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# Multihop Relay-Enhanced WiMAX Networks

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## 1. Introduction

The demand for high speed data service has been increasing dramatically since the Internet has become a part of people's lives. Most broadband wireless service providers have boosted data service rates by adopting recently developed technologies such as OFDM, MIMO, and smart antennas. However, in practice there are still problems such as coverage holes due to shadowing, and poor signal to interference and noise ratio (SINR) for the subscriber stations (SSs) that are far away from the base station (BS). A simple solution for this problem is to add more BSs, but it is a very inefficient solution especially when there are few SSs to be served (e.g., in rural areas.) As an alternative to adding BSs, deploying low-cost relay stations (RSs) provides a cost-effective way to overcome the above problem (RSs are a simplified version of a full BS resulting in with lower upfront cost than BS; additionally, RSs do not require backhaul connections, thus reducing operating costs). The WiMAX specification was amended (802.16j, 2009) to include multihop relays, an extension which has gained much attention and proved to be an attractive technology for the next-generation of wireless communications. Furthermore, the currently evolving Long Term-Evolution Advanced (LTE-A) standard considers multihop relaying as an essential feature (3GPP, 2009). In this chapter, we study the effect of using RSs on both capacity and coverage enhancements.

The IEEE 802.16j amendment focuses on the deployment of RSs in such a way that the network capacity can be enhanced or coverage of the network can be extended. Accordingly, two different types of RSs are specified in the amendment: *transparent* RS (T-RS) mode and *non-transparent* RS (NT-RS) mode. In T-RS mode, the framing information is always transmitted by the BS to the SSs directly, while data traffic can be relayed via RSs. Therefore, in cells with T-RSs, the SSs associated with an RS have to be located within the coverage of the BS. Conversely, in NT-RS mode, the framing information is transmitted along the same path as data traffic to the SSs, and thus the RS operates effectively as a BS for connected SSs. Therefore, T-RSs allow throughput enhancement only, whereas NT-RSs can extend the coverage as well as increase the throughput. Both types of relays can serve unmodified SSs (i.e., the SSs do not distinguish between genuine BSs and RSs). In this chapter, we analyze the benefits of using RSs for the capacity enhancement scenario with T-RSs and the coverage extension scenario with NT-RSs respectively.

In the first part of this chapter, we focus on improving cell capacity by deploying T-RSs inside a cell, and consider the placement of RSs that maximizes cell capacity. According to the location of RSs, the network capacity will vary significantly, i.e., when the RS is either very close to

the BS or far away from the BS, only a few SSs will benefit from the RS. In order to maximize the number of SSs that can achieve greater throughput through the T-RSs, we need to find the optimal placement of T-RSs such that the cell throughput is maximized. We also show how various network parameters such as reuse factor, terrain types, RS antenna gain, and the number of RSs affect the optimal placement of RSs and the capacity gain compared to the conventional scenario (i.e., without using RSs).

In the second part, we focus on deploying NT-RSs for the purpose of coverage extension. We explore three different issues in this part. First, we study several scheduling schemes such as orthogonal, overlapped, and optimal schemes in order to maximize cell throughput while serving the SSs in a fair manner. Second, we analyze cell coverage extension by varying both the location and number of RSs from a cost efficiency perspective. Finally, we explore an extension of the optimal scheme to a general multihop relaying scenario, and analyze the network throughput degradation due to the increase of relay hops under the optimal scheduling scheme.

The rest of this chapter is organized as follows. In the next section, we discuss the system model including system description, SINR analysis, fading channel, and relay strategy. In Section III, we present the capacity enhancement scenario with T-RSs. In Section IV, we analyze cost effective coverage extension scenarios with NT-RSs. The optimal scheduling scheme is also presented and compared with the orthogonal and overlapped schemes. Section V concludes the chapter.

## 2. System model

### 2.1 System description

In this chapter, we consider a single WiMAX cell consisting of a central BS and several RSs for the purpose of capacity enhancement, coverage extension, or both. The SSs are uniformly distributed throughout the cell and only  $N$  SSs are randomly chosen to be active at a time for each scenario. The BS is responsible for allocating resources for the SSs to be served and is connected to the backhaul network, while the RSs have no backhaul links but are wirelessly connected to the BS. The main responsibility of the RS is to relay data between the BS and SSs. All RSs and the BS are referred to as *service nodes* in the rest of this chapter. The RS to RS connection is also allowed for the coverage extension scenario. However, in the capacity enhancement scenario, we assume only two-hop relaying since more than two-hop relaying without extending coverage reduces the efficiency of using RSs. The one-hop links BS to RS and RS to RS are referred to as *relay links*, and the links BS to SS and RS to SS as *access links*.

We assume that every node in a cell has a single omni-directional antenna and operates in half-duplex mode, hence, no terminal can receive and transmit data simultaneously. The frequency reuse scheme is not considered in the scenario for the optimal placement of T-RSs, i.e., only one node can be active at a time. In contrast, for the coverage extension scenario, the proposed optimal scheduling scheme allows for frequency reuse in order to maximize the bandwidth efficiency, hence, the throughput degradation due to coverage extension can be minimized. The standard allows for two types of duplex methods to separate the uplink (UL) and downlink (DL) channels: time division duplex (TDD) and frequency division duplex (FDD); we assume TDD in this chapter since TDD makes more efficient use of the spectrum by dynamically allocating the amount of time slots to each direction. The system parameters used for the analysis are listed in Table 1.

System Parameters		OFDMA Parameters	
Operating Frequency	3.5 GHz	FFT Size	1024
Duplex	TDD	Sub-carrier Frequency Spacing	10.94 kHz
Channel Bandwidth	10 MHz	Useful Symbol Time	91.4 $\mu$ s
BS/RS Height	50 m	Guard Time	11.4 $\mu$ s
SS Height	1.5 m	OFDM Symbol Duration	102.9 $\mu$ s
BS/RS Antenna Gain	17 dBi	Data Sub-carriers(DL / UL)	720 / 560
SS Antenna Gain	0 dBi	Pilot Sub-carriers(DL / UL)	120 / 280
BS/RS Power	20 W	Null Sub-carriers(DL / UL)	184 / 184
SS Power	200 mW	Sub-channels(DL / UL)	30 / 35
BS/RS Noise Figure	3 dB		
SS Noise Figure	7 dB		

Table 1. Simulation Parameters

## 2.2 SINR analysis

The adaptive modulation and coding scheme (AMC) is the primary method of maintaining the quality of wireless transmission. WiMAX supports AMC by defining seven combinations of modulation and coding rate that can be used to achieve various data rates specified by the standard (Andrews et al., 2007). Table 2 shows the modulation and coding rates and the corresponding achievable data rate; the last column represents the minimum required threshold values of SINR computed by a bit error rate expression for M-QAM (Foschini & Salz, 1983) when bit error rate is  $10^{-6}$ . For example, when the received SINR is between 9.1 and 11.73dB, the achievable data rate will be 5.25Mbps. In general, a higher order modulation tends to be used close to the base station, whereas lower order modulations tend to be used at longer ranges.

The IEEE 802.16 working group has recommended the Erceg-Greenstein path loss model for fixed wireless application systems. Since we did not consider the mobility of the SSS in this analysis, we used this model to calculate path loss. The Erceg-Greenstein models are divided into three types of terrains, namely A, B and C. Terrain type A has the highest path loss, and is applicable to hilly terrains with moderate to heavy foliage densities. Type C has the lowest path loss and applies to flat terrains with light tree densities. Type B is suitable for intermediate terrains. The basic path loss equation with correction factors is presented in (Erceg & Hari, 2001):

$$L = 20 \log_{10} \left( \frac{4\pi d_0}{\lambda} \right) + 10\alpha \log_{10} \left( \frac{d}{d_0} \right) - 10.8 \log_{10} \left( \frac{h}{2} \right) + s + 6 \log_{10} \left( \frac{f}{2000} \right), \quad (1)$$

where  $d_0=100$ m,  $\alpha$  is the path loss exponent dependent on terrain type,  $d$  is the distance between the transmitter and receiver,  $h$  is the receiver antenna height,  $f$  and  $\lambda$  are the frequency and wavelength of the carrier signal, and  $s$  is a zero mean shadow fading component. When the path loss value between the transmitter and receiver is computed by using (1), the received signal power  $P_r$  can be calculated by:

$$P_r = \frac{G_t G_r P_t}{L}, \quad (2)$$

Modulation & Coding rate	Downlink Data Rate [Mbps]	Spectral Efficiency [bps/Hz]	Threshold [dB]
QPSK 1/2	5.25	1.0	9.1
QPSK 3/4	7.87	1.5	11.73
16 QAM 1/2	10.49	2.0	13.87
16 QAM 3/4	15.74	3.0	17.55
64 QAM 2/3	20.99	4.0	20.86
64 QAM 3/4	23.61	4.5	22.45
64 QAM 5/6	26.23	5.0	24.02

Table 2. SINR Threshold Set for a BER of  $10^{-6}$ 

where  $G_t$ ,  $G_r$ , and  $P_t$  represent the transmitting antenna gain, receiving antenna gain, and the transmission power. Once the received signal power is computed, the SINR value at the receiver can be easily determined by:

$$SINR = \frac{P_r}{P_N + \beta P_I'} \quad (3)$$

where  $\beta$  is the number of co-channel cells of the first tier,  $P_N$  is the noise power, and  $P_I$  is the interference signal power from a neighboring cell on the same frequency as the current cell. In a similar way to the received signal power, the interference signal power can be computed by using (1) and (2) with the information of co-channel distance. We assume that the co-channel distance is  $R\sqrt{3\tau}$  (Rappaport, 2001), where  $\tau$  is the reuse factor and  $R$  is the cell size. For the capacity enhancement scenario with T-RSs, only inter-cell interference is considered since no concurrent transmissions are allowed inside a cell, while for the coverage extension scenario with NT-RSs, intra-cell interferences is also considered as multiple nodes can transmit simultaneously.

