國立交通大學

電機學院通訊與網路科技產業研發碩士班

碩士論文

多躍式細胞系統之最佳中繼站位置設計

Design of Optimal Relay Location in Multi-Hop Cellular Systems

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中華民國九十六年九月

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A Thesis
Submitted to College of Electrical and Computer Engineering
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of
Master
in

Industrial Technology R & D Master Program on
Communication Engineering

September 2007

Hsinchu, Taiwan, Republic of China

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摘　　要

近年來，IEEE 802.16e 無線都會網路(wireless metropolitan area networks, WMANs) 變得非常的受歡迎，這是因為此網路有比 IEEE 802.11 無線區域網路(wireless local area networks, WLANs) 還要大很多的覆蓋面積，然而過大的覆蓋面積，很容易受到地形和距離的影響，因而造成使用者接收到的訊號強度太低;因此為了克服這個問題，許多的文章提出了訊號轉傳的概念來解決這一方面的問題，而由於中繼站(Relay Stations, RSs) 具有轉傳訊號的功能，所以在現今的無線網路中，中繼站被廣泛地使用在其中。

在現今的文章中，中繼站通常被應用在提升細胞系統邊界使用者的訊號強度，然而在一個細胞系統中，基地台(Base Station, BS) 透過一個中繼站在去做轉傳的工作需要經過兩個傳輸程序的時間，即是一個從基地台到中繼站的時間，另一個是從中繼站到使用者的時間，因此如果這兩個傳輸程序所經過的時間被考慮進去的話，那麼增加中繼站有可能會降低整個系統的容量，所以決定一個資料的傳送是經由直接傳送或是經過轉傳可由訊號的強度或是傳送量來做選取。

在這篇論文，我們主要的研究方向是要在細胞系統裡尋找一個最佳的中繼站放置的位置，讓整個系統的容量能夠達到最高的狀態。我們考量兩個中繼站選取的方法去決定是否這個轉傳的時機是必需和正確的;一個是以訊號強度來做選取，而另一個是以傳送量來做選取的動作。在這篇論文的結果中，我們可以發現以訊號強度來做選取的方法，可能有一些中繼站放置位置的系統容量會低於沒有加中繼站的情況產生;另外以傳送量來做選取的方法，我們可發現應用此方法去做選取能夠確保中站繼放置在任何位置都能產生不低於沒有加中繼站的情況。我們也確認了一個最佳的中繼站放置位置能夠達到最高的系統容量。此外增加中繼站的另一個優點就是能讓更多的使用者能夠達到最低的通訊可靠度，以及降低佈建成本，所以我們還做了一個研究是當中繼站被佈建在最佳的位置時，這整個細胞系統所能達到的最大覆蓋面積。

Summary

In recent years, the IEEE 802.16e wireless metropolitan area networks (WMANs) is becoming very popular. Due to larger coverage compared to the IEEE 802.11 wireless local area networks (WLAN). However, the larger coverage is easy to be influenced by terrain and distance effects. In order to overcome those issues, the concept of relay stations (RSs) is suggested.

Relay stations are usually used to enhance the signal strength for the users close to the cell boundary. However, transmission through a relay station needs two transmission phases, i.e., one is from the base station (BS) to the relay station and the other is from relay station to mobile stations (MSs). Thus, relay may also decrease system capacity if two-phase transmission time is considered. As a result, whether or not data are transmitted by one-hop or two-hop phases should be determined based on both signal strength and throughput. In this paper, we investigate the optimal relay location aiming to maximize system capacity. We consider two relay selection rules for determining whether a two-hop transmission is necessary: signal strength-oriented and throughput-oriented. We find that the signal strength-oriented two-hop transmission may yield even lower system capacity than the one-hop transmission. Based on the throughput-oriented rule, we find that the throughput in the two-hop transmission can be higher than that in the one-hop transmission at some locations. We also identify the optimal relay location that can achieve the highest system capacity, In addition, we also investigate the maximal coverage of the radio after placing RS at the optimal location.

Acknowledgments

I would like to thank my parents and old sister and brother. They always give me endless supports. I especially would like to thank Dr. Li-Chun Wang who gave me many valuable suggestions in the research during these two years. I would not finish this work without his guidance and comments.

In addition, I am deeply grateful to my laboratory mates, Jane-Hwa, Ming-Bing, Wei-Cheng, Chung-Wei, Chu-Jung, Yin-Chih, and Wei-Xian at WSL at the Department of Communications in National Chiao-Tung University. They provide me much assistance and share much happiness with me.

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CHAPTER 1

Introduction

In recent years, the rapid progress of wireless communication techniques, and various wireless networks have been widely deployed. Some important issues are worth studying that about enhance the system capacity, the coverage radius, and low deployment cost. Thus, the next generation wireless networks utilize various network devices to solve these issues effectively. For example, employing relay stations (RSs) can obviously improve the throughput for users close to the cell boundary and has the potential to extend the coverage radius of the radio for high signal strength in the infrastructure-based networks. Therefore, the effect of deploying multi-hop relay in the infrastructure-based networks will become more and more important for the next generation wireless networks.

In this thesis, we aim to investigate how to employ multi-hop relays to achieve the objectives of low cost, high transmission rates, and coverage extension. As shown in Fig. 1.1, on top of the infrastructure-based networks users at the cell boundary receive low signal strength. In order to overcome this issue, the multi-hop relays are applied in the cellular systems. We will evaluate the potential capacity enhancement and coverage enhancement by using multi-hop relay.

The concept of relay transmission was originated from the ad-hoc [1, 2] and peer-to-peer networks. Relay station concept was described in [3, 4]. Compared with BS, RS has a lower deployment cost and does not need to connect to the backhaul

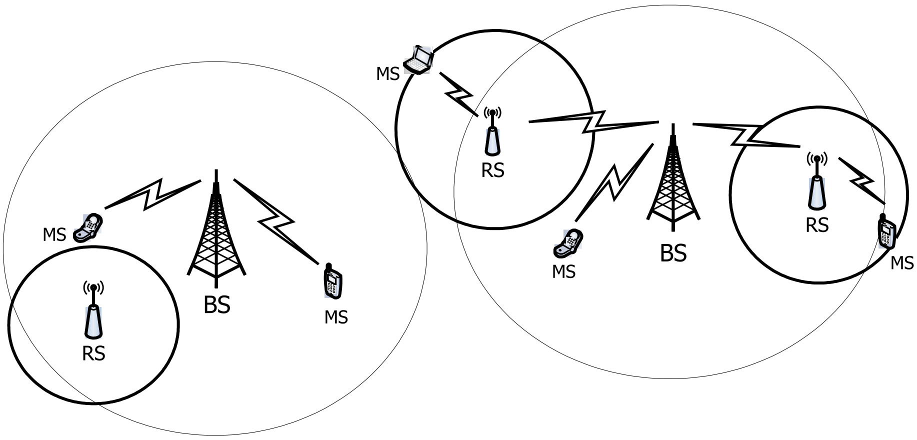


Figure 1.1: An infrastructure-based network and associated with relay station nodes.

network via cables. Therefore, relay stations are widely used in the infrastructure-based wireless networks. In general, relay station can be classified into two schemes : Amplify-and-Forward (AF) and Decode-and-Forward (DF). In this thesis, AF relay scheme is adopted in the cellular networks. Utilizing RSs can improve the signal strength of users and system capacity, thereby extending the coverage radius of the radio.

The objectives of this thesis are mainly to develop a method to find out the optimal relay location in the infrastructure-based networks that can achieve the maximal system capacity and the maximal coverage.

1.1 Problem and Solution

1.1.1 Capacity Enhancement by Optimal Relay Location

In this part, the objective is to design a method to determine the optimal relay location aiming to maximize the system capacity. In the literature, many studies have shown that deploying multi-hop relay can improve capacity in wireless cellular systems [5–7]. How to improve the system capacity in the multi-hop cellular systems is another important issue. First, transmission through a relay station needs two transmission phases, i.e., one is from the base station to the relay station and the other is from the relay station to mobile stations. Thus, relay may lower the system capacity due to two-phase transmission. Therefore, how to maintain or even to improve system capacity with two-phase transmissions is second issue. In this thesis, we discuss different relay selection rules to solve this issue. Second, the impact of RS locations on link reliability and system capacity is also an interesting issue. As shown in Fig. 1.2. When the relay station is deployed close to the BS, the near hop distance between BS and RS can obtain higher link capacity. However, the far users at the cell boundary will receive low signal strength. In case 2, when the relay station is deployed far away from BS, the users at the cell boundary can receive stronger signal to improve communication reliability. However, the longer hop distance between BS and RS results in lower relay link capacity. Therefore, determining appropriate relay location to improve the tradeoff between communication reliability and system capacity is important in the relaying networks.

In this section, we investigates how to deploy the relay stations in a two-hop network to maximize the system capacity. We consider two relay selection rules for determining whether a two-hop transmission will be used. The first one is the signal strength-oriented selection rule. For this rule, each user compares the received signal strength directly from BS and that from RS. The link with stronger signal strength will be adopted to improve the communication reliability. The second rule is the throughput-oriented selection. Based on this selection rule, each user will estimate the *effective transmission rate* for the link directly from BS and that via the two-hop communication. The link with better effective transmission rate is selected after comparison. We also consider two time-slot allocation schemes: equal time-duration and equal user-throughput. The former one allocates each user with the same fraction

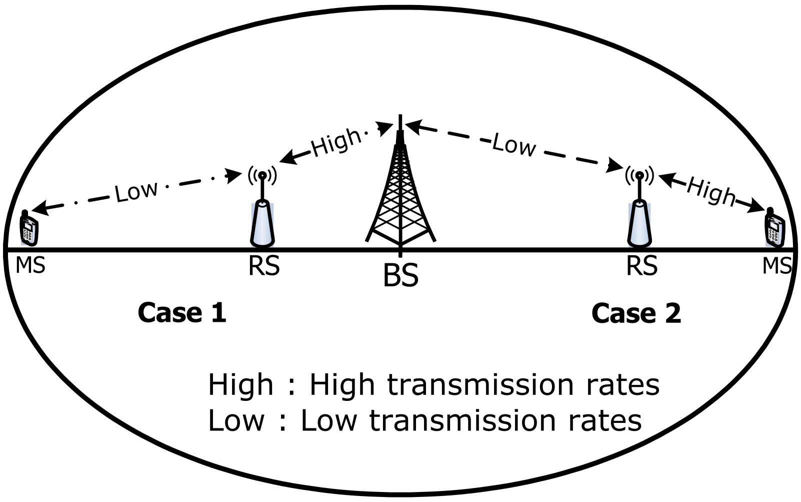


Figure 1.2: Effect of the relay location on the transmission rates

of time for data transmission. However, the later one allocates the radio resource (e.g. time-slot) to make each user have the same throughput. We will investigate the impact of time-slot allocation scheme on the optimal relay location. Based on these assumptions and simulations, we investigate how to find out the optimal relay location that can achieve the maximal system capacity.

