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Design of optimal relay location in two-hop cellular systems

Jane-Hwa Huang · Li-Chun Wang · Chung-Ju Chang · Wen-Shan Su

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Abstract Relay stations are usually used to enhance the signal strength for the users near cell boundary, thereby extending the cell coverage. However, transmission through a relay station needs two transmission phases. The first phase is from base station to relay station, and the second one is from relay station to mobile station. Thus, using relay station may decrease system capacity due to two-phase transmission time. As a result, whether or not data are transmitted by one-hop or two-hop phases should be determined according to 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 two-hop transmission will be used: signal strength-oriented and throughput-oriented selection rules. We find that the signal strength-oriented two-hop transmission may yield even lower system capacity than the one-hop transmission. In the throughput-oriented scheme, the two-hop transmission can achieve higher system capacity than the one-hop transmission. By simulations, we determine the optimal relay location and show the coverage enhancement by the relaying network. Extensive simulations are performed to investigate the impacts of relay transmission power and the number of relay stations on system capacity and optimal relay location. The simulation results reveal important insights into designing a relaying network with high system capacity.

Keywords Multi-hop cellular systems · Relaying networks · Relay location design

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1 Introduction

Recently, the relay transmission technique is widely used in the next-generation wireless systems [1–7], because relay stations (RSs) can help the base station (BS) forward data and improve signal quality for mobile stations (MSs) near cell boundary to extend coverage. Compared to BS, deploying RS can reduce infrastructure cost. In addition, since RSs do not need wireline connections to the backhaul network, the relaying networks can be quickly deployed on a large scale.

However, transmission through a relay station needs two transmission phases, which may degrade system capacity. Therefore, one interesting issue in the relaying networks is to determine whether a two-hop transmission is necessary. Furthermore, it is an important task to investigate the impact of RS location on link reliability and system capacity. Specifically, if the relay stations are deployed far away from BS, the user at cell boundary can receive stronger signal from RS. However, the longer hop distance between BS and RS will decrease the relay link capacity. Therefore, determining appropriate relay location to achieve the tradeoff between communication reliability and system capacity is an essential issue in the relaying networks.

This paper aims to determine the optimal relay location in a two-hop network to maximize system capacity subject to the outage probability requirement. We consider two relay selection principles for deciding whether a two-hop relaying transmission will be used. The first one is the signal strength-oriented selection rule, which is to compare the received signal strength directly from BS and that from RS. The link with stronger signal strength will be adopted for data transmission to improve link reliability. The second scheme is the throughput-oriented selection rule. According to this selection scheme, each user will estimate the *effective transmission rate* for the link directly from BS and that via the two-hop communication. Then, the user selects the link with higher effective transmission rate. We also consider two time-slot allocation schemes: equal time-duration and equal user-throughput schemes. The former scheme allocates each user with the same fraction of time for data transmission. The later one allocates the radio resource (e.g. time-slot) to make each user with the same throughput. We investigate the impact of time-slot allocation scheme on the optimal relay location. Moreover, we show the coverage enhancement while the RSs are deployed at the optimal locations.

Traditionally, the relaying communications are mostly used in the ad hoc networks [5, 6, 8, 9]. Recently, as deploying ubiquitous broadband wireless networks has become a critical topic, the relaying transmission is also widely exploited by the infrastructure-based wireless networks [3, 7, 10]. In the literature, the performance studies for relaying networks mainly focus on capacity enhancement [10–12] and coverage extension [13, 14]. In [15], the authors discussed three typical resource allocation schemes for relaying networks, including relaying in time-domain, relaying in frequency-domain, and hybrid time/frequency-domain relaying schemes. The work in [16] studied the impacts of the number of RSs and relay transmission power on throughput, given the locations of RSs. In [14], it was shown that the relaying node selection method can significantly affect the system coverage.

Different from the previous works, the main contribution of this paper is to investigate the impact of relay location on system capacity with considering the two-phase transmission overhead. In addition, by simulations we compare the capacity performance for two relay selection schemes, and we determine the optimal relay location. We also investigate the impacts of radio channel, relay transmission power, and the number of deployed RSs in a cell on the optimal relay location and the system capacity. The results obtained from extensive simulations can provide useful guidelines for network design to enhance system capacity in the relaying networks.

The rest of this paper is organized as follows. Section 2 describes the relaying network architecture and the radio channel effects. In Sect. 3, we clarify the tradeoff between link reliability and system capacity, and perform the optimization design for relay location. In Sect. 4, we discuss the relay selection rules and time-slot allocation schemes. Performance evaluations are shown in Sect. 5. Conclusions are given in Sect. 6.

2 Relaying network architecture and assumptions

2.1 Network architecture and multihop relay operation

We consider a two-hop relaying network as shown in Fig. 1. Each cell consists of one BS and K RSs, each with an omni-directional antenna. The coverage radii of BS and RSs are r_{bs} and r_{rs}, respectively. The RSs are regularly deployed around the BS with the separation distance d_{br} between BS and RS. There are N MSs uniformly distributed in the cell. If one-hop transmission is used, the transmission rate between BS and MS is R_{bm}. If two-hop transmission is selected, the transmission rate between BS and RS is R_{br}, and that between RS and MS is R_{rm}. Clearly, the relaying communication can improve link reliability due to shorter hop distance, but may lower system capacity due to two-phase transmission time. Therefore, one important task in relaying networks is how to decide whether a user should use the two-hop communication. Besides, since the hop distance affects the transmission rates R_{br} and R_{rm}, another challenge is designing the relay location to achieve the tradeoff between link reliability and system capacity.