### 2.3 Fading channel

In a wireless communication system, a signal can travel from transmitter to receiver over multiple paths, and hence the received signal can fade. This phenomenon is referred to as multipath fading. In a fading environment the received signal power varies randomly over time due to multipath fading. We assume well known fading channels such as the Rayleigh fading and Rician fading channel for the access link and the relay link respectively. The Rayleigh fading channel is most applicable when there is no propagation along the line of sight between the transmitter and receiver, while the Rician fading channel is more appropriate when there is a dominant line of sight component at the receiver. For an access link, the amplitude distribution of the received signal is accurately modeled by a Rayleigh distribution:

$$p(\rho) = \frac{\rho}{\sigma^2} \exp\left(-\frac{\rho^2}{2\sigma^2}\right), \rho \geq 0, \quad (4)$$

where  $\rho$  is the amplitude of the received signal and  $\sigma^2$  is the local mean power. From the probability density function (pdf) of the received signal amplitude (4), the pdf of received signal power,  $\gamma$ , can be derived and has the exponential pdf (Zhang & Kassam, 1999):

$$p(\gamma) = \frac{1}{\gamma^*} \exp\left(-\frac{\gamma}{\gamma^*}\right), \gamma \geq 0, \quad (5)$$

where  $\gamma^*$  is the mean power of the received signal. In a similar way, for a relay link, the amplitude distribution of the received signal is more accurately modeled by a Rician distribution:

$$p(\rho) = \frac{\rho}{\sigma^2} \exp\left(-\frac{\rho^2 + \nu^2}{2\sigma^2}\right) I_0\left(\frac{\rho\nu}{\sigma^2}\right), \rho \geq 0, \nu \geq 0, \quad (6)$$

where  $I_n(\cdot)$  is the  $n^{\text{th}}$ -order modified Bessel function of the first kind, and  $\frac{1}{2}\nu^2$  and  $\sigma^2$  are the power of the LOS component and the power of all other scattered components respectively. Thus, the total mean power of the received signal,  $\gamma^*$ , can be expressed as  $\gamma^* = \frac{1}{2}\nu^2 + \sigma^2$ . The ratio between the signal power in the dominant component and the local mean scattered power is defined as Rician  $K$ -factor (Erceg & Hari, 2001), where  $K = \frac{\nu^2}{2\sigma^2}$ . When the  $K$ -factor is equal to zero, the Rician distribution becomes a Rayleigh distribution; from the pdf of received signal envelope (6), the pdf of received signal power,  $\gamma$ , can be derived by transforming random variable  $\rho$  into  $\gamma$  by considering the relationship between amplitude and power of the signal,  $\gamma = \frac{1}{2}\rho^2$ . The pdf of received signal power can be expressed as:

$$p(\gamma) = \frac{(1+K)e^{-K}}{\gamma^*} \exp\left(-\frac{(1+K)\gamma}{\gamma^*}\right) I_0\left(\sqrt{\frac{4K(1+K)\gamma}{\gamma^*}}\right), K \geq 0, \gamma \geq 0, \quad (7)$$

where  $\gamma^*$  is the mean power of the received signal.

## 2.4 Relay strategy

The SSs that are outside of the transmission range of the BS have to be served via RSs, while the SSs located inside the transmission range of the BS can be served either directly from the BS or via RSs. In general, the SSs transmit/receive data to/from the BS via RSs only if the achievable relay data rate (BS-RS-SS) is greater than direct data rate (BS-SS). Since we assume that every node has a single antenna and operates in half duplex mode, the relay data rate is influenced by the link capacities and time durations of both hops involved. It is unlikely that the SSs having a good direct link capacity from the BS will use an RS to achieve a higher data rate. To compute the relay data rate in this chapter, we assume that the incoming data and outgoing data at the RSs should be equal. Let  $C_{BS-RS}$  and  $C_{RS-SS}$  be the capacities of BS to RS and RS to SS links respectively when each link is given the whole bandwidth, and also let  $t_{BS-RS}$  and  $t_{RS-SS}$  be the time durations of BS to RS and RS to SS links respectively. Focusing on the DL transmission,  $t_{BS-RS} + t_{RS-SS}$  should be equal to the total duration of DL subframe. The amount of data transferred from the BS to an RS is equal to the amount of data transferred from the RS to an SS:

$$C_{BS-RS} \cdot t_{BS-RS} = C_{RS-SS} \cdot t_{RS-SS}. \quad (8)$$

Thus, the average data rate of an SS using an RS is equal to the amount of data received divided by the time required to receive it:

$$C_{BS-SS} = \frac{C_{BS-RS} \cdot t_{BS-RS}}{t_{BS-RS} + t_{RS-SS}}, \quad (9)$$

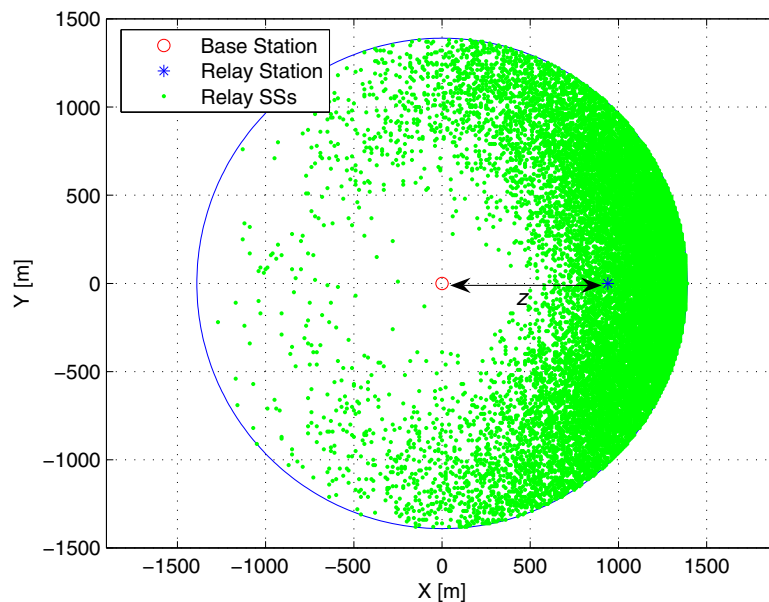


Fig. 1. A scenario with a single RS optimally placed at distance  $z$  from the BS showing the nodes that benefit from the RS.

as the RS cannot receive from the BS while transmitting to the SS. Consequently, using (8), the relay data rate of an SS can be rewritten as:

$$\frac{1}{C_{BS-SS}} = \frac{1}{C_{BS-RS}} + \frac{1}{C_{RS-SS}}. \quad (10)$$

### 3. Capacity enhancement

In this section, we focus on improving cell capacity by deploying T-RSs (transparent relays) inside a cell, and consider the placement of RSs that maximizes cell capacity. There has been a great deal of research directed toward improving the capacity of wireless networks at the physical layer. However, the achievable bit rate is still limited by the received signal strength due to the fact that wireless signal attenuates severely as it propagates between transmitter and receiver. Especially, the SSs located at the edge area of a cell achieve very limited data rates. To mitigate this problem, deploying RSs inside a cell can increase the achievable bit rate between a transmitter and a receiver leading to capacity enhancement.

#### 3.1 Optimal placement of transparent relay

A network operator always desires the most cost effective solution with a minimal deployment expenditure for the provision of satisfactory service. Therefore, in order to provide efficient multi-hop relay networks, we need to know the optimal location of RSs for maximizing network capacity. In this subsection, we show how to find the optimal location of a T-RS that maximizes the cell capacity; the results can be easily extended to scenarios with multiple RSs. We assume that multiple RSs are deployed in a circular pattern inside a cell. Thus, the optimal distances from the BS to the RSs are consistent, however the optimal distance could vary as the number of RSs changes.

As shown in Fig. 1, the BS is located at the center of the cell and the SSs are distributed uniformly in the coverage area of the BS with constant grid size 10m. The location of an SS can be uniquely identified by its coordinates. We define the set of coordinates of the SSs inside a cell,  $\mathcal{Q} = \{(x_1, y_1), (x_2, y_2), \dots, (x_N, y_N)\}$  where  $N$  is the total number of SSs inside a cell. When a T-RS is located at  $(x, y)$  and an SS  $i$  is located at  $(x_i, y_i)$ ,  $i \in \{1, 2, \dots, N\}$ , the distances of the links BS to RS, RS to SS, and BS to SS can be expressed as:

$$\begin{aligned} d_{BS-SS} &= \sqrt{x_i^2 + y_i^2}, \\ d_{BS-RS} &= \sqrt{x^2 + y^2}, \\ d_{RS-SS} &= \sqrt{(x_i - x)^2 + (y_i - y)^2}. \end{aligned} \quad (11)$$

Let us denote with  $C_{ss}(x_i, y_i)$  the achievable data rate of an SS that is located at  $(x_i, y_i)$ . We also denote with  $C_{ss}^{Direct}(x_i, y_i)$  and  $C_{ss}^{Relay}(x_i, y_i)$  the achievable direct data rate (BS-SS) and relay data rate (BS-RS-SS) of an SS located at  $(x_i, y_i)$  respectively when the whole channel bandwidth is used for that SS; with the distances computed by equation (11), the path losses and average received signal powers are calculated by using equations (1), (2). After that, the random values of the received signal powers can be generated by distributions (5), (7), and then the instantaneous SINR values can be computed by equation (3). Consequently, using the threshold SINR values in Table 2 and the equation (10) for the relay case, the achievable direct and relay data rates of an SS can be determined. To maximize the cell capacity, every SS will choose the best achievable data rate between direct and relay data rates:

$$C_{ss}(x_i, y_i) = \max \left( C_{ss}^{Direct}(x_i, y_i), C_{ss}^{Relay}(x_i, y_i) \right). \quad (12)$$