1.1.2 Coverage Enhancement by Optimal Relay Location

In this part, the objective is to investigate to what extend does the coverage can be improved by placing RS at the optimal location. In the literature, many studies have investigated the impact of deploying multi-hop relay on the radio coverage in the cellular systems. [8,9]. Hence, some interesting factors that influence the radio coverage are worth while further investigation, such as the impact of various shadowing standard deviations, relay transmit power, and the number of RS on the radio coverage. First, the radio coverage can be improved in an environment with less shadowing. That is to say, the lower the shadowing standard deviation, the larger the radio coverage. Second, the radio coverage can be improved with bigger the relay transmit power. This is because a higher relay transmit power can significantly increase the signal quality for users, thereby improving radio coverage. Last, the radio coverage can be improved by deploying more RSs, because more number of RSs can provide services to more users. Combined the above advantages, we can exploit the potential benefits that the enhanced coverage of the radio by placing relay stations to serve larger radio coverage than the conventional one-hop networks.

In this part, we utilize the optimal relay location to determine the maximal radio coverage. This part contribution is able to know accurately the maximal coverage of the radio. In order to serve more users and reducing the deployment cost.

1.2 Thesis Outline

The rest of this thesis are organized as follows. Chapter 2 introduces the backgrounds on the characteristics of the multi-hop relay in the cellular systems and some definitions of the performance metrics. In Chapter 3, we describe the capacity analysis for two relay selection rules, “throughput-oriented rule” and “signal strength-oriented” and two time-slot allocation schemes, “equal time-duration scheme” and “equal user-throughput scheme”. In Chapter 4, we present numerical results about capacity enhancement with the optimal relay location. In Chapter 5, we present numerical results about coverage enhancement with the optimal relay location. At last, Chapter 6 gives the concluding remarks and suggestions for the future works.

CHAPTER 2

Background

In this chapter, we introduce the background of the characteristics of multi-hop relay in the cellular systems, and some definitions of the performance metrics.

2.1 Notable Features of Multi-hop Relays

Conventional multi-hop relay wireless networks were originated from the ad-hoc and peer-to-peer networks. Recently, the application of multi-hop networks are widely used in the infrastructure-base networks. Hence, the relaying technologies become more and more advanced and complicated in comparison to the conventional relays. The notable features of multi-hop relays are discussed as follow:

2.1.1 Radio Resources Selection

In a downlink relay network system, the additional radio resources are used on the different links between transmitter (BS or RS) and receiver (RS or MS). Hence, there are three kinds of resource allocation schemes [10] including,

- Relaying in the time-domain scheme: The same carrier frequency is operated on both sides of the relay station. The frame structure is used to connect nodes via a time-multiplexing channel. And each user uses the different time-slot to transmit data in the same TDMA frame. The TDMA frame is subdivided into three links in the relay network, one for the direct BS-MS links, one for the BS-RS links and one for the RS-MS links.

- Relay in the frequency-domain scheme: This concept means that BS and RSs are operated at two different carrier frequency. That is to say, BS transmits data to RS with carrier frequency f_1, and then RS transmit the received data to MS with carrier frequency f_2. This will increase the complexity of the hardware and the frequency management.
- Relaying in the hybrid time-/frequency-domain scheme: The concept is investigated in [11]. The basic idea is that the RSs periodically switches between carrier frequency f_1 and f_2. This concept allows the BS to use carrier frequency f_1 at the same time, while the RSs serve MSs on carrier frequency f_2. No additional extra device is needed for this scheme. But the fast frequency switching has to be supported, which will cause hardware complexity.

2.1.2 Relay Function Selection

In general, relay station can be classified as two schemes according to its function: (1) Amplify-and-Forward (AF): the Amplify-and-Forward scheme means that the relay station received signal and then simply amplify the signal before retransmission; (2) Decode-and-Forward (DF): the Decode-and-Forward scheme means that the relay stations de-code received signal and then re-encode the signal before retransmission [12, 13].

2.1.3 Macro-diversity Function

Macro-diversity mean that the transmitter (BS or RS) can serve more than one user at the same time. The receiver (RS or MS) may also communicate with more than one transmitter [14–16].

2.1.4 Relay Deployment Strategies

In the infrastructure-based networks, the access links are generally sheltered with the buildings or at indoors. This phenomenon is called the non-line-of-sight (NLOS) transmission. However, deploying RS can improve improve the transmission in the NLOS environment and can ensure a line-of-sight (LOS) transmission for RS link. There are two strategies that can be used to deploy RS in the infrastructure-based networks. One is to deploy RS in a vast space according to a careful plan. The other is to increase the antenna height of RSs. These two strategies are not mutually exclusive. Therefore, a cellular network can employ both of them when RSs are deployed.

2.2 Definitions and Performance Metrics

Here are some definitions and performance metrics used in this thesis.

2.2.1 Link Outage Probability

To begin with, we first define the link outage probability that reflects how reliable a communication system can support the corresponding link quality. For a infrastructure-based network system in a flat fading channel. When the received SNR is lower than the required received threshold z_{th} due to large attenuations, i.e. $P_{outage} = Pr[SNR < z_{th}]$. This situation is called the link outage. Denote the link outage probability as P_{outage} [17]. In addition, we define the shadow margin that introduce the area noise outage probability. The area noise outage probability is defined as the probability that the transmitted carrier power higher than the received signal power when averaging over the entire cell area.

2.2.2 Communication Reliability of Cell Coverage

With P_{outage} being the link outage probability for users, we define the cell coverage is the farthest distance at which the link quality enough for maintaining a required received SNR z_{th} with the communication reliability of cell coverage $(1 - P_{outage})$. In this thesis, we focus on the farthest user at the cell boundary. In other words, if the farthest user can maintain the link quality, the other users will maintain the link quality too.

CHAPTER 3

Capacity Analysis in Multi-Hop Cellular Systems

In this chapter, we develop a model to evaluate the system capacity with the optimal relay location in multi-hop cellular systems. In this study, we consider two relay selection rules for determining whether a two-hop transmission will be used. The first one is the signal strength-oriented selection rule. The second one is the throughput-oriented selection rule. Based on these two relay selection rules, we also define two time-slot allocation schemes. One is the equal time-duration allocation scheme and the other is the equal user-throughput allocation scheme. In addition, in order to further study the advantage of placing RS at the optimal location. We also investigate the coverage performance after placing RS at the optimal location.

The rest of this chapter are organized as follows. In section 3.1 introduce the system scenario. In section 3.2 describes the radio channel effects. In section 3.3, we discuss the relay link selection rules and the time-slot allocation schemes.

3.1 System Scenario

We consider a two-hop relaying network as shown in Fig. 3.1. Each cell consists of one BS, K RSs, $k = 1, ..., K$, and N MSs, $n = 1, ..., N$. The BS and RSs have omni-directional antennas. The coverage radius of BS and RSs are r_{bs} and r_{rs}, respec-

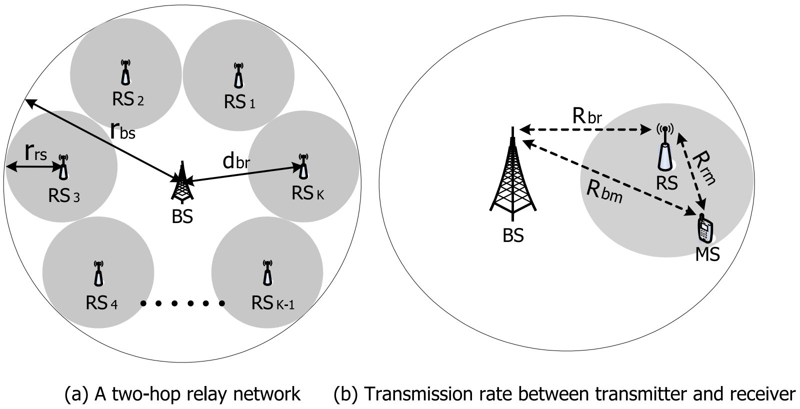


Figure 3.1: The architecture of a two-hop relay network with one BS and K RSs

tively. The RSs are regularly deployed around the BS with the separation distance d_{br} between BS and RS. The MSs are uniformly distributed in the cell. If one-hop transmission is used, the transmission rate R_{bm} can be achieved between BS and MS. If the two-hop transmission is used, the transmission rate R_{br} can be achieved between BS and RS, and the transmission rate R_{rm} can be achieved between RS and MS. Finally, according to each user received throughput to evaluate the system capacity in the time domain.

3.2 Radio Channel Effects

Due to the distance, for the users at the cell boundary received signal strength is low. Link outage occurs when the received SNR is lower than the required threshold. We denote the link outage probability as P_{outage}.