In general, there are two typical relaying operation modes in the multihop cellular networks, namely, *transparent* and *non-transparent* relay modes [1, 2]. The transparent mode aims at enhancing throughput, while the non-transparent mode is mainly used to extend coverage. In the transparent relay mode, an MS can directly receive the

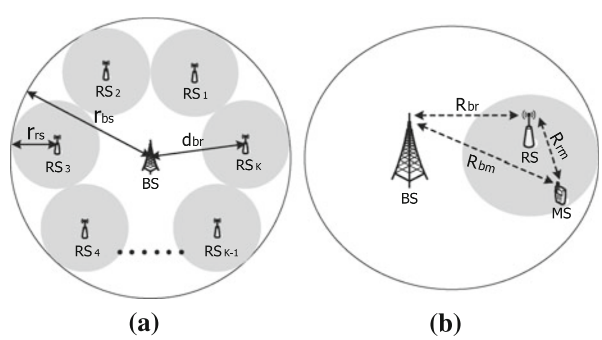


Fig. 1 The architecture of a two-hop relaying network with one BS and K RSs. **a** A two-hop relay neteork. **b** Transmission rate between transmitter and receiver

control information from BS, which identifies the duration and the subchannel for each RS to forward users' data. By this resource allocation information, an MS can estimate the channel quality from each RS according to the associated subchannel pilot symbols. In the non-transparent relay mode, each RS needs to transmit the control information including its relay preamble. Thus, an MS can estimate the channel quality of each RS directly by the relay preamble, and then decide which RS will be used.

2.2 Radio channel effects

This paper considers the radio channel effects of path loss and shadowing [17]. Subject to path loss, the received power strength 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 can be modeled by a log-normal random variable $10^{\xi/10}$. Therefore, supposing that the transmission power is P_t, the received power can be written as

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

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

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

According to the system model for IEEE 802.16j with relay stations [18], the path loss can be modeled as

$$L_r(dB) = \begin{cases} 20\log_{10}(\frac{4\pi r}{\lambda}) & \text{for } r \le r'_0 \\ A + 10\gamma\log_{10}(\frac{r}{r_0}) + \triangle L_{f_c} + \triangle L_{h_t} & \text{for } r > r'_0 \end{cases} \tag{3}$$

where λ is the wavelength in meter; $r_0 = 100$ (m) is a reference distance; γ, r'_0, and A are the parameters depending on the propagation environment. Assume that the antenna height of the transmitter (BS or RS) is h_b. For flat terrain, γ is defined as

$$\gamma = 3.6 - 0.005h_b + \frac{20}{h_b}. \tag{4}$$

Let f_c be the carrier frequency, and h_t be the antenna height of the receiver (RS or MS). According to [18], r'_0 and A are given as

$$r'_0 = r_0 10^{-(\frac{\triangle L_{f_c} + \triangle L_{h_t}}{10\gamma})} \tag{5}$$

$$A = 20\log_{10}(\frac{4\pi r'_0}{\lambda}) \tag{6}$$

where

$$\triangle L_{f_c} = 6\log_{10}(\frac{f_c(\text{MHz})}{2{,}000}) \tag{7}$$

$$\triangle L_{h_t} = \begin{cases} -10\log_{10}(\frac{h_t}{3}), & \text{for } h_t \le 3\,\text{m} \\ -20\log_{10}(\frac{h_t}{3}), & \text{for } h_t > 3\,\text{m}. \end{cases} \tag{8}$$

2.3 Link reliability

The transmission is outaged if the signal-to-noise ratio (SNR) is lower than a specified threshold z_{th}. Let N_0 be the noise power. Subject to the radio channel effects, the outage probability for the transmission can be calculated as

$$\begin{aligned} P_{\text{outage}} &= Pr[SNR < z_{th}] \\ &= Pr\left[\frac{P_t \cdot (L_r)^{-1} \cdot 10^{\xi/10}}{N_0} < z_{th}\right]. \end{aligned} \tag{9}$$

In this paper, we consider the area outage probability [19]. Suppose that the receivers are uniformly distributed in a circular area centered at the transmitter with radius r_c. The area outage probability is defined as

$$\begin{aligned} P_o &= \frac{1}{\pi r_c^2}\int_0^{r_c} Pr\left[\xi < 10\log_{10} z_{th} L_r \frac{N_0}{P_t}\right] 2\pi r dr \\ &= \frac{2}{r_c^2}\int_0^{r_c}\left[\int_{-\infty}^{10\log_{10} z_{th} L_r \frac{N_0}{P_t}} f_\xi(\xi)d\xi\right] r dr \\ &= \frac{2}{r_c^2}\int_0^{r_c}(1 - Q(\frac{10\log_{10} z_{th} L_r \frac{N_0}{P_t}}{\sigma}))r dr \\ &= f_{z_{th}}(r_c). \end{aligned} \tag{10}$$

where

$$Q(z) = \int_z^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy. \tag{11}$$

