in Hertz. In order to calculate noise power for standard LTE link budgeting, the temperature is assumed to be 290 K and the bandwidth is taken as 10 MHz. The total noise power can therefore be calculated to be approximately 4×10^{-11} mW.

In fading channels, small scale fading is represented by Rayleigh model which follows the probability density function:

$$p = \frac{1}{\Gamma}\, e^{-\frac{SNR}{\Gamma}} \tag{3}$$

where p is the probability of a particular Signal-to-Noise ratio (SNR) occurring and average SNR is represented by Γ.

2.2. Performance Analysis

Comparison of channel capacity is used in order to compare performance of different methods of transmission. In present-day WCDMA and LTE relaying networks, the decode-and-forward relaying protocol and the maximal ratio diversity combining method are used. The equations for channel capacity for direct transmission, conventional relaying and cooperative relaying are presented in Equatio 4-6 [10]:

Direct Transmission:

$$C = B \log_2(1 + SNR_{s,d}) \tag{4}$$

Conventional Relaying:

$$C = \frac{1}{2}B \min\{\log_2\big(1 + SNR_{s,r}\big)\ , \log_2(1 + SNR_{r,d})\} \tag{5}$$

Cooperative Relaying:

$$C = \frac{1}{2}B \min\{\log_2\big(1 + SNR_{s,r}\big)\ , \log_2(1 + SNR_{s,d} + SNR_{r,d})\} \tag{6}$$

In the Equations 4, 5 and 6, C represents the peak achievable bit rate of the channel expressed in bits per second, B is the bandwidth of the channel in hertz, SNR is the signal to noise ratio at the receiver for the link specified by the subscripts. For example $SNR_{s,d}$ refers to the signal to noise ratio at the destination node for the source-to-destination link.

These Equations will be utilized and simulated using different conditions, for the comparison between the different methods. By basing the varying SNR a function dependant on distance, it is possible to compute a distance limit within which cooperative relaying provides the greatest capacity of the three methods, thereby providing beneficial use of cooperation.

2.3. System Model

Although assumptions will be made with consideration of modern mobile networks, such as WCDMA and LTE, this study represents a general wireless relay channel. The analysis will be done in two stages. In the first stage, a linear relay channel will be considered, where the source, relay and destination are all placed in single straight line. The second stage will be to expand this to the analysis of networks in which the relay node can be placed anywhere in the vicinity of the source and destination node as opposed to being in a straight line.
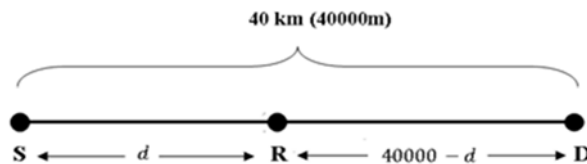

Figure 1. System model for the linear case

Figure 1 illustrates the system model used, where there is a linear 3-node network with a total length, from source to destination, of 40 km (40000m). Therefore, the only variable that is analyzed is the distance between the source and relay, denoted by d.
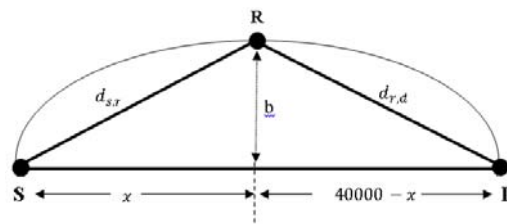

Figure 2. System model for the non-linear case

For the non-linear case, the relay geometry depicted in Figure 2 is considered, where the source and the destination node are at fixed distance ($d_{s,d}$ = 40 km) away from each other. However, unlike with the linear architecture, the relay will be placed in varying points along the elliptical curve. The channel capacity is plotted by changing the value of x. The values of $d_{s,r}$ and $d_{r,d}$ are given the following equations.

$$d_{s,r} = \sqrt{\left(1 - \frac{4b^2}{d_{sd}^2}\right)x^2 + \frac{4b^2}{d_{sd}}x} \tag{7}$$

$$d_{r,d} = \sqrt{\left(1 - \frac{4b^2}{d_{sd}^2}\right)x^2 + \left(\frac{4b^2}{d_{sd}} - 2d_{sd}\right)x + d_{sd}^2} \tag{8}$$