3.2.1 Radio Channel Characteristics

In this paper, the impacts of path loss and shadowing are considered [18]. Subject to path loss, the received power decays with the propagation distance r between the transmitter and the receiver. Shadowing is caused by obstacles between the transmitter and the receiver. Generally, shadowing is modeled by a log-normal random variable $10^{\xi/10}$. For transmission power is P_t, the received power can be written as

$$P_r = P_t \cdot (L_r)^{-1} \cdot 10^{\xi/10} \ . \tag{3.1}$$

where L_r represents the path loss; ξ is the Gaussian distributed random variable with zero mean and standard deviation (σ), and the probability of density function (*pdf*) is defined as

$$f_\xi(\xi) = \frac{1}{\sqrt{2\pi} \cdot \sigma} exp(-\frac{\xi^2}{2\sigma^2}) \ . \tag{3.2}$$

The path loss model is based on the basic model for IEEE802.16-2004 with relay station nodes [19]. The path loss model can be modeled as

$$L_r(dB) = \begin{cases} 20\log_{10}(\frac{4\pi r}{\lambda}) \ , & \text{for } r \leq r'_0 \\ A + 10\gamma\log_{10}(\frac{r}{r_0}) + \triangle L_{f_c} + \triangle L_{h_t} \ , & \text{for } r > r'_0 \end{cases} \tag{3.3}$$

where λ is the wavelength in meter, h_b is the antenna height of the transmitter (BS or RS), h_t is the antenna height of the receiver (RS or MS), f_c is the carrier frequency, and γ is the propagation parameter for appropriate terrain. Other parameters in (3.3) are defined as

$$A = 20\log_{10}(\frac{4\pi r'_0}{\lambda})$$

$$r_0 = 100m$$

$$r'_0 = r_0 10^{-(\frac{\triangle L_{f_c} + \triangle L_{h_t}}{10\gamma})}$$

$$\gamma = 3.6 - 0.005h_b + \frac{20}{h_b}$$

Table 3.1: **The Parameters for the Terrain A/B/C**

Terrain Type	**Terrain A**	**Terrain B**	**Terrain C**
a	**4.6**	**4**	**3.6**
b	**0.0075**	**0.0065**	**0.005**
c	**12.6**	**17.1**	**20**

$$\triangle\, L_{f_c} = 6\log_{10}\left(\frac{f_c(MHz)}{2000}\right)$$

$$\triangle\, L_{h_t} = \begin{cases} -10\log_{10}(\frac{h_t}{3}) \;\;, & \text{for } h_t \leq 3m \\ -20\log_{10}(\frac{h_t}{3}) \;\;, & \text{for } h_t > 3m \end{cases}$$

Three propagation scenarios according to different terrain are described as follows:

- Terrain A : Hilly terrain with moderate-to-heavy tree densities
- Terrain B : Intermediate path-loss condition
- Terrain C : Flat terrain with light tree densities

where the corresponding parameters for each propagation scenario are given in Table. 3.1.

3.2.2 Link Outage Probability

In general, the signal-to-noise (SNR) can be expressed as

$$SNR = \frac{P_t \cdot (L_r)^{-1} \cdot 10^{\xi/10}}{N_0} \tag{3.4}$$

where N_0 is the noise power. A data packet is outaged if the signal-to-noise (SNR) is lower than a specified threshold z_{th}. The SNR is equal to

$$\begin{aligned} P_{outage} &= Pr[SNR < z_{th}] \\ &= Pr[\frac{P_t \cdot (L_r)^{-1} \cdot 10^{\xi/10}}{N_0} < z_{th}] \ . \end{aligned} \tag{3.5}$$

Now we study the influence of the log-normal shadowing on the outage probability. There are two outage probability against the shadow margin. The first one is the *edge noise outage probability*, the second one is the *area noise outage probability* [20]. In the paper, we use the area noise outage probability to determine the required shadow margin. Assume that P_t is identical for all the BSs and MSs, the MSs are uniformly distributed throughout all the cell area. (3.5) can be rewritten as follows:

$$\begin{aligned} P_{outage} &= Pr[\xi < 10 \log_{10} z_{th} L_r \frac{N_0}{P_t}] \\ &= \frac{1}{\pi R^2} \int_0^R \int_{-\infty}^{10 \log_{10} z_{th} L_r \frac{N_0}{P_t}} f_\xi(\xi) \cdot 2\pi r dr d\xi \\ &= \frac{2}{R^2} \int_0^R (1 - Q(\frac{10 \log_{10} z_{th} L_r \frac{N_0}{P_t}}{\sigma})) \cdot r dr \ , \end{aligned} \tag{3.6}$$

where

$$Q(z) = \int_z^\infty \frac{1}{\sqrt{2\pi}} \cdot e^{-y^2/2} dy \ . \tag{3.7}$$

and R is the cell radius. We assume that the BS is located at the center of a cell. In the single cell case, we discuss the impact of shadowing on the radio coverage (BS/RS) for various shadowing standard deviations (σ).

3.3 Relay Selection Rules And Time-Slot Allocation Schemes

In a two-hop relay-based network as shown in Fig. 3.1, the data packets can be delivered directly from BS or by a two-hop transmission. This section discusses two selection rules for relay links: throughput-oriented and signal strength-oriented.

3.3.1 Relay Selection Rules

- **Throughput-Oriented (TO) Selection Rule:**

  In this scheme, data are delivered by two-hop transmissions if forwarding the packets via relay can have a higher transmission rate. Referring to Fig. 3.1(b), it is assumed that R_{bm} is the transmission rate in the link between BS and MS; R_{br} is the transmission rate between BS and RS; and R_{rm} is the transmission rate between RS and MS. Consider a packet with size P. With two transmission phases, the effective transmission rate R_{brm} for a two-hop communication can be computed as

$$R_{brm} = \frac{P}{t_{BS-RS-MS}} = \frac{P}{\frac{P}{R_{br}} + \frac{P}{R_{rm}}} = \left(\frac{1}{R_{br}} + \frac{1}{R_{rm}}\right)^{-1} \tag{3.8}$$

  where $t_{BS-RS-MS} = \frac{P}{R_{br}} + \frac{P}{R_{rm}}$ is the total transmission time via a two-hop communication. In this scheme, considering two-phase transmission time, data will be delivered by two-hop communications, if the following condition is sustained

$$R_{brm} > R_{bm} \ . \tag{3.9}$$

  Therefore, according to the throughput-oriented selection rule, the transmission rate $R_e(n)$ of user n is equal to

$$R_e(n) = \max(R_{bm}, R_{brm}) \ . \tag{3.10}$$

- **Signal Strength-Oriented (SSO) Selection Rule:**

  In this scheme, one will adopt the two-hop transmission to deliver data if the received signal strength from RS is stronger than that from BS. Clearly, this scheme aims at improve the link reliability. Therefore, the effective transmission rate $R_e(n)$ is equal to

$$R_e(n) = \begin{cases} R_{brm} \ , & \text{if } Signal_{RS} > Signal_{BS} \\ R_{bm} \ , & \text{Otherwise} \end{cases} \tag{3.11}$$

3.3.2 Time-Slot Allocation Schemes

In this thesis, we also consider two time-slot allocation schemes: equal time-duration and equal user-throughput allocation schemes.

- **Equal Time-Duration (ETD) Allocation:**

  In this scheme, each user is allocated with the same fraction of time for data transmission no matter data are transmitted directly from BS or by two-hop communication. As depicted in Fig. 3.2, we consider a cell with N users. The effective transmission rate for each user is $R_e(n)$. Since all the user evenly share the radio resource, the system capacity are given

$$C = \frac{\sum\limits_{n=1}^{N} R_e(n)}{N} \ . \tag{3.12}$$

- **Equal User-Throughput (EUT) Allocation:**

  The main concept of this scheme is to allocate the time-slot so that all the users have the same throughput. Clearly, this scheme can achieve the fairness for each user in terms of throughput. Suppose that during a time interval, each user sends a packet with the same size P as shown in Fig. 3.3. The total transmission time for

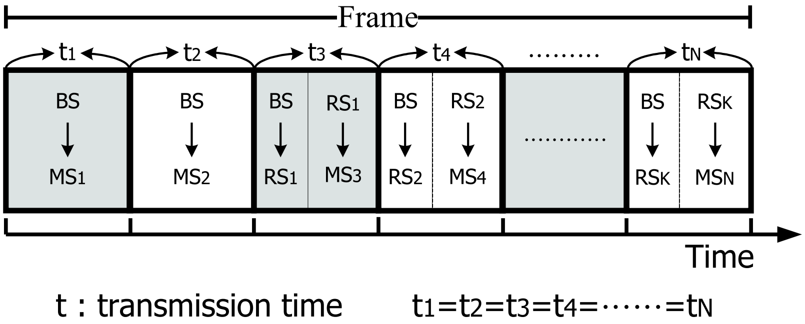


Figure 3.2: Frame structure of cell for the equal time-duration allocation scheme with N users

N packets is equal to $\sum_{n=1}^{N} \frac{P}{R_e(n)}$. Therefore, the system capacity can be expressed as

$$\begin{aligned} C &= \frac{Total\ transmitted\ data\ bits}{Total\ transmission\ time} \\ &= \frac{N \cdot P}{\sum_{n=1}^{N} \frac{P}{R_e(n)}} \\ &= N \cdot \left(\sum_{n=1}^{N} \frac{1}{R_e(n)}\right)^{-1} \ . \qquad (3.13) \end{aligned}$$

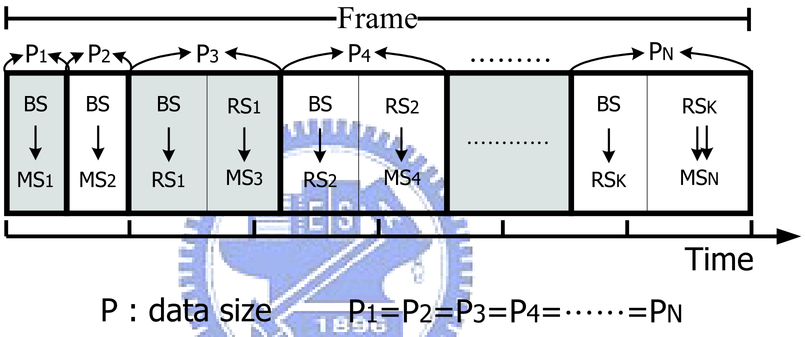


Figure 3.3: Frame structure of cell for the equal user-throughput allocation scheme with N users

CHAPTER 4

Capacity Enhancement by Optimal Relay Location

In this chapter, we compare the achieved system capacity according to the throughput-oriented and signal strength-oriented relay selection rules. In the numerical results, we assume that there are a few RSs in a cell and the users are uniformly distributed in the cell. We consider the seven modulation coding schemes (MCSs) in the IEEE 802.16 standard, as shown in Fig. 4.1. The figure shows that the transmission rate and the adopted modulation coding schemes are determined according to the separation distance between transmitter (BS/RS) and receiver (RS/MS). Table. 4.1 lists the required SINR and net data rate for the seven MCSs [21]. Simulation parameters are listed in Table. 4.2. We can estimate system capacity with the outage probability is 0.1.