Suppose that the outage probability requirement is $P_{o,req}$. The corresponding maximum reception range is $r_{MAX} = f_{z_{th}}^{-1}(P_{o,req})$ for a modulation and coding scheme (MCS) with the SNR threshold z_{th}. That is, if the separation distance between receiver and transmitter is less than r_{MAX}, the average outage probability can be less than $P_{o,req}$ for the given MCS. In (10), the outage probability P_o is a nonlinear function of coverage radius. By the numerical method, we can obtain the maximum reception range $r_{MAX} = f_{z_{th}}^{-1}(P_{o,req})$.

This paper considers the effects of path loss and shadowing on the system-level performance (such as the cell capacity and coverage) for simplicity, as the system-level analysis in [20, 21]. If the multipath fading is considered, a proper fading margin is required. Therefore, the cell coverage and per-user throughput will decrease. However, the proposed optimal relay-location design approach in Sect. 3 still can be straightforwardly applied to the case including the effect of small-scale fading. We also note that the link-level simulations to find the SNR threshold z_{th} actually have incorporated the impact of multipath fading [22].

3 Optimal relay location design

Link reliability and throughput are both essential factors in designing a relaying network. From a link reliability perspective, deploying RSs far away from BS can improve the signal strength for the users near cell boundary. However, from the link capacity standpoint, it is better to deploy the RSs near the BS since a higher relay link capacity between BS and RS can forward more traffic for the users.

To achieve the tradeoff between link reliability and throughput, we formulate an optimization problem to find out the optimal relay location, aiming to maximize system capacity subject to the outage probability requirement. The system capacity C is defined as the aggregated throughput of BS. In a relaying network, the system capacity indeed depends on the relay location, the relay link selection rule, and the resource allocation scheme as detailed in Sect. 4. The decision variables in the optimization problem include the relay location d_{br}, the direct link set $\mathbf{S_{bm}}$, and the relay link set $\mathbf{S_{rm}}$. According to the relay link selection rule, the users in the set $\mathbf{S_{bm}}$ will receive their data via the direct link from BS, and those in $\mathbf{S_{brm}}$ will use the two-hop transmission. Based on these considerations, the capacity maximization issue can be formulated as a nonlinear programming problem as expressed in the following:

$$\underset{d_{br},\mathbf{S_{bm}},\mathbf{S_{brm}}}{\mathrm{MAX}} \quad C(\text{Overall throughput of a cell}) \tag{12}$$

$$\text{subject to} \begin{cases} P_{o,bm} \le P_{o,req}, & \text{if using direct link,} \\ P_{o,br}, P_{o,rm} \le P_{o,req}, & \text{otherwise.} \end{cases} \tag{13}$$

In (13), $P_{o,br}$, $P_{o,rm}$, and $P_{o,bm}$ represent the outage probabilities for the link between BS and RS, that between RS and MS, and that between BS and MS, respectively. The constraint states the link reliability requirement that the outage probability in each link should be less than an outage probability threshold $P_{o,req}$.

4 Relay selection rules and time-slot allocation schemes

In a two-hop relaying network as shown in Fig. 1, the data packets can be delivered directly from the BS or relayed by the RS. The system capacity and per-user throughput are dependent on the rate adaptation, relay link selection rule, and time-slot allocation scheme, as the procedures shown in Fig. 2. We explain these three steps in the following.

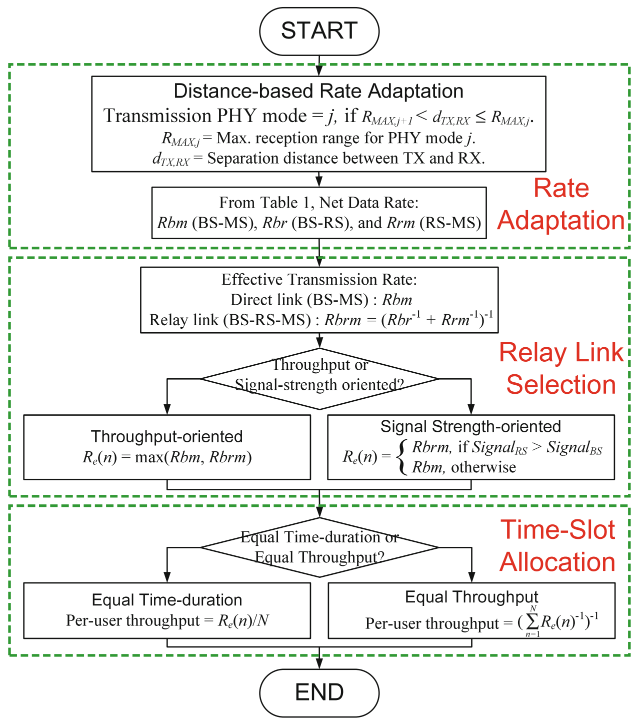


Fig. 2 Procedures of the resource allocation for a user, including three steps: (1) rate adaptation, (2) relay link selection, and (3) time-slot allocation