Due to the fading channel effect (i.e., received signal power is a random variable), an SS that is close to the BS does not always achieve a higher data rate than an SS that are further away from the BS. Likewise, as shown in Fig. 1 a few SSs located on the left side of the cell can benefit from the RS placed on the right side of the cell. We denote with *relay SSs* and *direct SSs* the SSs whose relay data rate is higher than direct data rate and the SSs whose direct data rate is higher than relay data rate respectively. We also define the mean cell capacity,  $C_{cell}$ , as the summation of every SS's achievable data rate divided by the total number of SSs in a cell. Therefore, the optimal placement of an RS can be determined in such a way that the mean cell capacity is maximized:

$$\arg \max_{(x,y)} \frac{1}{N} \sum_{(x_i,y_i) \in \mathcal{Q}} C_{ss}(x_i, y_i; x, y). \quad (13)$$

### 3.2 Impact of network parameters

In this subsection, we show how various network parameters such as reuse factor, terrain types, RS antenna gain, and the number of RSs affect the optimal placement of RSs and the cell capacity. To evaluate the performance of using RSs in comparison to the conventional scenario (without using RSs), we define the capacity gain parameter. Let  $C_{cell}^{Relay}$  and  $C_{cell}^{Direct}$  be the cell capacity with RS and without RS respectively, the relative capacity gain can be defined



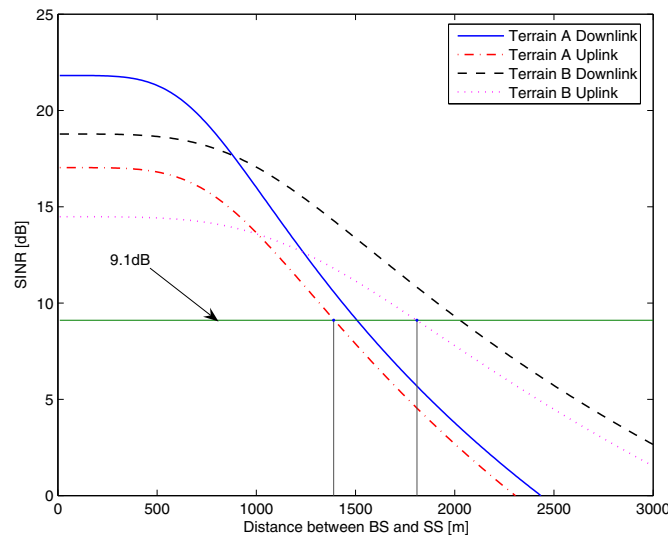


Fig. 2. Downlink and uplink edge SINR as a function of cell size for two different terrain types.

as:

$$Capacity\ Gain = \frac{C_{cell}^{Relay} - C_{cell}^{Direct}}{C_{cell}^{Direct}}. \quad (14)$$

We assume that our basic system has a reuse factor of seven, one sector per cell, terrain type A, 17dBi RS antenna gain, and four RSs deployed to enhance cell capacity. The system is analyzed by varying one specific parameter without changing the rest of basic system parameters. For each scenario, the cell size (cell radius) will vary since the received SINR value at the SS is affected by the different network parameters. Fig. 2 shows how cell size can be determined for a specific scenario. The SINR value of an SS located at the edge of the cell decreases as the distance between BS and SS increases on both DL and UL regardless of the terrain types. The decrease in SINR is more significant for terrain type A. However, when the edge SS is close to the BS, the SINR values under terrain type A are even higher than that of terrain type B because the co-channel interference values are significant when the received signal powers are similar in both terrain types. Once either the DL or UL SINR value reaches the minimum threshold value 9.1dB, that distance from the BS is considered as a cell size.

The first scenario is to evaluate the capacity gain and the optimal placements of RSs by varying the reuse factor. The reuse factor represents the number of cells grouped in a cluster. When the number of cells in a cluster increases, the co-channel distance also increases. The co-channel interference is a function of co-channel distance, hence, the larger the reuse factor the smaller the interference power from neighboring cells. Moreover, the cell size is affected by the reuse factor. When the reuse factor decreases, the cell size also decreases as the co-channel interference increases. When the cell size is small, most of the SSs do not benefit from the RSs since they are close enough to the BS leading to the smaller capacity gain. In other words, it is not very useful to deploy RSs in scenarios with a smaller reuse factor. Fig. 3(a) shows the cell capacity gain as a function of the location of RS in each reuse factor scenarios four, seven, nine, and twelve. The maximum cell capacity gain of 31.54% is achieved for a reuse factor of twelve, while only a capacity gain of 13.22% is obtained in the scenario with a reuse factor of four. Although RSs are optimally placed in a cell, only small number of SSs can benefit from

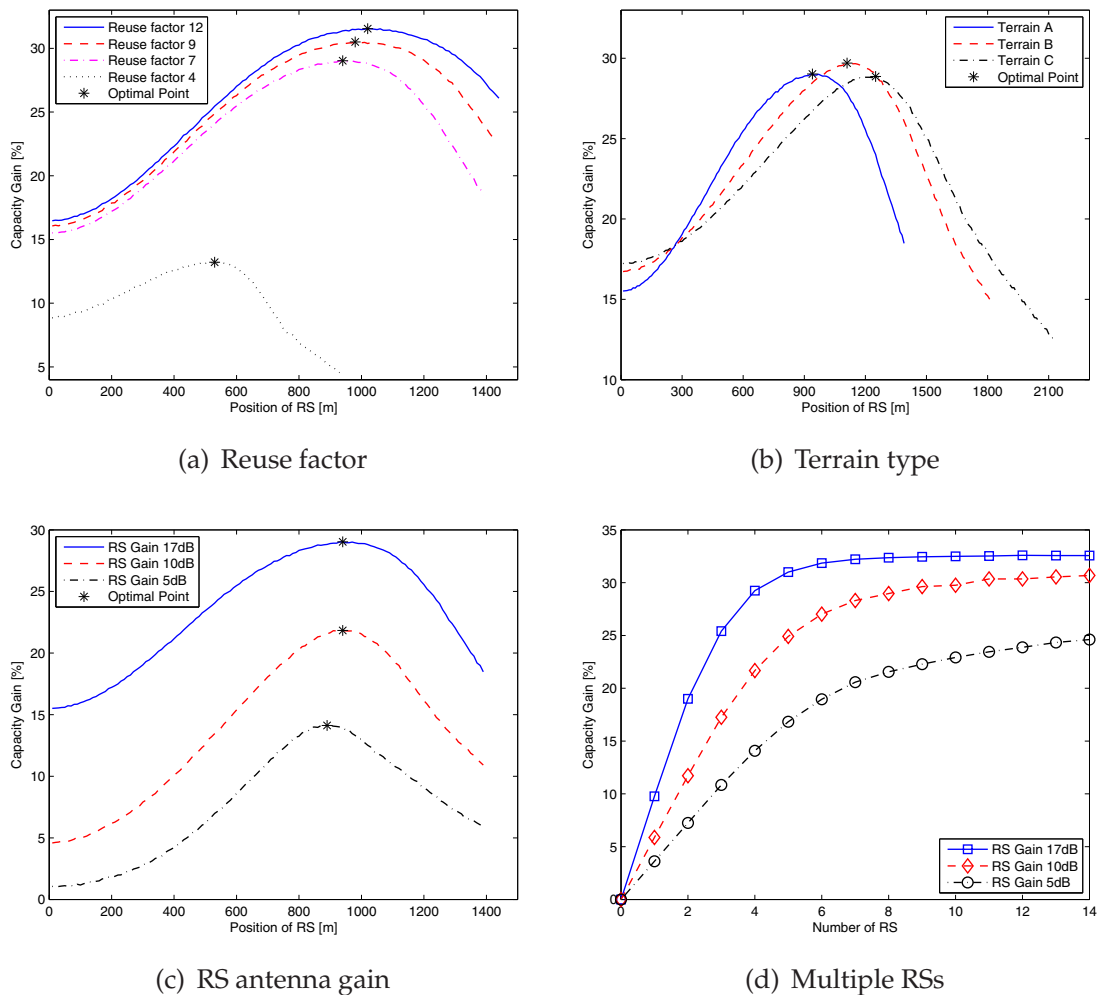


Fig. 3. Cell capacity gains for different network parameters when using four T-RSs.

RSs in the scenario with the reuse factor four. It is interesting to note that RSs are increasing the capacity of the cell even if placed near the base station due to Rayleigh fading that may result in SUs preferring the link to the RSs to the link to the BS. The exact cell capacities and relay locations are listed in Table 3.

In the second scenario we study the impact of terrain types mentioned in section 2.2 on the capacity gain and the optimal placements of RSs. When terrain type changes from A to C, the path loss decreases between transmitter and receiver. Thus, the received signal mean power increases leading to a bigger cell size as terrain types changes from A to C. The cell sizes for terrain type A, B, and C are 1390m, 1810m, and 2120m respectively. Fig. 3(b) shows achievable capacity gains with respect to the location of RS for different terrain type scenarios. The maximum capacity gains for each scenario are very similar to each other, 29.7% is achieved for terrain type B and 28.87% is achieved for terrain type C. However, the ratio of optimal location of RS to each cell radius decreases as terrain type changes from A to C. When terrain type is A, the optimal location of RS is 67.63% of the cell radius, while optimal location of RS for terrain type C is 58.96%.