Fig. 4.2 shows the flow chart, for finding the optimal relay location. From the flow chart, we can obtain some interesting numerical results as follows:

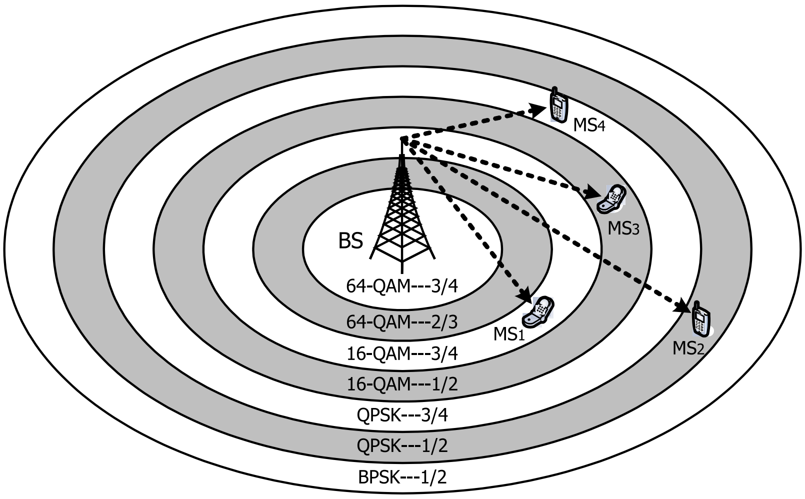


Figure 4.1: The transmission range of the modulation coding schemes in a cellular network.

Table 4.1: **The Required SINR And Net Data Rate With Different Modulation Coding Schemes**

MCS	Modulation	Code Rate	SINR	Net Date Rate
1	BPSK	1/2	0.0 dB	1.29 Mbit/s
2	QPSK	1/2	2.5 dB	2.59 Mbit/s
3	QPSK	3/4	6.0 dB	3.88 Mbit/s
4	16-QAM	1/2	9.0 dB	5.18 Mbit/s
5	16-QAM	3/4	12.0 dB	7.77 Mbit/s
6	64-QAM	2/3	16.0 dB	10.37 Mbit/s
7	64-QAM	3/4	21.0 dB	11.66 Mbit/s

Table 4.2: **Essential Simulation Parameters**

Parameter	**Value**
BS transmit power (P_t)	**40 dBm**
RS transmit power (P_t)	**37 dBm**
Noise power (N_0)	**-102 dBm**
Outage requirement	**0.1**
BS radius (R)	**1750 m**
BS antenna height (h_t)	**30 m**
RS antenna height (h_t/h_r)	**15 m**
BS/RS antenna	**Omni-directional**
MS antenna height (h_r)	**2 m**
Carrier frequency (f_c)	**3.5 GHz**
System bandwidth (BW)	**3.5 MHz**
Standard deviation (σ)	**8 dB**
Modulation coding scheme (MCS)	**BPSK 1/2, 4-QAM 1/2 and 3/4, 16-QAM 1/2 and 3/4, 64-QAM 2/3 and 3/4**

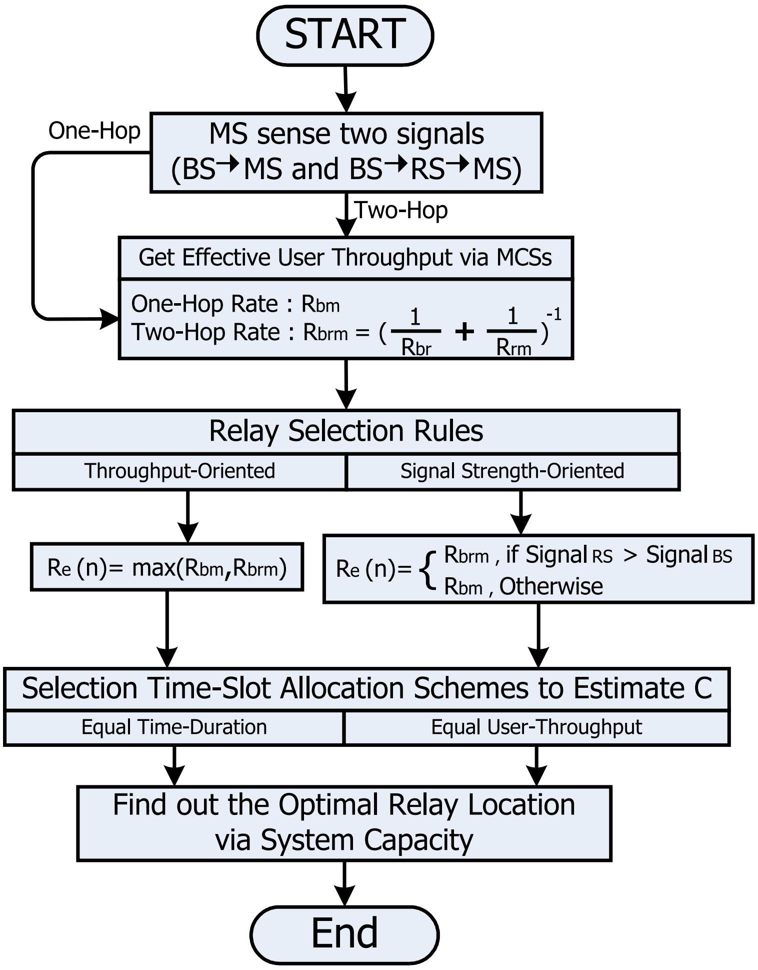
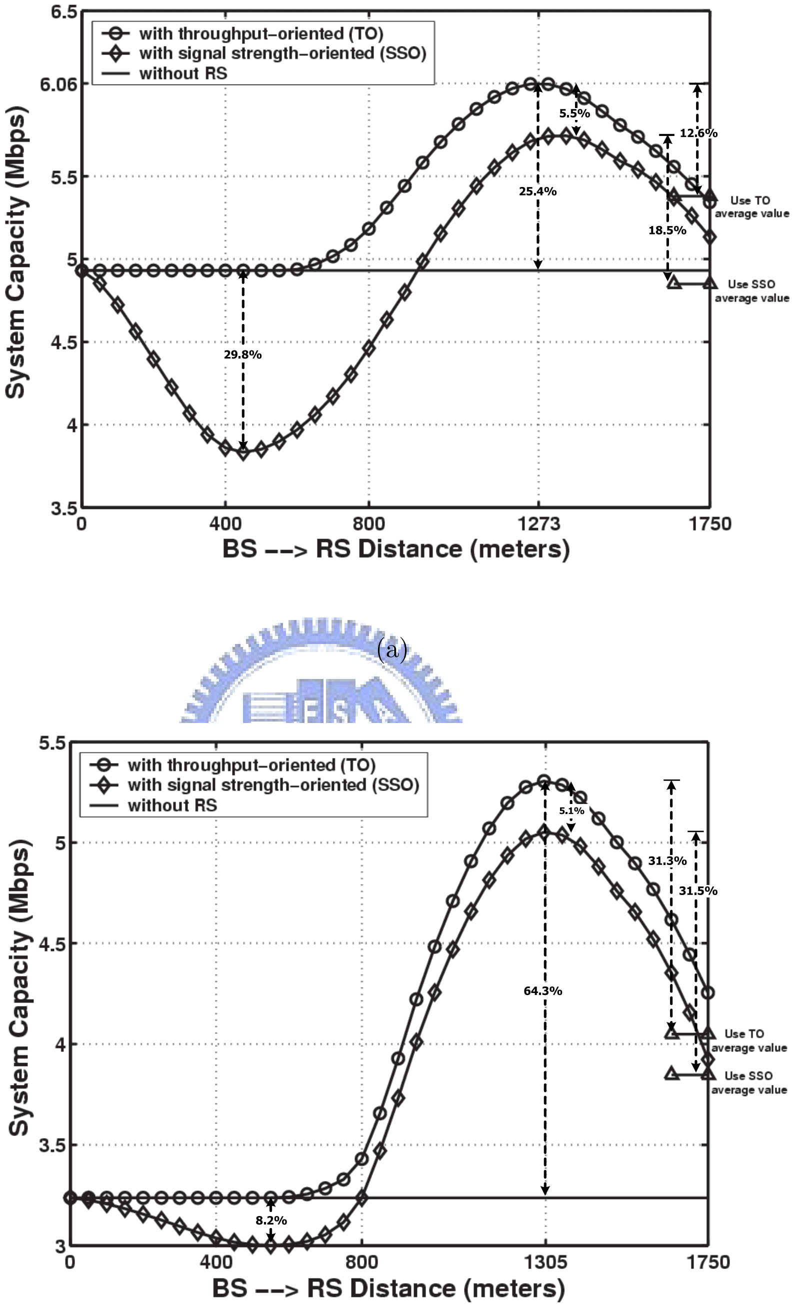


Figure 4.2: Flow chart for determining the optimal relay location.



(a)

(b)

Figure 4.3: Achieved system capacity according to various relay selection rules, for (a) the equal time-duration allocation scheme and (b) the equal user-throughput allocation scheme.