4.1 Distance-based rate adaptation

In a wireless multihop network, the separation distance between the transmitter (BS/RS) and the receiver (RS/MS) will affect the throughput and the transmission PHY mode (i.e., the modulation and coding scheme). In this paper, we consider seven transmission PHY modes in the IEEE 802.16 System as listed in Table 1. In the table, the SNR thresholds and the net data rates for the transmission PHY modes are shown [22]. According to the transmission power (P_t), the SNR threshold (z_{th}), and the outage probability requirement ($P_{o,req}$), we can determine the maximum reception range $r_{MAX,j}$ for each transmission mode as discussed in Sect. 2.3, where $r_{MAX,1} > r_{MAX,2} > \cdots > r_{MAX,7}$. In principle, the communication pairs with a shorter separation distance can adopt a transmission mode with higher net data rate. Suppose that the separation distance between transmitter and receiver is $d_{TX,RX}$. By the distance-based rate adaptation, the transmission PHY mode is determined as

$$\text{Transmission PHY mode} = j, \text{if } r_{MAX,j+1} < d_{TX,RX} \le r_{MAX,j}. \tag{14}$$

Table 1 The SNR threshold and the net data rate for seven modulation and coding schemes in the IEEE 802.16 System

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

By this distance-based rate adaptation, the outage probability requirement for each link can be ensured. Furthermore, once the transmission PHY mode is given, from Table 1 we can obtain the net data rate for each link, i.e., the net data rate for the direct link between BS and MS (R_{bm}), that between BS and RS (R_{br}), and that between RS and MS (R_{rm}).

4.2 Relay link selection rules

- *Throughput-Oriented (TO) Selection Rule:*
  In this scheme, data will be delivered by two-hop transmission if forwarding the packet by relay station can achieve higher effective transmission rate. Clearly, the objective of this scheme is to increase per-user throughput. Let P be the packet size. With two transmission phases, the effective transmission rate R_{brm} for the two-hop communication can be given as

$$R_{\mathrm{brm}} = \frac{P}{t_{\mathrm{BS-RS-MS}}} \tag{15}$$

$$= \frac{P}{\frac{P}{R_{\mathrm{br}}} + \frac{P}{R_{\mathrm{rm}}}} = \left(\frac{1}{R_{\mathrm{br}}} + \frac{1}{R_{\mathrm{rm}}}\right)^{-1} \tag{16}$$

  where $t_{\mathrm{BS-RS-MS}} = \frac{P}{R_{\mathrm{br}}} + \frac{P}{R_{\mathrm{rm}}}$ is the total two-phase transmission time. In this scheme, data will be delivered by two-hop communication, as long as

$$R_{\mathrm{brm}} > R_{\mathrm{bm}}. \tag{17}$$

  Therefore, by the throughput-oriented selection rule, the transmission rate $R_{\mathrm{e}}(n)$ for user n is equal to

$$R_{\mathrm{e}}(n) = \max(R_{\mathrm{bm}}, R_{\mathrm{brm}}). \tag{18}$$

- *Signal Strength-Oriented (SSO) Selection Rule:*
  In this scheme, the user will adopt the two-hop transmission to deliver data if the received signal strength from RS ($Signal_{\mathrm{RS}}$) is stronger than that from BS ($Signal_{\mathrm{BS}}$). Clearly, this scheme aims at improving the link reliability. In addition, the effective transmission rate $R_{\mathrm{e}}(n)$ is equal to

$$R_{\mathrm{e}}(n) = \begin{cases} R_{\mathrm{brm}}, & \text{if } Signal_{\mathrm{RS}} > Signal_{\mathrm{BS}} \\ R_{\mathrm{bm}}, & \text{Otherwise.} \end{cases} \tag{19}$$

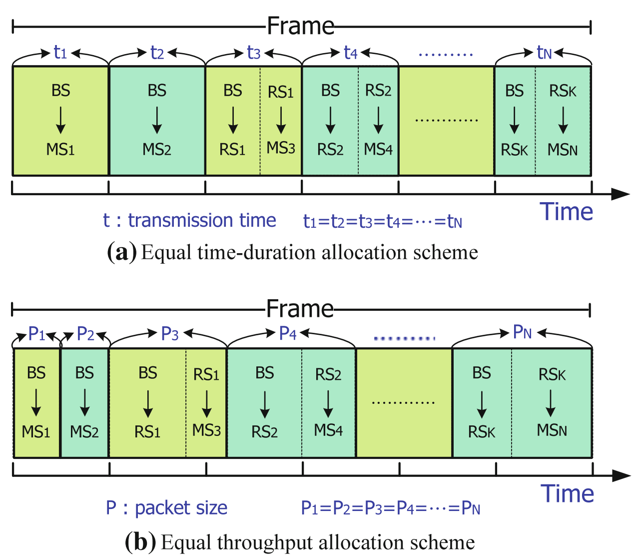
4.3 Time-slot allocation schemes

In this paper, two time-slot allocation schemes are considered: equal time-duration and equal user-throughput allocation schemes. The radio resource is allocated in a time division multiplexing (TDM) fashion. At each time slot, only one transmitter will send data. Therefore, the intra-cell interference is not considered in this paper. In other multihop cellular systems, BS and RSs may transmit data in parallel to improve spectrum efficiency and system capacity. However, such a concurrent transmission system should face a difficult challenge in managing the complicated interference.