In the third scenario we analyze the capacity gain and the optimal placements of RSs by varying the RS antenna gain. The cost of an RS is assumed to be much less than a BS since

Scenario	Radius [m]	$C_{cell}^{Direct}$ [Mbps]	Optimal Location	$C_{cell}^{Relay}$ [Mbps]	Capacity Gain[%]
Reuse factor 4	930	16.6132	530	18.8094	13.22
Reuse factor 7	1390	12.9280	940	16.6804	29.03
Reuse factor 9	1420	12.6865	980	16.5553	30.50
Reuse factor 12	1440	12.5138	1020	16.4602	31.54
Terrain B	1810	12.4314	1110	16.1237	29.70
Terrain C	2120	12.2409	1250	15.7743	28.87
RS Gain 10dB	1390	12.9272	940	15.7502	21.84
RS Gain 5dB	1390	12.9266	890	14.7527	14.13

Table 3. Capacity and optimal relay position for the basic scenario and variations of the reuse factor, terrain type, and RS antenna gain.

an RS does not have a backhaul link, but the antenna gain of an RS could be as good as the BS antenna gain. We use 17dBi RS antenna gain for our basic system, and change that to 10dBi and 5dBi to analyze the impact of RS antenna gain on the system. Fig. 3(c) shows the cell capacity gain results for different RS antenna gains. The maximum capacity gain 29.03% is achieved when RS antenna gain is 17dBi and the lowest capacity gain 14.13% is achieved when RS antenna gain is 5dBi. It is clear that the cell capacity gain is significantly impacted by the antenna gain of RS. That is, the lower the RS antenna gain the lower the capacity gain achieved. It is also shown that the different antenna gains of RS had no significant impact on the optimal placement of RS.

In the last scenario of this subsection we explore the impact of the number of RSs on cell capacity. In general, the more RSs, the higher the cell capacity. However, the network cost will also increase as the number of RS increases. Fig. 3(d) shows how much capacity gain can be achieved with respect to the number of RS for different RS antenna gain scenarios. The increase rate of capacity gain for each scenario is clearly decreasing as the number of RS increases. When the RS antenna gains are 17dBi, 10dBi, and 5dBi, the capacity gains are limited to approximately 33%, 31%, and 25% respectively. Therefore, it is clear that the addition of RSs after a certain number of RSs does not further improve the cell capacity, e.g., deploying more than six RSs in 17dBi antenna gain scenario is not useful. The capacity gain with 14 RSs of antenna gain 5dBi is lower than that of a system with five RSs of antenna gain 10dBi or three RSs of antenna gain 17dBi. That is, the RS antenna gain has more significant impact on the capacity gain than the number of RSs.

#### 4. Coverage extension

In this section, we focus on deploying NT-RSs for coverage extension. In order to analyze the benefits of using RSs from a coverage extension perspective, we need to examine how deploying RSs affects cost and throughput as well as coverage increase. To analyze the variation of throughput under the influence of RSs, the scheduling scheme has to be taken into account since the achievable throughput could differ significantly according to the scheduling schemes used. We first present three scheduling schemes: orthogonal, overlapped, and optimal that can be used in two-hop relaying networks. We then analyze the cost effective coverage extension problem by varying both the location and number of RSs (Kim & Sichitiu, 2010a). Finally, we explore an extension of the optimal scheduling scheme to a general multihop relaying scenario, and examine the impact of an increased number of relay hops on the network performance (Kim & Sichitiu, 2011a). Fig. 4 shows an example coverage

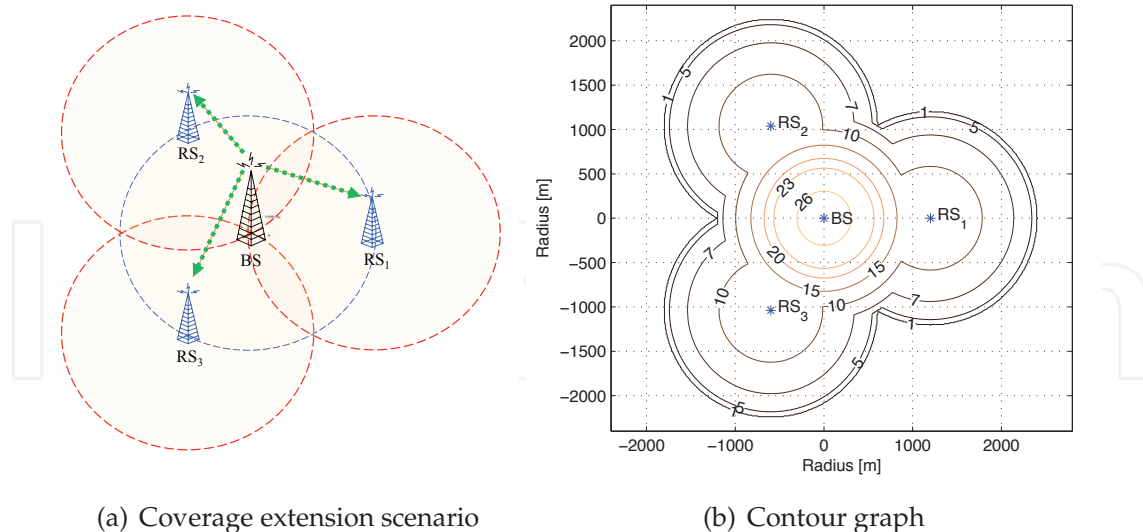


Fig. 4. (a) Coverage extension scenario and (b) Contour graph of achievable average data rate when three RSs are deployed at the edge of the cell.

extension scenario where three NT-RSs are deployed at the edge of the BS transmission range. Using this scenario, we evaluate the performance of the scheduling schemes presented in the following subsection. The cell radius for the coverage extension scenario is assumed to be 1200m (determined by the condition that the cell coverage probability under the Rayleigh fading channel is greater than 90% (Erceg & Hari, 2001)), and the rest of network parameters are the same as the basic system in Section 3.

#### 4.1 Scheduling schemes

According to the standard (802.16j, 2009), it is possible for the NT-RSs and BS to transmit and receive simultaneously to/from the associated SSs during the access zone period. Therefore it is challenging to schedule transmission opportunities to each link in the network, especially for serving SSs in a fair manner. We first present two existing scheduling schemes, namely the orthogonal and overlapped schemes (Park et al., 2009), and then introduce an optimal scheme (Kim & Sichitiu, 2011b). The orthogonal scheme minimizes interference by disallowing frequency reuse; however it can lead to lower throughput performance, whereas the overlapped scheme can achieve higher throughput by maximizing frequency reuse, but the outage rate is also increased due to significant intra-cell interference. In (Park et al., 2009), the boundary between access and relay zones was not dynamically selected according to the traffic load but statically determined for each scenario. To overcome this problem, we formulate the optimization problem for both orthogonal and overlapped schemes such that the cell throughput is maximized by optimally determining the boundary between the access and relay zones. Furthermore, we introduce an optimal scheduling scheme to combine the advantages of orthogonal and overlapped schemes. The optimal scheme maximizes the frequency reuse efficiency while avoiding outage events due to interference. The formulated optimization problems can be solved by using linear programming.

OFDMA based WiMAX networks allow scheduling to be done in the tiling frame structure (two-dimensional time $\times$ frequency) to attain frequency selectivity and multiuser diversity. However, due to the fact that the original tile scheduling problem is NP-hard (Deb et al., 2008), we will not consider multiuser scheduling over the frequency domain. Thus the entire

Notation	Description
$\mathcal{R}$	Set of RSs
$\mathcal{R}^+$	Set of service nodes (BS and RSs)
$\mathcal{U}$	Set of possible transmission subsets of service nodes
$\mathcal{V}$	Set of possible transmission subsets of relay links
$\mathcal{L}$	Set of possible relay links ( $l_{ij} \in \mathcal{L}$ )
$l_{ij}$	Relay link between service node $i$ and $j$ ( $i \in \mathcal{R}^+, j \in \mathcal{R}$ )
$\mathcal{S}$	Set of SSs
$\mathcal{S}_b$	Set of SSs associated with BS
$\mathcal{S}_R$	Set of SSs associated with RSs
$\mathcal{S}_r^u$	Set of SSs associated with RS $r \in \mathcal{R}$ in the subset $u$
$\mathcal{S}_{r^+}^u$	Set of SSs associated with $r^+ \in \mathcal{R}^+$ in the subset $u$
$C_s^u$	Achievable data rate of SS $s \in \mathcal{S}$ in the subset $u$
$C_r$	Achievable data rate of RS $r \in \mathcal{R}$ from the BS
$C_{ij}^v$	Achievable data rate for a relay link $l_{ij}$ in the subset $v$
$\lambda_s^u$	Time fraction allocated to SS $s \in \mathcal{S}$ in the subset $u$
$\lambda_r$	Time fraction allocated to RS $r \in \mathcal{R}$ in relay zone
$\lambda^u$	Time fraction of subset $u \in \mathcal{U}$ in access zone
$\lambda^v$	Time fraction of subset $v \in \mathcal{V}$ in relay zone
$\lambda_{ij}^v$	Time fraction allocated for a relay link $l_{ij}$ in the subset $v$
$T_s$	Throughput of SS $s \in \mathcal{S}$

Table 4. Notations used

spectrum is allocated to each node whenever they are allowed to transmit, i.e., scheduling is done by assigning time slots to nodes. For scheduling, fairness is an important issue. The well known fairness schemes such as max-min and proportional fairness for the relay enhanced WiMAX system are evaluated in our previous paper (Kim & Sichitiu, 2010b). The goal of max-min fairness is to allocate network resources in such a way that none of the active SSs can achieve more throughput than other active SSs without decreasing the throughput of other SSs. We formulate the optimization problem for each scheduling scheme under the max-min fairness constraints (Tassiulas & Sarkar, 2002). The notations used for the formulations are listed in Table 4.