4.1 Impact of Relay Selection Rule on System Capacity

Fig. 4.3(a) shows the achieved system capacity versus the separation distance between BS and RS, where the equal time-duration allocation scheme is used. Obviously, the throughput-oriented two-hop transmission can achieve higher system capacity. Furthermore, if employing the throughput-oriented relay selection rule, there exists an optimal relay location to maximize the system capacity. In this example, the optimal relay location is at 1273 meter away from the center of a cell. Compared with the signal strength-oriented rule, the system capacity of the optimal relay location increases 5.5%. Compared with the average value of throughput-oriented rule, the system capacity of the optimal relay location is 12.6% higher. Compared with the network without RS, the system capacity with the optimal relay location improves 25.4%. In addition, this figure also shows that the signal strength-oriented two-hop transmission may yield lower system capacity than the one-hop transmission at some locations, where at most 29.8% capacity reduction is possible. Compared with the average value of signal strength-oriented rule, the system capacity of the optimal relay location increases 18.5% . This phenomenon is due to the fact that transmission through a relay station requires two transmission phases. By using the signal strength-oriented relay link selection, some users exploit the two-hop communications to improve link reliability at the cost of lower capacity.

Fig. 4.3(b) illustrates the system capacity for the equal user-throughput allocation scheme. In the figure, one can see that the optimal relay location is at 1305 meter according to the throughput-oriented relay selection rule. Compared with the signal strength-oriented rule, the system capacity of the optimal relay location is 5.1% higher. Compared with the average value of throughput-oriented rule, the system capacity of the optimal relay location improves 31.3%. Compared with the network without RS, the system capacity of the optimal relay location is increased by 64.3%. In addition, it is also shown that the signal strength-oriented two-hop transmission causes lower system capacity than the one-hop transmission at some locations. At most 8.2% capacity degradation occurs. But compared with the average value of signal strength-oriented rule, the system capacity of the optimal relay location improve 18.5%. From Fig. 4.3(a) and Fig. 4.3(b), it is also shown that the equal user-throughput allocation scheme results in a lower system capacity. According to the equal user-throughput allocation scheme, the user with lower transmission rate will be allocated with more radio resource to achieve the same throughput for each user, thereby lowering the overall system capacity.

4.2 PMF of Effective User Throughput

Fig. 4.4, shows the probability mass function (PMF) of effective user throughput with the optimal relay location for various relay selection rule. We can use the figure to explain Fig. 4.3(a) and Fig. 4.3(b). First, compared these two relay selection rules of the throughput-oriented and without RS, it is obvious that the throughput-oriented rule reduces the probability of using the effective user throughput from $1Mbps$ to $4Mbps$, but increases the probability of using the effective user throughput from $4Mbps$ to $6Mbps$. The system capacity of the throughput-oriented rule is superior to the network without RS. Secondly, compared these two relay link selection rules of the throughput-oriented rule and the signal strength-oriented rule, we can find the signal strength-oriented rule seriously reduces the probability of using the higher effective user throughput between from $5Mbps$ to $10Mbps$, but increases the probability of using the lower effective user throughput from $4Mbps$ to $5Mbps$. In short, the system capacity of the throughput-oriented rule is superior to the signal strength-oriented rule.

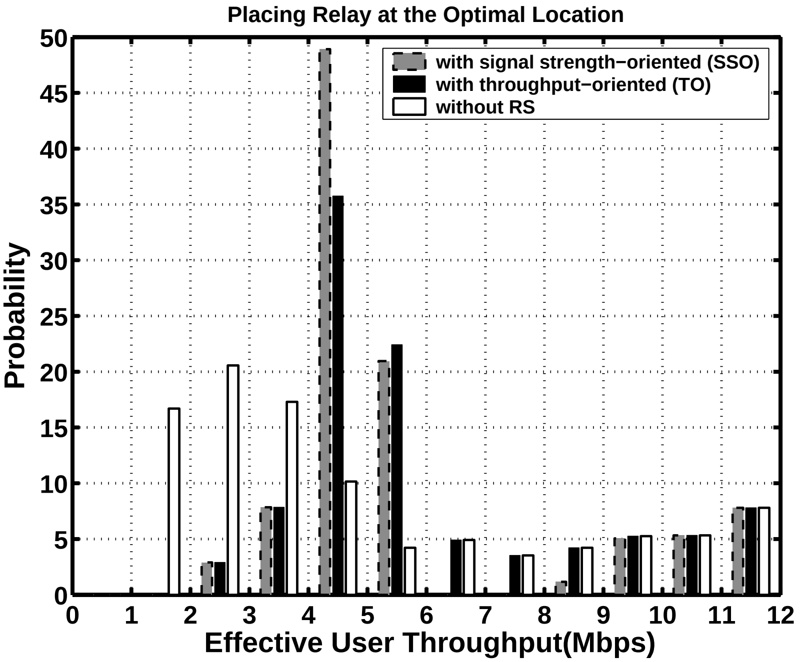


Figure 4.4: The PMF of effective user throughput according to various relay selection rules, when the equal time-duration allocation scheme is used.

4.3 Impact of Shadowing Standard Deviation on the Optimal Relay Location

In order to further understand the impact of the optimal relay location, we study the effects of shadowing standard deviation, relay transmit power, and the constant total relay transmit power. In Fig. 4.5, shows the achieved system capacity versus the separation distance between BS and RS, for various shadowing standard deviations. We can see that the smaller the shadowing standard deviation, the larger the system capacity. Fig. 4.6(a), shows the optimal relay location against the separation distance between BS and RS, for various shadowing standard deviations. It was shown that as the shadowing standard deviation increases, the optimal separation distance between

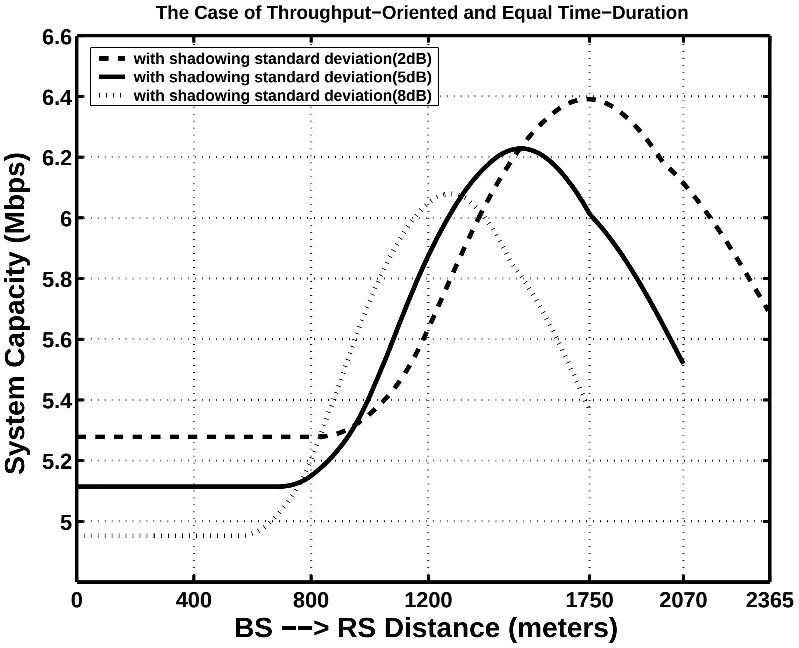
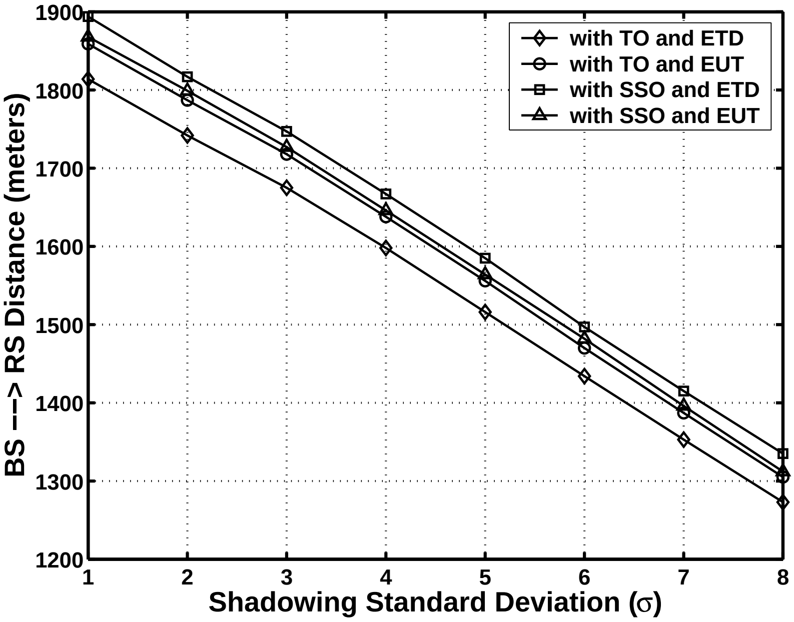
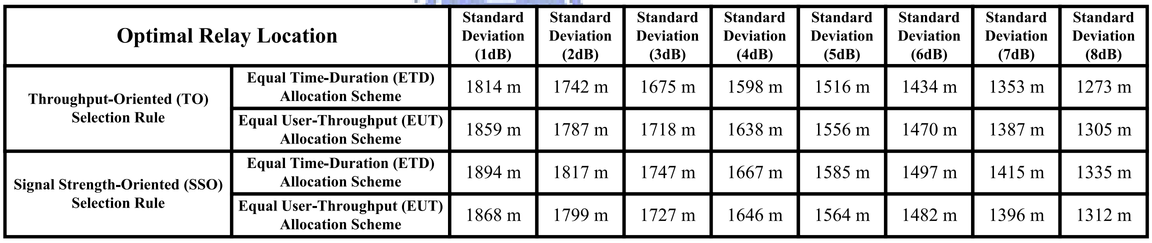


Figure 4.5: Effect of shadowing on the optimal relay location.