- *Equal Time-Duration (ETD) Allocation:*
  As shown in Fig. 3(a), in this scheme each user is allocated with the same fraction of time for data transmission, no matter whether the data are transmitted directly from BS or by two-hop communication. Consider a cell with N users, each with the effective transmission rate $R_{\mathrm{e}}(n)$. Since all the users evenly share the radio resource, the system capacity is given as

$$C = \frac{\sum_{n=1}^{N} R_{\mathrm{e}}(n)}{N}. \tag{20}$$

- *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. This



(a) Equal time-duration allocation scheme

(b) Equal throughput allocation scheme

Fig. 3 Frame structure for the equal time-duration and equal user-throughput allocation schemes with N users. (**a**) Equal time-duration allocation scheme: each user can send data in one slot of each frame. (**b**) Equal user-throughput allocation scheme: each user can send a packet with size P in each frame scheme can achieve the fairness for each user in terms of throughput. Suppose that during a time interval, each user can send a packet with the same size P as shown in Fig. 3(b). The total transmission time for N packets is equal to $\sum_{n=1}^{N}\frac{P}{R_e(n)}$. Therefore, the system capacity can be expressed as

$$C = \frac{\text{Total transmitted data bits}}{\text{Total transmission time}} = \frac{N\cdot P}{\sum_{n=1}^{N}\frac{P}{R_e(n)}} = N\cdot\left(\sum_{n=1}^{N}\frac{1}{R_e(n)^{-1}}\right)^{-1}. \tag{21}$$

5 Simulation results

In this section, we compare the system capacity according to the throughput-oriented and signal strength-oriented relay selection rules, with considering the effect of relay location. Besides, we investigate the impacts of radio channel, the number of RSs, and the transmission power of RS on the system capacity and the optimal relay location. The system parameters are listed in Table 2. We consider seven transmission PHY modes as listed in Table 1. The SNR threshold for outage events is $z_{th} = 0$ dB. The outage probability requirement is $P_{o,req} = 0.1$. With this requirement, the coverage radius of BS is $r_{bs} = 1750$ (m) when the transmission power of BS is 40 dBm. Unless otherwise specified, there are 8 RSs in a cell, each with the transmission power of 37 dBm. The RSs are deployed around the BS shown in Fig. 1, with the separation distance d_{br} between BS and RS. In this paper, we consider $N = 20$ active MSs uniformly distributed in the cell as an example. The MSs follow the resource allocation procedures in Fig. 2 to decide whether the relaying transmission is used. We obtain the system performance by averaging the results from the 10,000-round simulation for a given relay location. In addition, by the exhaustive search method, we can find the optimal relay location.

Table 2 System parameters

Item	Nominal value
Carrier frequency (f_c)	3.5 GHz
System bandwidth (BW)	3.5 MHz
BS transmission power	40 dBm
RS transmission power	37 dBm
Coverage radius of BS (r_{bs})	1750 m
BS antenna height	30 m
RS antenna height	15 m
MS antenna height	2 m
Outage probability requirement ($P_{o,req}$)	0.1
Standard deviation for shadowing (σ)	8 dB
Noise power (N_0)	−102 dBm

5.1 Impact of relay link selection rule on system capacity and optimal relay location

Figure 4 shows the achieved system capacity versus the separation distance between BS and RS, where the equal time-duration allocation scheme is used. Clearly, the throughput-oriented two-hop transmission can improve system capacity. Furthermore, there exists an optimal relay location to maximize system capacity. In this example, the optimal relay location is 1,273 m. Besides, the throughput-oriented selection scheme can achieve higher optimal system capacity than the signal strength-oriented scheme by 5.5%, and than the case without relay by 25.4%. This figure also shows that the signal strength-oriented two-hop transmission may yield lower system capacity than the one-hop transmission. For example, if deploying RSs at the distance of 450 m, the system capacity is lower than that without RS by about 30%. These phenomenons are due to the fact that by the signal strength-oriented scheme, an MS will choose the relaying transmission as long as the MS is closer to the RS rather than the BS. Thus, when the MS is between BS and RS, the MS may still choose the two-hop communication although using the direct communication can achieve higher throughput. In result, the signal strength-oriented scheme achieves lower overall system capacity while it can improve signal quality. On the other hand, the throughput-oriented scheme will choose the relaying transmission only if the RS can help increase per-user throughput. Therefore, the throughput-oriented scheme can always achieve higher system capacity than the signal strength-oriented scheme.