#### 4.1.1 Orthogonal scheduling scheme

The orthogonal scheme is an extreme solution for schedule resources since it does not allow frequency reuse in order to minimize intra-cell interference during the access zone period. In this scheme, only one service node can be active at a time to transmit to the associated SSs. Hence, there is no outage problem due to interference, but the achievable network throughput will be degraded due to inefficient radio resource utilization. To determine the time duration of each transmission for the orthogonal scheme, we formulate the optimization problem such that the cell throughput is maximized under max-min fairness constraints. Since it is impossible to increase the throughput of an SS without decreasing that of other SSs in the orthogonal scheme, the max-min fairness is equivalent to absolute fairness, i.e., every active SS achieves an equal throughput.

We denote with  $\mathcal{R}$  and  $\mathcal{S}$  the sets of RSs and SSs respectively, and the set of service nodes (the BS and RSs) is denoted as  $\mathcal{R}^+$  (i.e.,  $|\mathcal{R}^+| = |\mathcal{R}| + 1$ ). Let  $\mathcal{U}$  be the set of possible

simultaneously active service nodes during the access zone period. Each element  $u \in \mathcal{U}$  represents one subset of  $\mathcal{R}^+$  with all the service nodes in that subset able to transmit concurrently to their associated SSs. In the orthogonal scheme, only single element subsets are possible in  $\mathcal{U}$  since simultaneous transmission among service nodes is not allowed, hence, the two sets  $\mathcal{U}$  and  $\mathcal{R}^+$  have the same cardinality (i.e.,  $|\mathcal{U}| = |\mathcal{R}^+|$ ) in the orthogonal scheme. Let  $C_s$  be the achievable data rate of an SS from the service node that the SS is associated with. In other words,  $C_s$  represents the instantaneous link capacity between an SS and its service node. Similarly, the achievable data rate of an RS from the BS is denoted by  $C_r$ . Also, let  $\lambda_s$  and  $\lambda_r$  be the time fraction allocated to an SS and the time fraction allocated to an RS respectively. When the transmission subset  $u \in \mathcal{U}$  changes, an SS can be associated with a different service node. Thus, the achievable data rate and time fraction of an SS in each transmission subset  $u$  are denoted by  $C_s^u$  and  $\lambda_s^u$  respectively. The ultimate throughput of an SS,  $T_s$ , during the current DL subframe can be expressed as the summation of throughputs received in each transmission subset  $u$  when the SS was allocated the time fraction  $\lambda_s^u$ :

$$T_s = \sum_{u \in \mathcal{U}} C_s^u \lambda_s^u, \quad \forall s \in \mathcal{S}. \tag{15}$$

Our goal of maximizing cell throughput corresponds to maximizing the throughput,  $T_s$ , of any subscriber  $s \in \mathcal{S}$  in the orthogonal scheme. Finding the maximum achievable throughput of an SS can be formulated as a linear programming problem as follows:

$$\max_{s \in \mathcal{S}} T_s. \tag{16}$$

**Subject to:**

$$T_{s_1} = T_{s_2}, \quad \forall s_1, s_2 \in \mathcal{S} (s_1 \neq s_2). \tag{17}$$

$$C_r \lambda_r = \sum_{s \in \mathcal{S}_r} C_s \lambda_s, \quad \forall r \in \mathcal{R}. \tag{18}$$

$$\lambda^u = \sum_{s \in \mathcal{S}_{r^+}^u} \lambda_s^u, \quad \forall r^+ \in \mathcal{R}^+, \forall u \in \mathcal{U}, |\mathcal{S}_{r^+}^u| > 0. \tag{19}$$

$$\sum_{u \in \mathcal{U}} \lambda^u + \sum_{r \in \mathcal{R}} \lambda_r \leq 1. \tag{20}$$

$$0 \leq \lambda_s^u, \lambda_r \leq 1, \quad \forall u \in \mathcal{U}, \forall s \in \mathcal{S}, \forall r \in \mathcal{R}. \tag{21}$$

Here,  $\mathcal{S}_r$  and  $\mathcal{S}_{r^+}$  denote the set of SSs associated with RS  $r \in \mathcal{R}$  and service node  $r^+ \in \mathcal{R}^+$  respectively. In each transmission subset  $u$ , the sets  $\mathcal{S}_r$  and  $\mathcal{S}_{r^+}$  are denoted by  $\mathcal{S}_r^u$  and  $\mathcal{S}_{r^+}^u$ . The first constraint ensures that every active SS in a cell achieves an equal throughput. The second constraint states that there is no data loss at the RSs, the data transferred from BS to RS  $r \in \mathcal{R}$  is equal to the data transferred from RS  $r$  to the associated SSs. The third constraint ensures that resources within the duration of each transmission subset  $u$  are fully utilized by the associated SSs. Thus, the time fraction of each transmission subset  $u$ ,  $\lambda^u$ , is equal to the summation of time fractions allocated to SSs associated with  $r^+$  when  $r^+$  is the element of subset  $u$ . The fourth constraint captures the fact that the DL subframe consists of an access zone and a relay zone. The summation of time fractions of every transmission subset will be equivalent to the access zone time fraction, and the summation of time fractions allocated to RSs is the same as the relay zone time fraction. The sum of access and relay zone time fractions should be less than or equal to one. The final constraint restricts the amount of each time fraction allocated to SSs

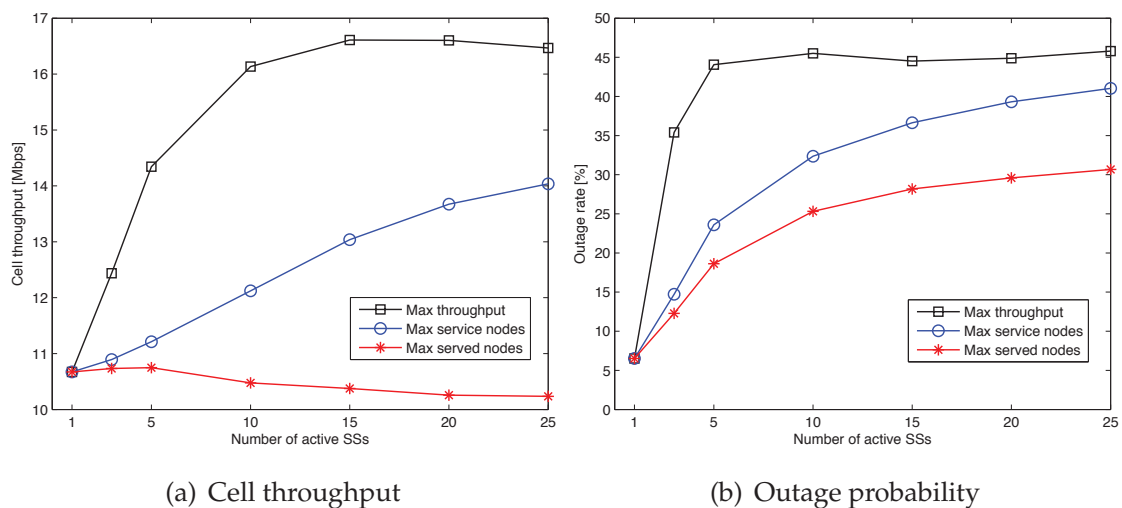


Fig. 5. (a) Cell throughput and (b) outage probability as a function of the number of active SSs within a cell for different subset selection objectives for the overlapped scheme.

and RSs to be positive and smaller than one. By using these scheduling constraints (17)-(21), the objective function (16) can be maximized. Once the throughput of an SS (16) is maximized, the cell throughput can be computed by:

$$\text{Cell Throughput} = \sum_{s \in \mathcal{S}} T_s. \quad (22)$$

#### 4.1.2 Overlapped scheduling scheme

The main goal of the overlapped scheme is to fully reuse radio resources during the access zone period. Multiple service nodes can transmit data to the associated SSs simultaneously, thereby enhancing network throughput, but at the same time outage events increase due to significant intra-cell interference. All the service nodes in a cell can be active simultaneously to maximize the chance of frequency reuse, however according to the number of active SSs and distributions of the SSs, some of the service nodes may not have to be active since it is possible that none of the active SSs are associated to that service node. Therefore, the decision regarding which service node should be active over a frame needs to be made at the beginning of a frame before scheduling. In other words, the overlapped scheme will consider only one transmission subset of the active service nodes over one frame duration. That is, once the subset of active service nodes is determined at the beginning of a frame, it will last for the duration of the entire current frame. For determining the set of active service nodes, we should also consider an additional *subset selection objective* (Kim & Sichitiu, 2011b):

- maximizing cell throughput,
- maximizing the number of active service nodes, or
- maximizing the number of served SSs.