3. RESULTS AND DISCUSSION
3.1. Performance with Linear Relay Geometry
Using the equations for channel capacity, the performance can be simulated for direct transmission, conventional relaying and cooperative relaying. The results for the channel capacity with respect to distance are shown in the following plots. Simulation was carried out for both AWGN and Rayleigh fading channels, as show in Figure 3.
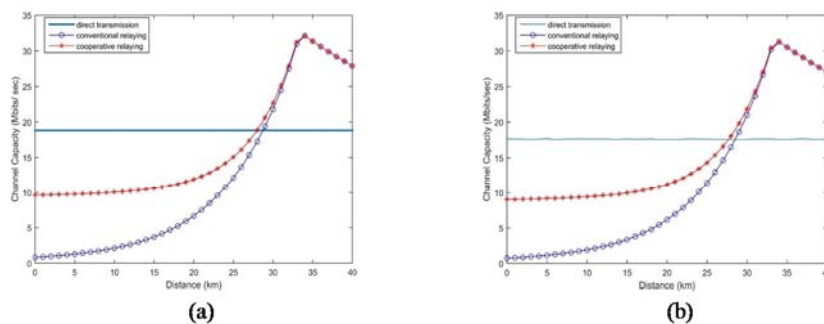

Figure 3. Channel Capacity for 3-node relay network in an (a) AWGN channel, b) Rayleigh Fading Channel

For an AWGN channel with direct transmission, the maximum achievable data rate is 18.83 Mbits/sec while in a Rayleigh fading channel this value decreases to 17.39 Mbits/sec. In AWGN channel, the peak channel capacity is 32.11 Mbits/sec for both relay channels whereas when fading is taken into account the capacity decreases to 31.27 Mbits/sec. It can be observed from the graphs that performance in a Rayleigh fading channel is decreased when compared to an AWGN channel. Other research papers have confirmed this phenomenon. Mutual information for the fading relay channel is always less than or equal to that of an

AWGN channel [5]. In both AWGN and Rayleigh fading cases, the peak occurs when $d_{s,r} = 34$ km. Also, the channel capacity is identical for both conventional and cooperative relaying when $d_{s,r} > 34$ km. However, conventional relaying results in a higher data transmission rate when the relay node is moved closer to the source node. The intersection between plots for cooperative relaying and direct transmission occurs when $d_{s,r}$ is 26.981 km with AWGN, and 26.661 km with Rayleigh fading channel. Therefore, it is possible to infer that the channel capacity for cooperative relaying in an AWGN channel is optimum compared to other methods of transmission when 26.981km$< d_{s,r} <$34km. The corresponding range in with fading taken into consideration is 26.661km$< d_{s,r} <$34km. It can consequently be concluded that cooperative relaying is useful when the relay node is positioned within these range.

3.2. Performance with non-Linear Relay Geometry

By using (7) and (8), distances of the source-to-relay and relay-to-destination links are calculated. Through the variation in the quantity for b, it is possible to obtain plots for the performance of relay nodes with different overall outlines. For example, $b = 0$ represents the special case of a linear network while $b = 20$ is representative of circular shape. For the purpose of this simulation, the channel was assumed to be an AWGN channel. The results are shown in Table 1.