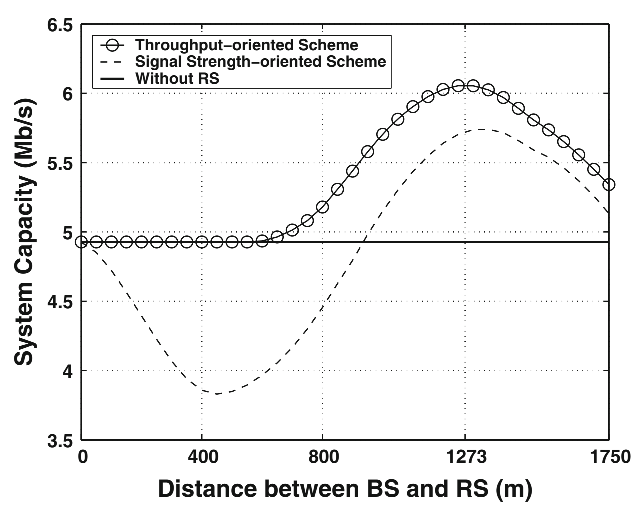


Fig. 4 Achieved system capacity for different relay selection rules, where the equal time-duration allocation scheme is used

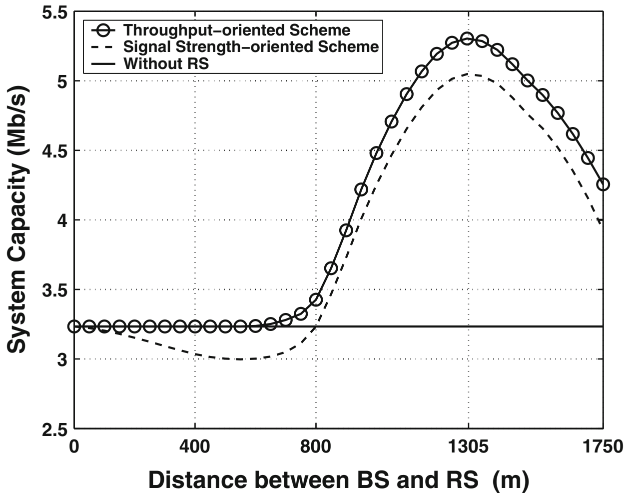


Fig. 5 Achieved system capacity for different relay selection rules, where the equal user-throughput allocation scheme is used

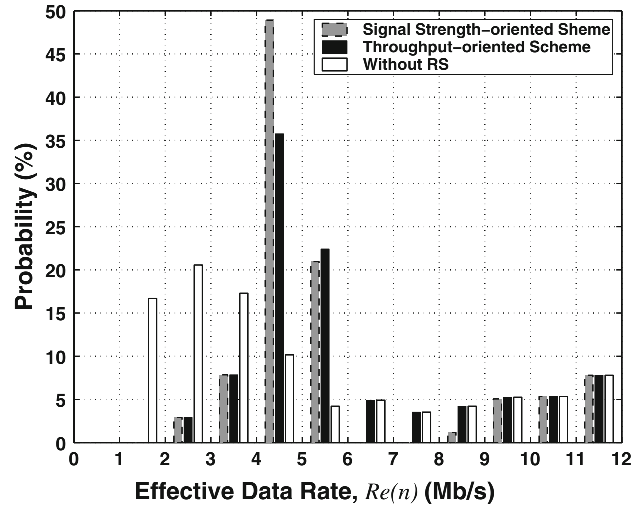


Fig. 6 The PMF of effective data rate $R_e(n)$ according to different relay selection rules, where the equal time-duration allocation scheme is used and the RSs are deployed at the optimal locations

Figure 5 illustrates the system capacity for the equal user-throughput allocation scheme. In the figure, the optimal relay location is 1,305 (m) for the throughput-oriented selection rule. It is shown in Figs. 4 and 5 that the equal user-throughput allocation scheme achieves lower system capacity than the equal time-duration scheme. This is because the equal user-throughput scheme allocates more radio resource for the users with lower transmission rates to achieve the same throughput for each user, thereby lowering the overall system capacity.

5.2 Impact of relay selection rule on effective data rate and SNR

Figure 6 shows the probability mass function (PMF) of effective data rate $R_e(n)$ for various relay selection rules using the equal time-duration scheme, where the RSs are deployed at the optimal location. In the multihop cellular system, the users near BS can be served directly by BS with higher data rates. Hence, in the figure the probability of higher data rate (e.g., 9 ∼ 12 Mb/s) for all the cases are almost the same. For the case without relay, the users near cell boundary are served by BS with very low data rates. Accordingly, many users have lower effective data rates. In this example, about 55% of the users experience the effective data rate lower than 4 Mb/s. Relay station can improve the effective data rate especially for the users near cell boundary. This figure shows that by using RSs, most of users can have effective data rate of 4 ∼ 6 Mb/s. Noteworthily, according to the throughput-oriented selection rule, 13% of the users can have effective data rate of 6 ∼ 8 Mb/s. However, by the signal strength-oriented scheme, only 1% of the users can achieve 6 ∼ 8 Mb/s effective data rate. In the signal strength-oriented rule, the users near the RS will use the two-hop transmission with stronger signal strength. In result, the effective data rate decreases due to higher overall transmission time.