According to which of these objectives are selected, a different subset of active service nodes is determined for the overlapped scheme. Now, we can formulate the optimization problem as in Section 4.1.1 to maximize cell throughput for the overlapped scheme by considering only one subset  $u \in \mathcal{U}$  instead of the entire set  $\mathcal{U}$ . When the service nodes of the selected subset are active simultaneously, each active SS can be associated only to the service node that has the strongest link capacity to that SS over the entire duration of that frame. However, not every

active SS can fully use resources during the access zone period because we assume max-min fairness and also the relay links (BS to RSs) have to share the resources orthogonally to transfer data from the BS to the RSs. Therefore, for the SSs that are served via RSs, the SSs with low link capacity are allocated large fractions of time while the SSs with high link capacity may have smaller time fractions, hence, the absolute fairness still holds for the SSs associated with RSs, but the SSs associated with the BS directly may achieve a higher throughput under max-min fairness since these larger throughputs do not affect the throughput of the rest of SSs associated with the RSs. Consequently, the objective of maximizing the throughput of an SS does not correspond to maximizing the cell throughput for the overlapped scheme since the equivalence of the absolute and max-min fairness constraint does not hold. Therefore, the objective of the optimization problem for the overlapped scheduling scheme is expressed as:

$$\max \sum_{s \in \mathcal{S}} T_s. \tag{23}$$

Let  $\mathcal{S}_b$  and  $\mathcal{S}_R$  be the set of SSs associated with the BS and RSs respectively over a frame period. The max-min fairness ensures that every SS achieves an equal throughput in each subset  $\mathcal{S}_b$  and  $\mathcal{S}_R$ . However, the throughput of an SS in  $\mathcal{S}_b$  could be higher than the throughput of an SS in  $\mathcal{S}_R$ . Therefore, the first constraint (17) in the orthogonal scheme is modified for the overlapped scheme as follows:

$$\begin{aligned} T_{s_1} &= T_{s_2}, & \forall s_1, s_2 \in \mathcal{S}_b (s_1 \neq s_2) \\ T_{s_3} &= T_{s_4}, & \forall s_3, s_4 \in \mathcal{S}_R (s_3 \neq s_4) \\ T_{s_5} &\geq T_{s_6}, & \forall s_5 \in \mathcal{S}_b, \forall s_6 \in \mathcal{S}_R. \end{aligned} \tag{24}$$

The second and fifth constraints (18), (21) do not change for the overlapped scheme as there is no data loss at the RSs, but the third and fourth constraints (19), (20) are modified because there may be wasted resources in the access zone due to fairness and only one subset of  $\mathcal{R}^+$  is considered in the overlapped scheme:

$$\lambda^u \geq \sum_{s \in \mathcal{S}_{r^+}^u} \lambda_s^u, \forall r^+ \in \mathcal{U}, \forall u \in \mathcal{U}, |\mathcal{S}_{r^+}^u| > 0 \tag{25}$$

$$\lambda^u + \sum_{r \in \mathcal{R}} \lambda_r \leq 1. \tag{26}$$

Consequently, the cell throughput for the overlapped scheme can be maximized by solving linear programming with the objective (23) under constraints (18), (21), (24), (25), (26). Any subset could be chosen at the beginning of a frame based on the subset selection objectives, and the selected service nodes in that subset will be optimally scheduled to maximize cell throughput by using the optimization problem formulated above. However, the cell throughput and outage rate can vary according to the subset of active nodes chosen. Fig. 5 shows the cell throughput and outage rate as a function of the number of active SSs for different subset selection objectives for the overlapped scheme. The max throughput objective achieves the highest cell throughput, while the max served nodes objective attains the lowest cell throughput. In contrast, the outage rate performance of the max served nodes objective case is the best among three objective cases, while the outage rate of the max throughput objective case is the worst.



### 4.1.3 Optimal scheduling scheme

The key drawback of the orthogonal scheme is the bandwidth inefficiency because it prevents frequency reuse during the access zone period. For the overlapped scheme, the high outage probability is a serious problem. To eliminate these problems, an optimal scheduling scheme is proposed. The main task of an optimal scheme is to maximize bandwidth efficiency by allowing frequency reuse while avoiding outage events due to intra-cell interference. In order to accomplish the main task of the optimal scheme, we need to consider all possible transmission subsets of service nodes during the access zone period, i.e., the set  $\mathcal{U}$  is the power set of  $\mathcal{R}^+$  excluding the empty set in the optimal scheme scenario ( $|\mathcal{U}| = 2^{|\mathcal{R}^+|} - 1$ ). In each subset of service nodes, an active SS can be either outage due to interference or associated with the active service node that has the highest link capacity to that SS. The achievable data rate of an SS,  $C_s^u$ , varies for each subset of active service nodes because intra cell interference changes according to the number of active service nodes in each subset.

Similar to the orthogonal scheme, the objective of the optimization problem for the optimal scheme is to maximize the throughput of any active SS in a cell since the equivalence of the absolute and max-min fairness holds for the optimal scheme. In this scheme, the whole bandwidth should be fully utilized without wasting resources, thus none of the active SSs can achieve more throughput without decreasing the throughput of the other SSs. The first, fourth and fifth constraints (17), (20), (21) in the orthogonal scheme do not change for the optimal scheme, but the second and third constraints (18), (19) are modified to take into account every possible subset of service nodes for the optimal scheme. In the orthogonal and overlapped schemes, the set of SSs associated with RS  $r$ ,  $\mathcal{S}_r$ , does not change over one DL subframe interval because an RS  $r$  can be active only one time to transfer data to the SSs associated to that RS, i.e., an RS  $r$  can not be included in more than two subsets. However, in the optimal scheme, an RS  $r$  can be active more than once as part of different subsets, i.e., an RS  $r$  can be an element of multiple subsets. Thus, the second constraint can be rewritten as:

$$C_r \lambda_r = \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}_r^u} C_s^u \lambda_s^u, \quad \forall r \in \mathcal{R}. \quad (27)$$

To ensure that resources within the duration of each transmission subset  $u$  are fully utilized by the associated SSs in the optimal scheme, there should not be any wasted resources. For example, when  $r_1^+$  and  $r_2^+$  are active service nodes in the subset  $u$ , the summation of time fractions allocated to SSs associated with  $r_1^+$  should be equal to the summation of time fractions allocated to SSs associated with  $r_2^+$ :

$$\lambda^u = \sum_{s \in \mathcal{S}_{r_1^+}^u} \lambda_s^u = \sum_{s \in \mathcal{S}_{r_2^+}^u} \lambda_s^u, \quad (28)$$

$$\forall r_1^+, r_2^+ \in u, \forall u \in \mathcal{U}, |\mathcal{S}_{r_1^+}^u| > 0, |\mathcal{S}_{r_2^+}^u| > 0.$$

Therefore, the cell throughput for the optimal scheme can be maximized by solving the linear programming problem with the objective (16) under constraints (17), (20), (21), (27), (28).

To evaluate the performance of the optimal scheduling scheme, we compare its performance with the orthogonal and overlapped schemes. Fig. 6 shows the cell throughput and outage rates as a function of the number of active SSs in a cell. To obtain the average cell throughput value, the simulation is repeated 10,000 times for each scenario with  $N$  active SSs randomly placed in the cell with a uniform distribution. For the overlapped scheme, the max served

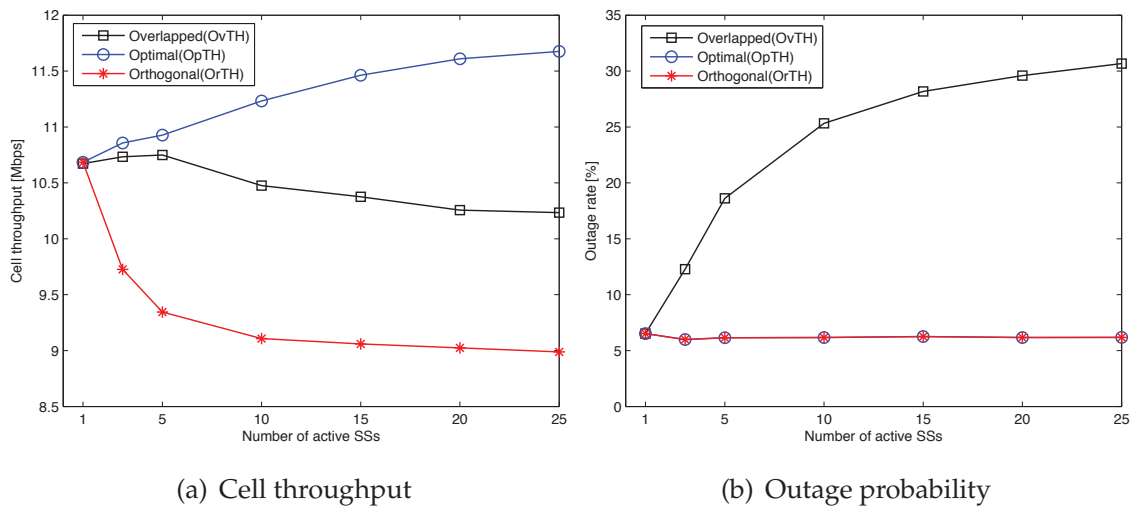


Fig. 6. (a) Cell throughput and (b) outage probability as a function of the number of active SSs within a cell for different two-hop scheduling schemes.

nodes subset selection objective is assumed. When there is only one active SS in a cell, there is no difference between the three scheduling schemes on both the cell throughput and outage rate since there is no frequency reuse and intra-cell interference. However, the differences becomes significant as the number of active SSs increases. The cell throughput achieved by the orthogonal scheme decreases because it is more likely to have SSs with low link capacities consuming large fractions of the time in order to preserve fairness, while the cell throughput for the optimal scheme grows as the number of active SSs increases since the optimal scheme maximizes frequency reuse without increasing outage rates. As shown in Fig. 6(b), the outage rate from the optimal scheme is identical to the result from the orthogonal scheme, while the outage rate for the overlapped scheme continues to rise significantly as more SSs join the cell. Although there is no interference between service nodes in the orthogonal scheme, about 6% of active SSs still encounter outage due to the Rayleigh fading channels. Overall, the cell throughput and outage rate performance can be dramatically enhanced by using the optimal scheduling scheme.