Table 1. Channel Capacity for non-linear 3-node AWGN relay channel

| b (km)	Distance for Peak Channel Capacity(km)	Intersection with direct transmission (km)	Intersection with conventional relaying (km)
5km	$x = 34$ ($d_{s,r} = 36.187, d_{r,d} = 6.982$)	$x = 28.84$ ($d_{s,r} = 29.19, d_{r,d} = 12.028$)	$x = 35$ ($d_{s,r} = 36.16, d_{r,d} = 6$)
10km	$x = 36$ ($d_{s,r} = 36.49, d_{r,d} = 7.211$)	$x = 31.254$ ($d_{s,r} = 32.33, d_{r,d} = 12.03$)	$x = 37$ ($d_{s,r} = 37.37, d_{r,d} = 6..062$)
15km	$x = 38$ ($d_{s,r} = 38.56, d_{r,d} = 6.84$)	$x = 32.206$ ($d_{s,r} = 34.33, d_{r,d} = 14.21$)	$x = 38$ ($d_{s,r} = 38.56, d_{r,d} = 6.84$)
20km	$x = 39$ ($d_{s,r} = 39.497, d_{r,d} = 6.325$)	$x = 36.34$ ($d_{s,r} = 38.126, d_{r,d} = 12.1$)	$x = 39$ ($d_{s,r} = 39.497, d_{r,d} = 6.325$)
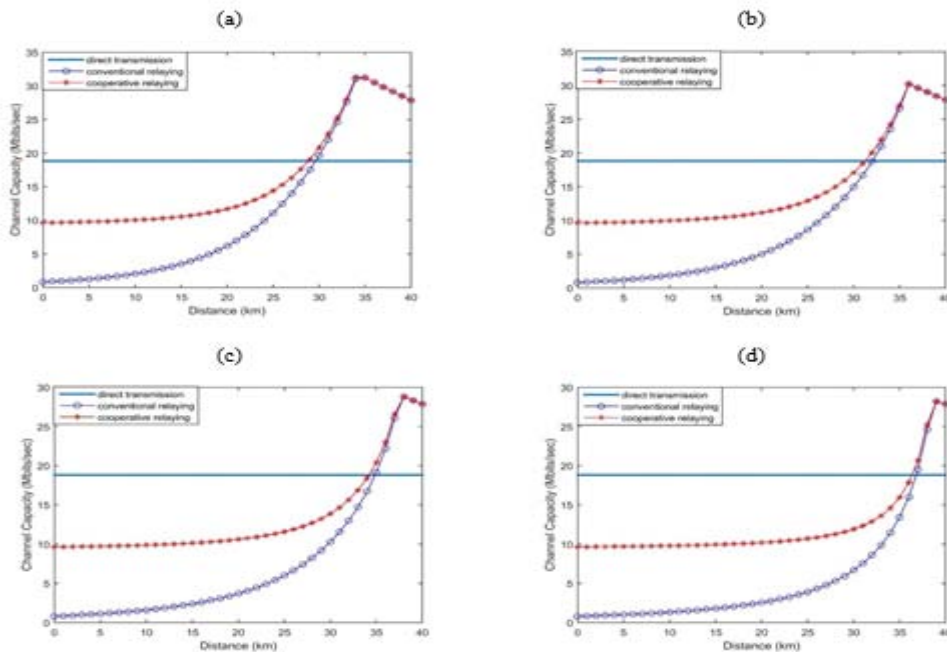
Figure 4. Channel capacity for non-linear 3-node AWGN relay channel (a) b=5, (b) b=10, (c) b=15, (d) b=20

It can be observed from the plots above that as the quantity of b increases the optimum relay node placement corresponds to increasing values of x. Also, the range of cooperative relaying in terms of x decreases as b becomes greater. The results are summarized in the preceding table. In addition to relay position, performance optimization can also be sought through optimizing power and and time allocation. In

the first case, a constraint of total power is assumed. Then relaying performance is optimized by finding the portion of power to be allocated to the relay. Similarly, the available transmission time can be optimally shared between

4. CONCLUSION

Cooperative relaying offers increased throughput and reliability of transmission through spatial diversity. The principle behind cooperative relaying is to send multiple copies of the same information signal through different wireless channels, so they can then be combined at the destination. The wireless channel is based on models presented by previous works and are used to observe the effect of distance on channel capacity in a three node network. This proposed approach adopted for this study would be beneficial in order to offer increased data rates for cooperative relaying. However, the model used for the wireless channel is very specific and therefore the results may not be applicable to other scenarios. Despite this, the same model can be modified in order to take into account different environments and wireless networking technologies. Also, this work could be extended in order to take into account the effects on randomly distributed nodes. One way to extend this work is to study the case of multi-user with randomly distributed sources together with multi-hop relaying.

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Tariq Muhamad Amjad recently obtained a degree in Communications Engineering from the International Islamic University Malaysia (IIUM), Malaysia. He is interested in data communications and information theory. His focus area is modern mobile wireless communications systems. His current research work involved the investigation of the performance of relay channels and wireless cooperative networks.

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