(a)



Optimal Relay Location		Standard Deviation (1dB)	Standard Deviation (2dB)	Standard Deviation (3dB)	Standard Deviation (4dB)	Standard Deviation (5dB)	Standard Deviation (6dB)	Standard Deviation (7dB)	Standard Deviation (8dB)
Throughput-Oriented (TO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	1814 m	1742 m	1675 m	1598 m	1516 m	1434 m	1353 m	1273 m
	Equal User-Throughput (EUT) Allocation Scheme	1859 m	1787 m	1718 m	1638 m	1556 m	1470 m	1387 m	1305 m
Signal Strength-Oriented (SSO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	1894 m	1817 m	1747 m	1667 m	1585 m	1497 m	1415 m	1335 m
	Equal User-Throughput (EUT) Allocation Scheme	1868 m	1799 m	1727 m	1646 m	1564 m	1482 m	1396 m	1312 m

(b)

Figure 4.6: (a) The optimal relay location for various shadowing standard deviations, (b) Corresponding data of figure (a)

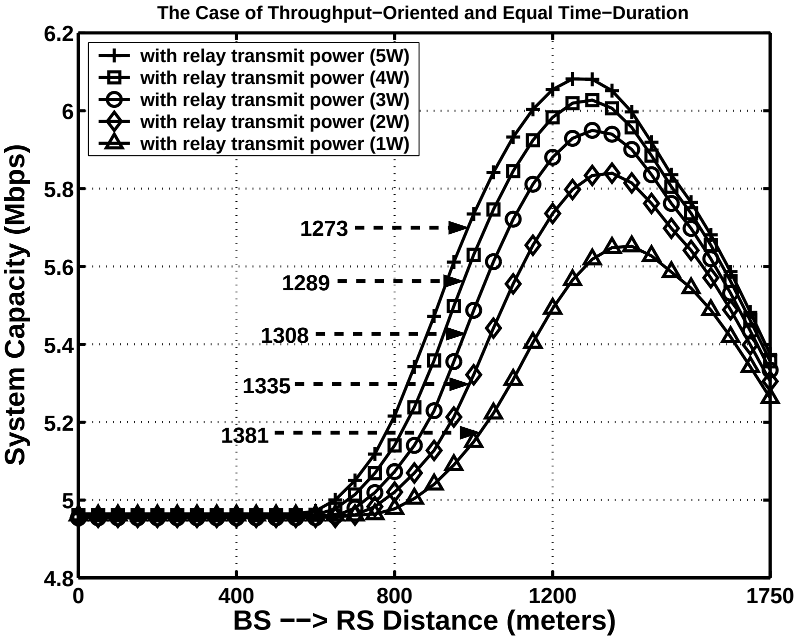
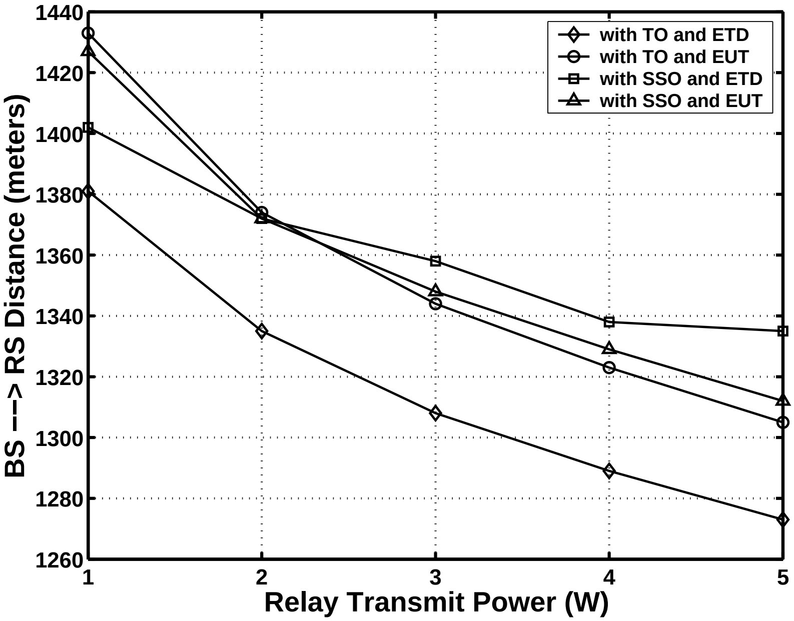


Figure 4.7: Effect of relay transmit power on the optimal relay location.

BS and RS decreases. This is because for a large the shadowing standard deviation has a smaller coverage radius of the radio (BS/RS). Therefore, as the shadowing standard deviation increases, the optimal distance between BS and RS relative decreases. Fig. 4.6(a) shows that the corresponding data of the optimal relay location for various shadowing standard deviations.

4.4 Impact of Relay Transmit Power on the Optimal Relay Location

Fig. 4.7, shows that the achieved system capacity versus the separation distance between BS and RS, for various relay transmit power levels. We can observe that the larger the relay transmit power, the higher the system capacity and the coverage



(a)

Optimal Relay Location		RS Power (1W)	RS Power (2W)	RS Power (3W)	RS Power (4W)	RS Power (5W)
Throughput-Oriented (TO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	1381 m	1335 m	1308 m	1289 m	1273 m
	Equal User-Throughput (EUT) Allocation Scheme	1433 m	1374 m	1344 m	1323 m	1305 m
Signal Strength-Oriented (SSO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	1402 m	1372 m	1358 m	1338 m	1335 m
	Equal User-Throughput (EUT) Allocation Scheme	1427 m	1372 m	1348 m	1329 m	1312 m

(b)

Figure 4.8: (a) The optimal relay location for various relay transmit power, (b) Corresponding data of figure (a)

radius of RSs. Fig. 4.8(a) shows the optimal relay location against the separation distance between BS and RS, for various relay transmit power. It is expected that a higher relay transmit power can achieve a higher system capacity. This figure also shows that the optimal separation distance between BS and RS decreases as the relay transmit power increases. For a larger relay transmit power, a relatively coverage radius of RS become larger. Therefore, reducing the separation distance between BS and RS can help more users to improve their throughput, thereby increasing the overall system capacity. In Fig. 4.8(b), it is shown that the corresponding data of the optimal relay location for various relay transmit power.

4.5 Impact of Constant Total Relay Transmit Power on the Optimal Relay Location

In Fig. 4.9, we show that the achieved system capacity versus the separation distance between BS and RS, for various constant total relay transmit power. One can see that the combination of more RSs and the lower relay transmit power can achieve a higher system capacity [22]. Because the combination can support more users, so that it can get higher system capacity. Fig. 4.10(a), shows that the optimal relay location against the separation distance between BS and RS, for constant total relay transmit power. From the figure, one can see that the combination of fewer RSs and the larger relay transmit power has a smaller optimal separation distance between BS and RS. Fig. 4.10(b) shows that the corresponding data of the optimal relay locations for constant total relay transmit power.

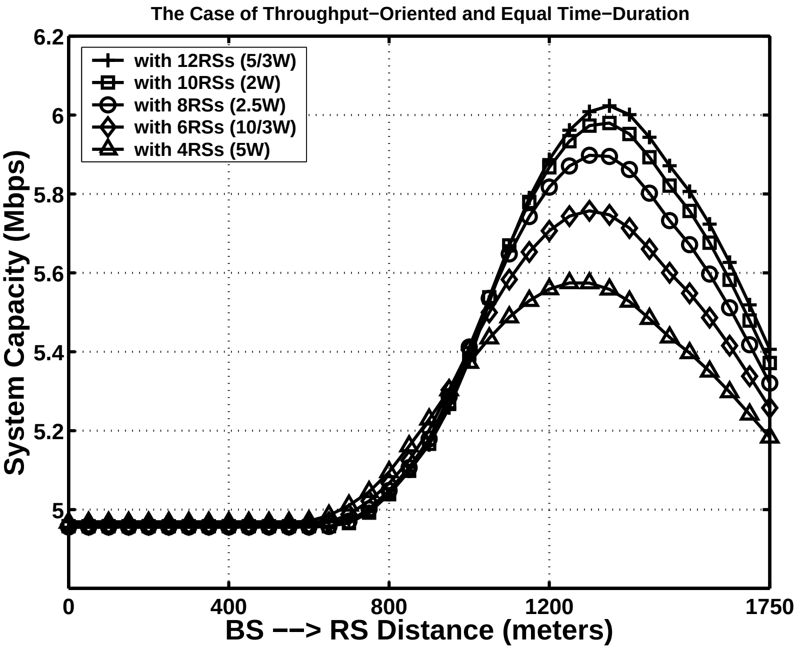
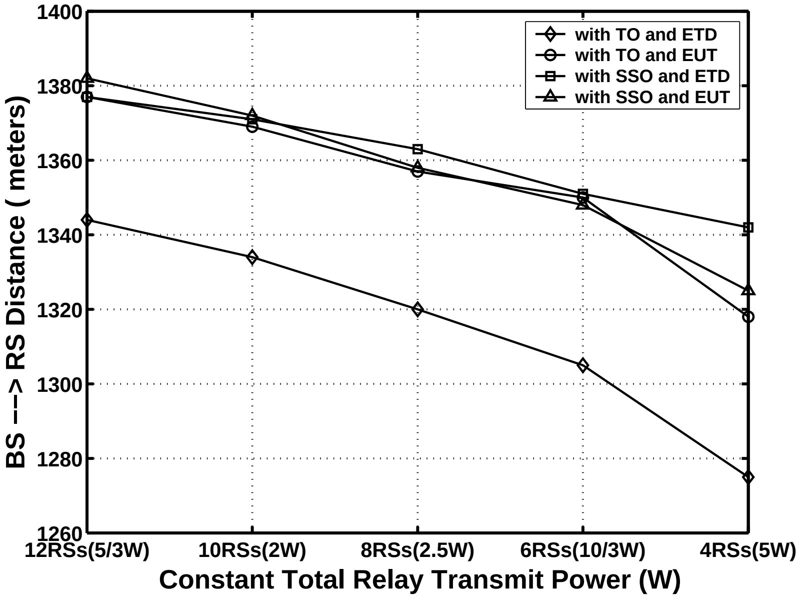


Figure 4.9: Effect of constant total relay transmit power on the optimal relay location.