**4.2 Cost effective coverage extension**

In this subsection we analyze a cost effective coverage extension scenario by varying both the location and number of RSs. We use the optimal scheduling scheme presented in the previous subsection to compute the cell throughput for each coverage extension scenario and analyze the impact of varying the location and number of RSs on network throughput as well as network cost. We assume that each cell has between one and six RSs arranged in a circular pattern at the same distance from the BS to extend the cell coverage, and the cost of an RS is assumed to be 40% of the cost of a BS (Upase & Hunukumbure, 2008). To compare the network cost enhanced with RSs with the network cost without RSs, we define the relative cost parameter:

$$Relative\ Cost[\%] = \frac{Cost\ of\ network\ with\ RS}{Cost\ of\ network\ without\ RS} \times 100. \tag{29}$$

For example, assume that the total network service area is covered by 100 BSs without RSs (i.e., 100 cells); when two RSs are deployed in each cell to extend the cell coverage, the total

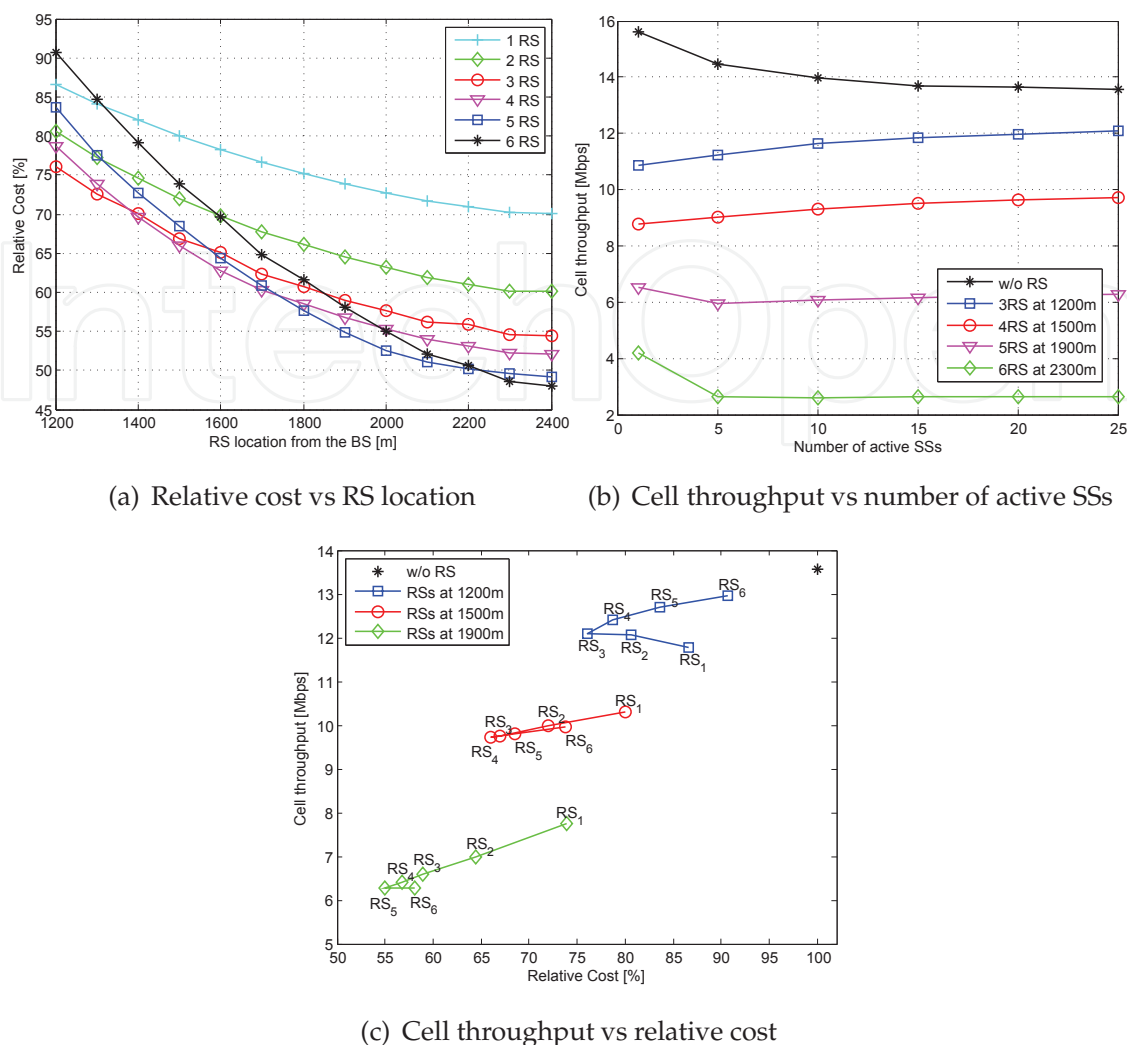


Fig. 7. Cost effective coverage extension scenario results

number of cells needed to cover the service area will be decreased. Assume that the new number of cells is 50 (i.e., 50 BSs and 100 RSs); then the relative cost of this relay enhanced network is 90% ( $50 + 100 \times 0.4$ ). We consider this relative cost as the network cost.

Figure 7(a) shows relative costs as a function of the RS location for a different number of RSs per each cell. The distance between the BS and RSs varies from 1200m to 2400m, which is twice the cell size. Since the RSs have higher antenna gains and transmission power than those of the SSs, the location of RS could be outside of the BS coverage. As the location of RSs from the BS increases, the relative costs decrease because the cell coverage extends when the RSs are further away from the BS leading to fewer required cells to cover the network area, hence, lower cost. When the number of RSs increases from one to three, the relative cost decreases regardless of the location of RSs, however, when the number of RSs is greater than four, the relative cost of the higher number of RSs is not necessarily lower than that of a smaller number of RSs. For example, the minimum relative cost is achieved by the three RSs case, i.e., deploying more than four RSs at 1200m is not desirable as they are more costly. From 1400m to 1700m deploying four RSs is the optimal case, and from 1800m to 2200m five RSs is better, and six RSs is better for distances from 2300m to 2400m.

To evaluate the effect of varying locations and numbers of RSs on the cell throughput, the optimal scheduling scheme is used such that every active SS can achieve the same throughput and a reduced outage rate. Fig. 7(b) shows cell throughput as a function of the number of active SSs for different locations and numbers of RSs. In the case without-RSs, the cell coverage area is the minimum, while the cases with-RSs increase the cell coverage as the placement of the RS is further away from the BS. Thereby, the cell throughput decreases as the cell coverage increases. However, the cell throughput of the case without-RSs decreases as the number of active SSs increases, while some of the cases with RSs show that cell throughput tends to increase with the number of active SSs. This change in cell throughput is due to the fact that it is more likely to have SSs with small link capacities consuming a large fraction of the time in order to preserve fairness as the number of active SSs increase, but in the cases with RSs the frequency reuse efficiency can overcome this tendency, hence, it is clear that the frequency reuse scheme has a positive impact on the cell throughput. Especially, when the location of RSs is less than 1500m, the achievable cell throughput continues to grow with the number of active SSs.

To be able to determine the cost effective coverage extension scenario, we need to simultaneously examine the effects of using RSs on both cost and throughput. Fig. 7(c) shows the cell throughput as a function of relative cost when the number of active SS is 25. Cell throughputs for three different RS locations and one to six RSs are plotted in this graph. Overall, the relative cost decreases as the location of RSs is further away from the BS and the number of RSs increases, but at the same time cell throughput also decreases. In other words, lower network cost can be achieved at the expense of the cell throughput. However, when the location of RSs is 1200m, the cell throughput continues to increase as the number of RSs increases due to the increase in frequency reuse. Especially, when the number of RSs changes from one to three, the relative cost decreases significantly. That is, deploying up to three RSs at 1200m is beneficial from both throughput and cost points of view, but deploying more than four RSs at 1200m is enhancing throughput at more cost. Therefore, cost effective coverage extension without significant throughput degradation is always feasible by carefully choosing both the location and number of RSs.

#### 4.3 Generalization for multihop scenario

We explore an extension of the optimal scheduling scheme to a general multihop relaying scenario by allowing more than three-hop relaying in a cell. Although the two-hop scenario is technically a multihop scenario, we will use the term "multihop" to refer to scenarios with more than one relay tier. Many researchers have focused on two-hop relaying networks since this scenario has the largest throughput gain and more hops per connection cause a greater delay. On the other hand, it is clear that the cell coverage will be significantly extended by increasing the number of relay hops. Therefore, it is of interest to explore how increasing the number of relay hops can affect the network performance under an optimal scheduling scheme. The optimal scheme presented in the previous subsection is aimed at two-hop relaying networks where the relay zone is orthogonally shared by relay links (BS to RSs). In a multihop relaying scenario, the RSs should be able to relay data to/from other RSs, hence, frequency reuse between relay links is also possible during the relay zone period. Therefore, the extension of the optimal scheduling scheme should take into account frequency reuse in both the access and relay zone periods. We present an extended optimal scheduling scheme in this subsection, and evaluate its performance using two example three-hop relaying scenarios.

### 4.3.1 Optimal scheme for multihop

In the two-hop relaying scenario, the SSs are receiving data from the BS either directly or via only one RS, while in the multihop scenario, the SSs can receive data through multiple RSs. Also, multiple paths from the BS to each SS exist in a cell. If we assume that there is no frequency reuse in the relay zone, as it is in two-hop scenario, the optimal path to each SS will be the path that has the highest achievable relay data rate of the SS. However, to minimize throughput degradation due to the increase of number of hops, frequency reuse must be considered. Thereby, it is possible that a lower capacity relay link can also be scheduled for RSs to relay data, since multiple relay links can be active simultaneously during the relay zone period. To formulate the optimization problem for the multihop optimal scheduling scheme, we need to consider every possible link between service nodes as relay links, and then consider every possible set of relay links that can be active simultaneously.