Figure 7 shows the complementary cumulative distribution function of the received SNR for the users. One can see that relay station can improve the received SNR. In the throughput-oriented scheme, the users near the relay may still use direct transmission from BS to improve per-user throughput. Because of longer hop distance, the received SNR in the throughput-oriented scheme is slightly lower than that in the signal strength-oriented scheme. However, the throughput-oriented scheme can increase system capacity as shown in Figs. 4 and 5.

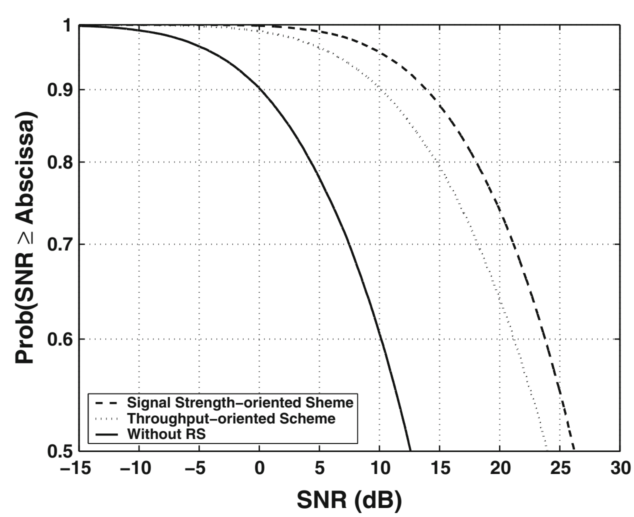


Fig. 7 The complementary CDF of users' SNR according to various relay selection rules, where the equal time-duration allocation scheme is used and the RSs are deployed at the optimal locations

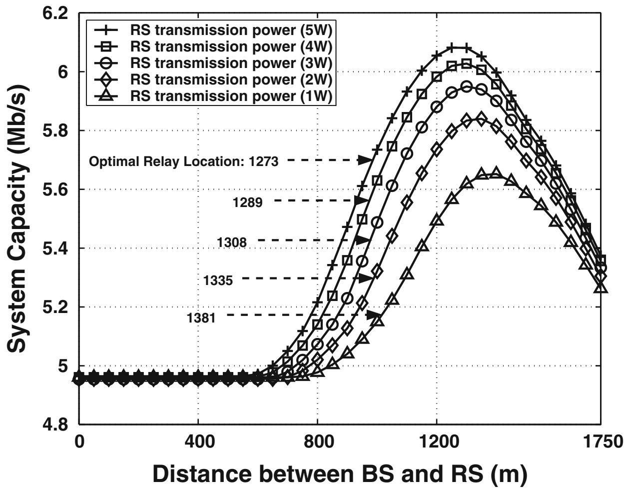


Fig. 8 Achieved system capacity and optimal relay location for various relay transmission power, where there are 8 RSs in a cell

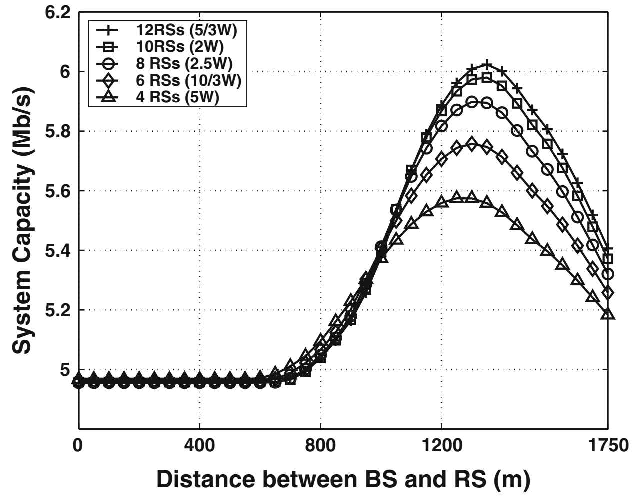


Fig. 9 Achieved system capacity and optimal relay location for different number of deployed RSs, where the total transmission power of RSs is fixed at 20 W

5.3 Impact of relay transmission power and the number of RSs on system capacity

Figure 8 shows the system capacity against the relay location for various RS transmission power, where there are 8 RSs in a cell. Obviously, there exists optimal relay location to maximize the system capacity. In addition, the optimal system capacity can be improved as the RS transmission power increases. Besides, to improve the throughput and the signal strength of outer users, the RS should be deployed closer to cell boundary as the transmission power decreases. This figure also shows that increasing the transmission power (e.g., more than 3 W) may not significantly increase system capacity. This phenomenon is due to the fact that in a relaying network, only the users near cell boundary benefit from the RS. Since the link capacity between BS and RS is limited, the improvement of effective data rate for outer users gradually diminishes for a higher RS transmission power.

Figure 9 illustrates the system capacity against the relay location, where the number of RSs varies from 4 to 12. The total transmission power of RSs is fixed at 20 W. In the figure, since the hop distance between RS and the outer user can be reduced as the number of RSs increases, the system capacity increases. In addition, as more RSs are deployed each with a lower transmission power, the optimal distance between BS and RS should be increased to improve link quality for the outer users. Noteworthily, deploying more RSs (e.g., greater than 8 RSs) will not remarkably improve system capacity. This is because limited by the relay link capacity between BS and RS, per-user throughput and system capacity will not significantly increase as more RSs are deployed.