(a)

Optimal Relay Location		**12RS-5/3W**	**10RS-2W**	**8RS-2.5W**	**6RS-10/3W**	**4RS-5W**
Throughput-Oriented (TO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	1344 m	1334 m	1320 m	1305 m	1275 m
	Equal User-Throughput (EUT) Allocation Scheme	1377 m	1369 m	1357 m	1350 m	1318 m
Signal Strength-Oriented (SSO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	1377 m	1371 m	1363 m	1351 m	1342 m
	Equal User-Throughput (EUT) Allocation Scheme	1382 m	1372 m	1358 m	1348 m	1325 m

(b)

Figure 4.10: (a) The optimal relay location for constant total relay transmit power, (b) Corresponding data of figure (a)

CHAPTER 5

Coverage Enhancement by Optimal Relay Location

Usually, RS are used to improve higher signal strength for users at the cell boundary. That is, RS can extend coverage of a BS. In this thesis, we utilize the result of Chapter 4 to evaluate the maximal radio coverage. We compare the coverage of the radio according to two relay selection rules and two time-slot allocation schemes, for various shadowing standard deviations, relay transmit power, and constant total relay transmit power. In our simulation, the maximal radio coverage is determined for outage probability of 0.1.

Fig. 5.1, illustrates the flow chart of computing the radio coverage. In this chart, we can produce some interesting numerical results.

5.1 CDF of Users' SINR

In order to further understand the advantage of placing RS at the optimal location, we observe the optimal relay location for various relay selection rules from the viewpoint of signal strength. Fig. 5.2, shows that the cumulative distribution function (CDF) of users' SINR. Because of the outage probability requirement is 0.1, we will pay attention to the abscissa line of 0.9. We find that the SINR of the throughput-oriented rule and the signal strength-oriented rule are obviously higher than the network without

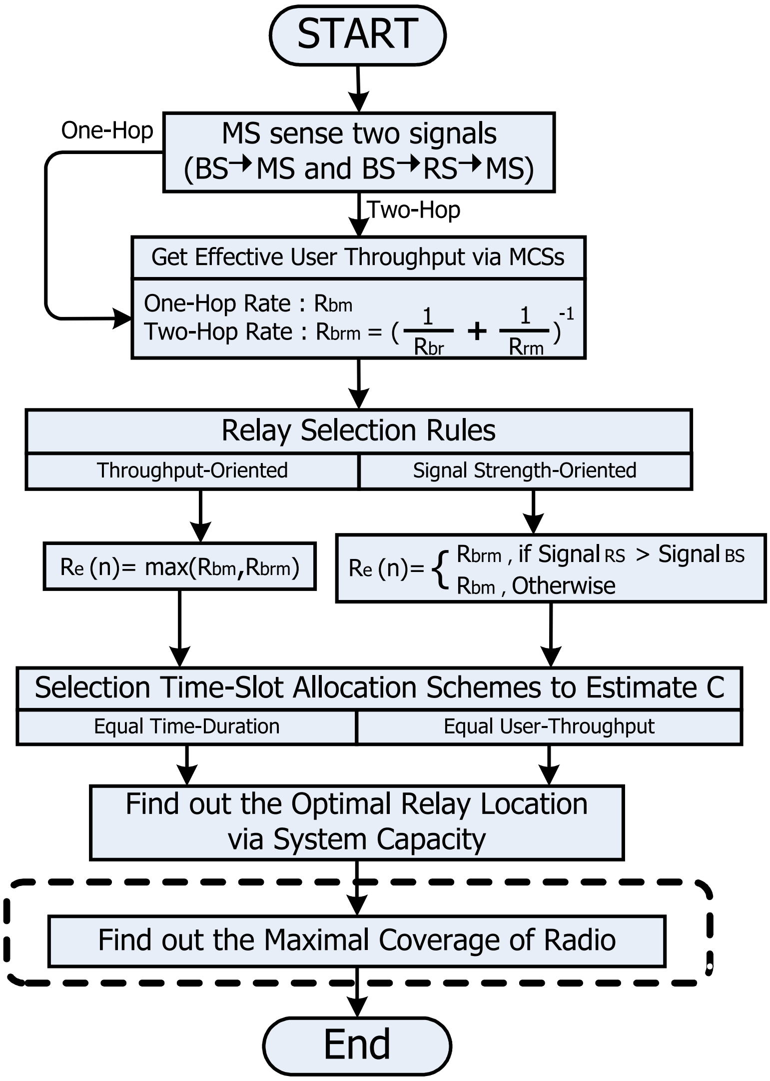


Figure 5.1: Flow chart for determining the enhancement coverage of the radio.

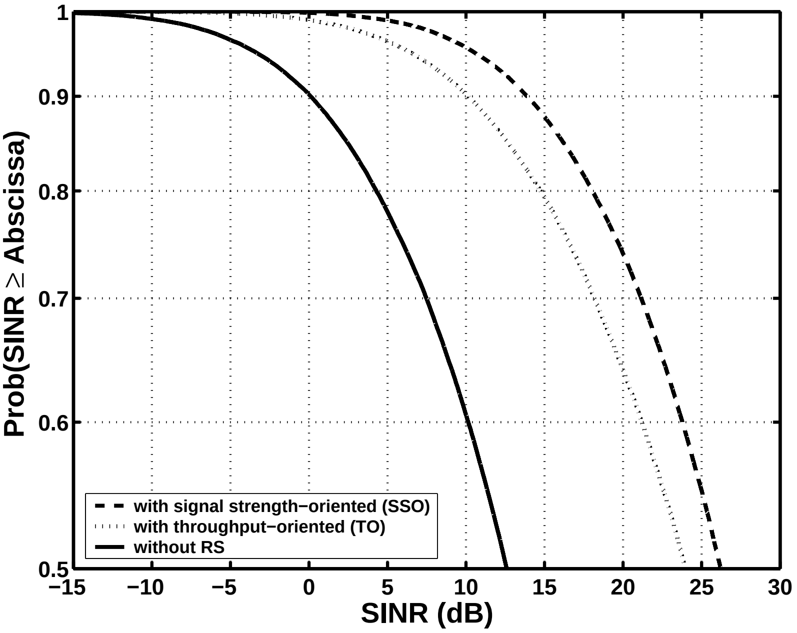


Figure 5.2: The CDF of users' SINR according to various relay selection rules, when the equal time-duration allocation scheme is used.

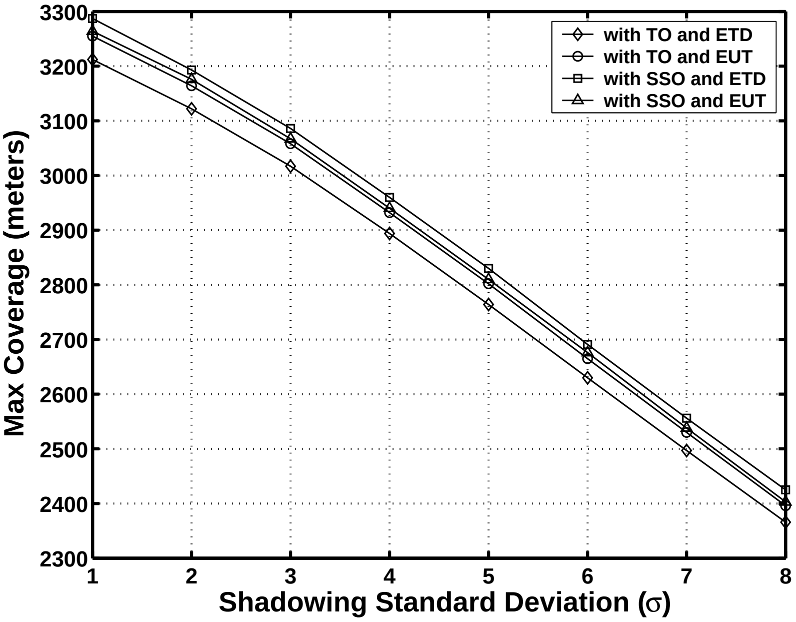
RS. From this result, we can understand that the coverage of BS can be enhanced and it can serve more users after placing RS at the optimal location.

5.2 Impact of Shadowing Standard Deviation on Coverage Enhancement

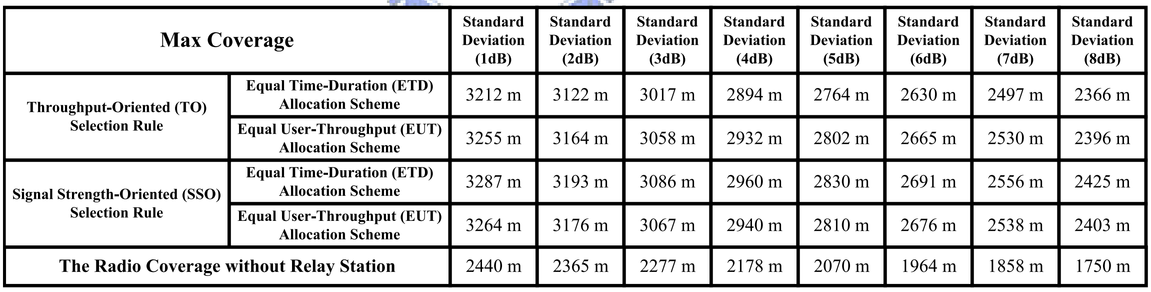
After placing RS at the optimal location, we can utilize the outage requirement to estimate the maximal coverage of the radio. Fig. 5.3(a), shows the enhanced coverage of the radio after placing RS at the optimal location for various shadowing standard deviations. We can observe a phenomenon that as the value of standard deviation increases, the enhancement coverage of the radio decreases. For a larger the shadowing standard deviation, smaller coverage radius of the radio (BS/RS) and the smaller optimal relay location against the separation distance between BS and RS occur. When the shadowing standard deviation increases, the enhancement coverage of the radio also relatively decreases compared with the smaller shadowing standard deviation. In Fig. 5.3(b), we see that the corresponding the maximal radio coverage for various shadowing standard deviations.