Let  $l_{ij}$  be a relay link from the service node  $i \in \mathcal{R}^+$  to  $j \in \mathcal{R}$ , and let  $\mathcal{L}$  be the set of all possible relay links (i.e.,  $l_{ij} \in \mathcal{L}$ ). To consider every possible simultaneous transmissions between relay links, we denote with  $\mathcal{V}$  the power set of  $\mathcal{L}$  excluding the empty set and any sets of links that cannot be active at the same time. Thus, each element  $v \in \mathcal{V}$  is a subset of relay links that can be active at the same time. Also, we denote with  $C_{ij}$  and  $\lambda_{ij}$  the achievable data rate and time fraction allocated for a relay link  $l_{ij}$  respectively. For the simultaneous transmission subset  $v$ , the achievable data rate and time fraction allocated for a relay link could vary due to intra-cell interference, hence, the  $C_{ij}$  and  $\lambda_{ij}$  when the relay links in the subset  $v$  are active are denoted by  $C_{ij}^v$  and  $\lambda_{ij}^v$  respectively. To simplify the notation, let  $T_r$  be the total amount of data transferred from an RS  $r$  to the associated SSs during the DL subframe interval as shown in (27):

$$T_r = \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}_r^u} C_s^u \lambda_s^u, \quad \forall r \in \mathcal{R}. \quad (30)$$

The objective of the multihop optimal scheme is to maximize the throughput of any active SS in a cell since the equivalence of the absolute and max-min fairness holds for the multihop optimal scheme. Finding the maximum achievable throughput of an SS can be formulated as a linear program as follows:

$$\max_{s \in \mathcal{S}} T_s. \quad (31)$$

**Subject to:**

$$T_{s_1} = T_{s_2}, \quad \forall s_1, s_2 \in \mathcal{S} (s_1 \neq s_2). \quad (32)$$

$$\sum_{v \in \mathcal{V}} \sum_{l_{ij} \in v} C_{ij}^v \lambda_{ij}^v = \sum_{v \in \mathcal{V}} \sum_{l_{jk} \in v} C_{jk}^v \lambda_{jk}^v + T_j, \quad \forall i \in \mathcal{R}^+, \forall j, k \in \mathcal{R}. \quad (33)$$

$$\lambda^u = \sum_{s \in \mathcal{S}_{r_1^+}^u} \lambda_s^u = \sum_{s \in \mathcal{S}_{r_2^+}^u} \lambda_s^u, \quad \forall r_1^+, r_2^+ \in \mathcal{U}, \forall u \in \mathcal{U}, |\mathcal{S}_{r_1^+}^u| > 0, |\mathcal{S}_{r_2^+}^u| > 0. \quad (34)$$

$$\sum_{u \in \mathcal{U}} \lambda^u + \sum_{v \in \mathcal{V}} \lambda^v \leq 1. \quad (35)$$

$$\lambda^v = \lambda_{l_1}^v = \lambda_{l_2}^v, \quad \forall l_1, l_2 \in v, \forall v \in \mathcal{V}. \quad (36)$$

$$0 \leq \lambda_s^u, \lambda_r \leq 1, \quad \forall u \in \mathcal{U}, \forall s \in \mathcal{S}, \forall r \in \mathcal{R}. \quad (37)$$

The first constraint ensures that every active SS in the cell achieves an equal throughput. The second constraint states that there is no data loss at the RSs: the data transferred from any of service node  $i \in \mathcal{R}^+$  to an RS  $j$  is equal to the sum of data transferred from the RS  $j$  to any

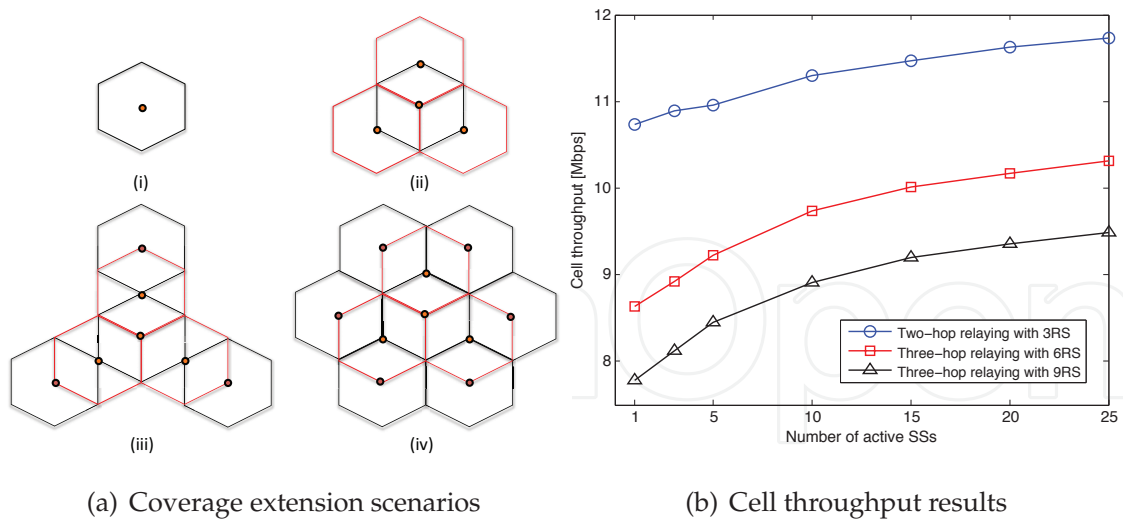


Fig. 8. (a) A coverage extension scenario with (i) no RS, (ii) three RSs, (iii) six RSs, (iv) nine RSs and (b) cell throughput results for different multihop scenarios.

of service nodes  $k \in \mathcal{R}$  and data transferred from the RS  $j$  to the associated SSs. The third constraint ensures that resources within the duration of each transmission subset  $u$  are fully utilized by the associated SSs. The fourth constraint captures the fact that the sum of access and relay zone time fractions should be less than or equal to one. The summation of every time fraction of subset  $\lambda^v$  is equivalent to the relay zone time fraction. The fifth constraint ensures that resources within the duration of each transmission subset  $v$  are fully utilized by the associated relay links. The final constraint restricts the amount of each time fraction allocated to SSs and RSs to be positive and smaller than one. By using these scheduling constraints (32)-(37), the objective function (31) can be maximized and the cell throughput with multihop optimal scheduling scheme can be easily computed.

To evaluate the performance of the multihop optimal scheduling scheme, we show two three-hop relaying scenarios with six and nine RSs respectively. Fig. 8(a) shows how the RSs are deployed to extend the cell coverage for the two-hop and three-hop scenarios. We do not assume a hexagonal cell shape in this work, but use it to demonstrate how much cell coverage can be extended with the increase in the number of hops. For example, when three RSs are deployed in the two-hop scenario, the extended cell coverage is three times larger than the cell without RSs. Similarly, the coverage of three-hop scenarios with six and nine RSs can be five and seven times larger than that of a cell with no RSs. Fig. 8(b) shows the cell throughput results for two-hop and three-hop relaying scenarios. It is clear that the cell throughput decreases as the number of hops increases. The throughput increase rates of three-hop cases are slightly higher than that of the two-hop case as the number of active SSs increases. When the number of active SSs is 25, the throughput degradations from two-hop to three-hop with six and nine RSs are approximately 12% and 19% respectively, which is surprisingly low considering the significant increase in cell coverage.

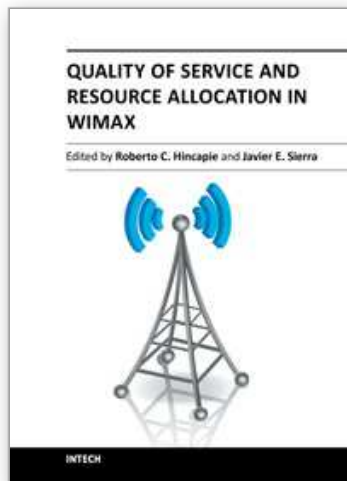
## 5. Conclusion

In this chapter we studied the impact of deploying RSs on both capacity and coverage aspects in relay-enhanced WiMAX networks. In particular, this chapter is composed of two main parts: Section 3 is targeted at optimizing the placement of transparent RSs that maximize the cell capacity; Section 4 is focused on cost effective coverage extension in the non-transparent

RS mode. In Section 3, we present the optimal placement of transparent RSs in WiMAX networks. The results show how various network parameters such as reuse factor, terrain types, RS antenna gain, and the number of RSs affect the optimal placement of RSs. In Section 4, we explore three different issues with regard to coverage extension scenario. First, we present three scheduling schemes called orthogonal, overlapped, and optimal to maximize cell throughput while preserving fairness. The results show that the cell throughput and outage rate performance can be dramatically enhanced by using the optimal scheduling scheme. Second, we suggest some design guidelines allowing network operators to achieve cost-effective coverage extensions without significant throughput degradation. In general, the lower the relative cost the lower the cell throughput; however, a higher cell throughput can be achieved with lower relative cost by carefully choosing both location and number of RSs. Finally, we extend our optimal scheduling scheme to a general multihop relaying scenario in order to show the impact of an increased number of relay hops on the network performance.

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## **Quality of Service and Resource Allocation in WiMAX**

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This book has been prepared to present state of the art on WiMAX Technology. It has been constructed with the support of many researchers around the world, working on resource allocation, quality of service and WiMAX applications. Such many different works on WiMAX, show the great worldwide importance of WiMAX as a wireless broadband access technology. This book is intended for readers interested in resource allocation and quality of service in wireless environments, which is known to be a complex problem. All chapters include both theoretical and technical information, which provides an in depth review of the most recent advances in the field for engineers and researchers, and other readers interested in WiMAX.

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