5.4 Impact of radio channel on system capacity and coverage

In Fig. 10, the system capacity against the relay location for various shadowing standard deviation σ is shown. The figure shows that the optimal system capacity and the coverage of BS increase for a smaller σ. In addition, the optimal relay location is increasing as the standard deviation σ decreases. This is because the case with a smaller σ can have better link reliability, thereby enhancing system capacity and coverage of BS.

Figure 11 shows the coverage radius of a two-hop cell for various shadowing standard deviation σ, where the relays are deployed at the optimal locations and the outage probability requirement for each link is $P_{o,req} = 0.1$. Different

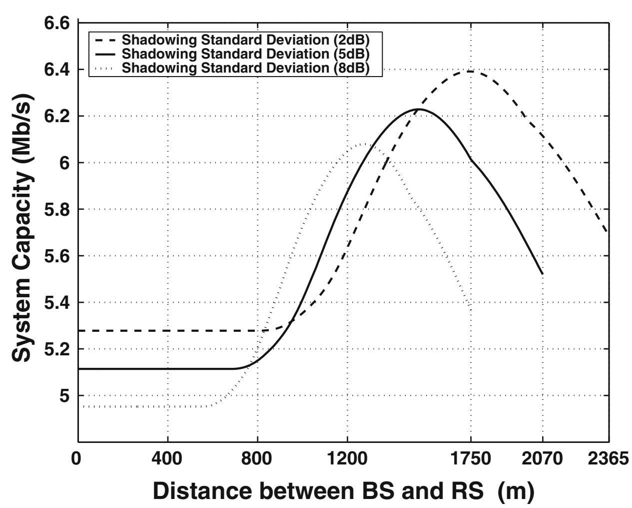


Fig. 10 System capacity versus relay location for various shadowing standard deviation σ, using the throughput-oriented selection scheme and the equal time-duration allocation scheme

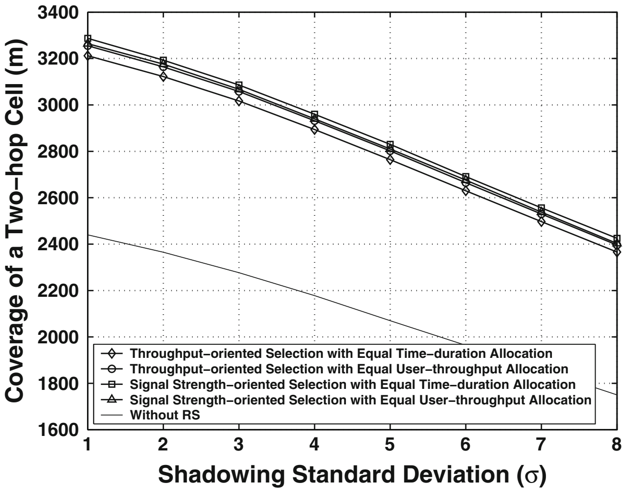


Fig. 11 Coverage of a two-hop cell for various shadowing standard deviation σ, where 8 RSs are deployed at the optimal locations and the outage probability requirement is $P_{\mathrm{o,req}} = 0.1$

from Figs. 4, 5, 6, 7, 8, 9 and 10 which focus on the capacity enhancement by deploying RSs in a fore-deployed cellular system, here we aim at understanding the coverage extension by RSs. This is a useful information for network planning to reduce the infrastructure cost since we can deploy fewer BSs in an area. This figure shows that by deploying the RSs at the optimal location as shown in Fig. 10, the coverage radius of two-hop cell can be significantly increased. In this example, compared to the case without RS, RS can extend the coverage by about 36% for $\sigma = 8$ dB.

6 Conclusions

In this paper, we investigate the impact of relay location on system capacity and discuss how to decide whether the two-hop relay communication should be used to deliver data. The contributions of this work are described in the following. First, we compare the signal strength-oriented and throughput-oriented link selection rules. Simulation results show that the signal strength-oriented scheme can improve SNR, whereas may achieve lower system capacity than the one-hop transmission. By contrast, the throughput-oriented scheme can yield higher system capacity, although the received SNR is slightly lower than that in the signal strength-orient scheme. Second, we perform optimization design for relay location to maximize system capacity. It is shown that properly designing relay location can significantly improve system capacity; however, deploying the RS at random location may even degrade system capacity. Third, the impacts of RS transmission power, the number of RSs in a cell, and the radio channel on system capacity and coverage are investigated. Some important observations are obtained as follows:

- Due to capacity limitation in the link between BS and RS, continually increasing RS transmission power and the number of RSs may not significantly improve system capacity. In the simulation example, eight RSs in a cell can be a good choice.
- For different number of RSs, various propagation environments and transmission power, the relay location should be appropriately designed to maximize system capacity.
- With a proper location design, RS can not only improve capacity but extend coverage. In the example, RS can extend system coverage by about 33% for various shadowing standard deviations σ.

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