5.3 Impact of Relay Transmit Power on Coverage Enhancement

Fig. 5.4(a) shows the maximal radio coverage after placing RS at the optimal location for various relay transmit power. From Fig. 4.8(a), we know that a larger relay transmit power results in a smaller optimal separation distance between BS and RS, but the radio coverage is extended as shown in Fig. 5.4(a). This is because the impact of relay transmit power on the coverage radius of RS higher than the distance



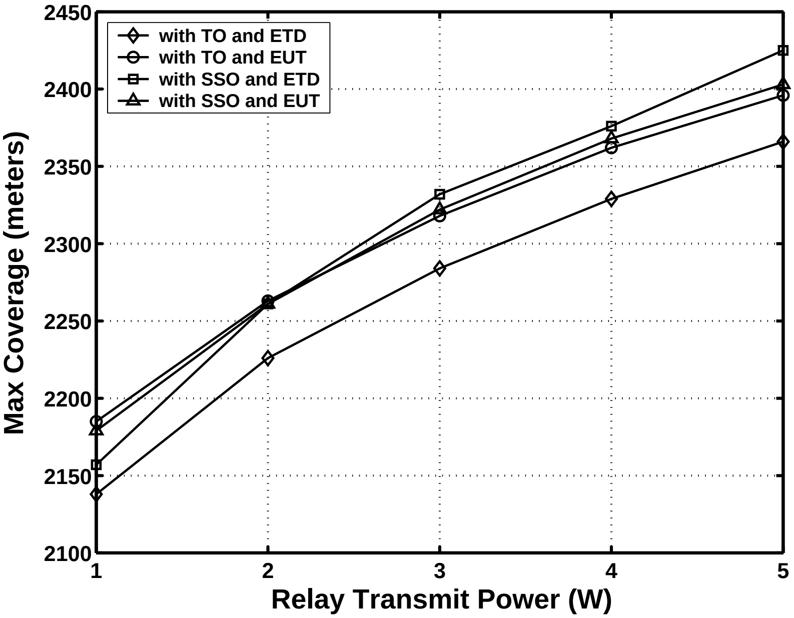
(a)



Max Coverage		Standard Deviation (1dB)	Standard Deviation (2dB)	Standard Deviation (3dB)	Standard Deviation (4dB)	Standard Deviation (5dB)	Standard Deviation (6dB)	Standard Deviation (7dB)	Standard Deviation (8dB)
Throughput-Oriented (TO) Selection Rule	Equal Time-Duration (ETD) Allocation Scheme	3212 m	3122 m	3017 m	2894 m	2764 m	2630 m	2497 m	2366 m
	Equal User-Throughput (EUT) Allocation Scheme	3255 m	3164 m	3058 m	2932 m	2802 m	2665 m	2530 m	2396 m
Signal Strength-Oriented (SSO) Selection Rule	Equal Time-Duration (ETD) Allocation Scheme	3287 m	3193 m	3086 m	2960 m	2830 m	2691 m	2556 m	2425 m
	Equal User-Throughput (EUT) Allocation Scheme	3264 m	3176 m	3067 m	2940 m	2810 m	2676 m	2538 m	2403 m
The Radio Coverage without Relay Station		2440 m	2365 m	2277 m	2178 m	2070 m	1964 m	1858 m	1750 m

(b)

Figure 5.3: (a) The maximal coverage for various shadowing standard deviations, (b) Corresponding the maximal radio coverage of figure (a)



(a)

Max Coverage		**RS Power (1W)**	**RS Power (2W)**	**RS Power (3W)**	**RS Power (4W)**	**RS Power (5W)**
Throughput-Oriented (TO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	2138 m	2226 m	2284 m	2329 m	2366 m
	Equal User-Throughput (EUT) Allocation Scheme	2185 m	2263 m	2318 m	2362 m	2396 m
Signal Strength-Oriented (SSO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	2157 m	2261 m	2332 m	2376 m	2425 m
	Equal User-Throughput (EUT) Allocation Scheme	2179 m	2261 m	2322 m	2368 m	2403 m
The Radio Coverage without Relay Station		1750 m				

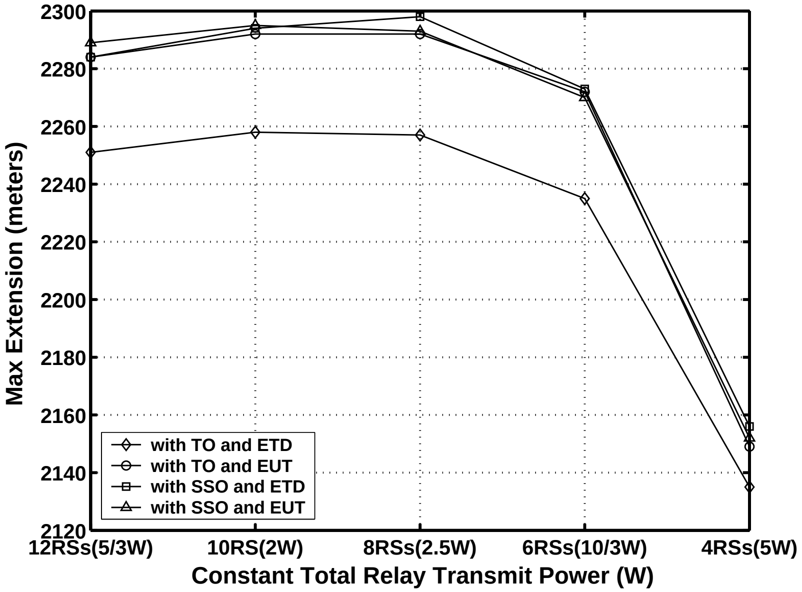
(b)

Figure 5.4: (a) The maximal coverage for various relay transmit power, (b) Corresponding the maximal radio coverage of figure (a)

of the optimal relay location between various relay transmit power. Therefore, a larger relay transmit power can lead to a larger radio coverage. Fig. 5.4(b) shows the corresponding the maximal radio coverage for various relay transmit power.

5.4 Impact of Constant Total Relay Transmit Power on Coverage Enhancement

Fig. 5.5(a) shows the maximal radio coverage after placing RS at the optimal location for constant total relay transmit power. In the figure, we can find that the combination of fewer RSs and higher relay transmit power can results in least coverage enhancement. This is because the smaller the number of RSs, the larger the gap between RSs. Hence more users suffer from poor communication reliability and results in least coverage improvement. In addition, this figure also shows that the radio coverage of various comparisons. One can see that the maximal radio coverage appear at the combination of $8RSs$ and $2.5W$ with the case of signal strength-oriented rule and equal time-duration scheme. Fig. 5.5(b) shows that the corresponding data of the maximal coverage for constant total relay transmit power.



(a)

Max Coverage		**12RS-5/3W**	**10RS-2W**	**8RS-2.5W**	**6RS-10/3W**	**4RS-5W**
Throughput-Oriented (TO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	2251 m	2258 m	2257 m	2235 m	2135 m
	Equal User-Throughput (EUT) Allocation Scheme	2284 m	2292 m	2292 m	2272 m	2149 m
Signal Strength-Oriented (SSO) Selection Rule	**Equal Time-Duration (ETD) Allocation Scheme**	2284 m	2294 m	2298 m	2273 m	2156 m
	Equal User-Throughput (EUT) Allocation Scheme	2289 m	2295 m	2293 m	2270 m	2152 m
The Radio Coverage without Relay Station		1750 m				

(b)

Figure 5.5: (a) The maximal coverage for constant total relay transmit power, (b) Corresponding the maximal radio coverage of figure (a)

CHAPTER 6

Conclusions and Future Research Suggestions

There are two major contributions in this thesis. First, we develop a systematic method based on simulations to find out the optimal relay location to achieve the maximal system capacity. In the literature, many studies analyze the system capacity in the multi-hop cellular systems, but neglect the effect of relay stations location. In this thesis, we evaluate the system capacity for different relay station locations according to two relay selection rules “throughput-oriented rule” and “signal strength-oriented rule” and two time-slot allocation schemes “equal time-duration scheme” and “equal user-throughput scheme”. Second, we further investigate the maximal radio coverage by placing RS at the optimal location. In previous papers, many studies analyze the effect of multi-hop relay on the coverage in the multi-hop cellular systems, but not take into account the effect of the optimal relay locations. In this thesis, we first obtain the optimal relay location with the maximal capacity and then according to this location to evaluate the radio coverage. Therefore, we can employ the results of Chapter 4 to find the maximal radio coverage for various situations.

6.1 Capacity Enhancement by Optimal Relay Location

In Chapter 4, we investigate how to find the optimal relay location that can achieve the maximal system capacity. In this part, the main contribution is that determining an optimal relay location to achieve the tradeoff between communication reliability and system capacity. From our numerical results, we know that the throughput-oriented relay selection rule with the optimal relay location can achieve the maximal system capacity compared with the signal strength-oriented relay selection rule and the network without RS. That's because the throughput-oriented rule will choose the better effective transmission rate. Thus it can reduce the probability of use the lower user throughput. Therefore, it can provide higher system capacity. In addition, we also change some simulation parameters, such as shadowing standard deviations, relay transmit power, and constant total relay transmit power. Finally, we can obtain useful results about the optimal relay location and system capacity.

6.2 Coverage Enhancement by Optimal Relay Location

In Chapter 5, we focus on the maximal radio coverage by placing RS at the optimal location. By the way, we compute the maximal radio coverage for serving more users with better communication reliability. From our numerical results, we know that the communication reliability obviously higher than the network without RS at the cell boundary of the BS. From these results, the effect of various shadowing standard deviations, relay transmit power, and constant total relay transmit power on the maximal coverage of the radio are examined.

6.3 Suggestions for Future Research

For the future research, the following topics are suggested:

- The impact of the constant total power on the optimal relay location and the maximal coverage.
- Develop a method for the optimal relay location and the maximal coverage in frequency domain and hybrid time/frequency domain of a cellular system.

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