Cost Effective Coverage Extension in 802.16j Mobile Multihop Relay Networks

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***Abstract*—WiMAX (IEEE 802.16) has emerged as a promising radio access technology for providing high speed broadband connectivity to subscribers over large geographic regions. New enhancements allow deployments of relay stations (RSs) that can extend the coverage of the base station (BS), increase cell capacity, or both. In this paper, we focus on deploying RSs for the purpose of coverage extension. We propose a simple scheduling scheme for serving the subscriber stations (SSs) in a fair manner and evaluate the performance of WiMAX networks with relays under this scheduling scheme. Through simulation and numerical analysis, we make several fundamental observations about cost-effective coverage in such networks.**

I. INTRODUCTION

IEEE standard 802.16, often referred to as WiMAX, is considered a "last mile" broadband wireless access alternative to conventional DSL and Cable Internet. The initial standard is focused on providing a point to multipoint (PMP) single hop service from a single base station (BS) to multiple stationary users with subscriber stations (SSs). However, several extensions have been standardized including a mesh mode, several physical layers, as well as extensions for mobility. One such extension that is recently receiving a great deal of attention is the IEEE 802.16j Mobile Multi-hop Relay (MMR) amendment [1]. The main focus of this amendment is the development of simple and lower cost relay stations (RSs) that can enhance network coverage and capacity. A cost effective way to provide high speed data service to mobile users and the corresponding high signal to interference and noise ratio (SINR) is to use RSs.

According to the published amendment [1], RSs are classified into two categories, non-transparent mode and transparent mode. A non-transparent RS operates as a BS for connected SSs, i.e., the RS transmits management messages and forwards data traffic, while a transparent RS forwards only data traffic to and from SSs based on the frequency allocation information obtained from BS. Thus, an SS physically connected to a transparent RS is not aware of the existence of the RS. Additionally, a major difference between the two modes is that the frequency reuse is not allowed in the transparent mode. Therefore, transparent RSs are suitable for throughput improvement, while non-transparent RSs are appropriate for coverage extension and/or throughput improvement. In this paper, we focus on deploying non-transparent 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. We assume that the radio resources should be allocated to active SSs in a fair manner, i.e., focusing on downlink, when there are active SSs that need to be served by either BS or RS within the same DL frame duration, every SS can achieve same data rate regardless of its location. In this paper, we propose a simple scheduling scheme to achieve fairness. With this scheduling scheme, we compute the average cell throughput and evaluate performance of network with RSs by varying parameters such as the number of active SSs in a cell, position of the RSs, and the number of RSs. Through simulation and numerical analysis, we make several fundamental observations about cost-effective coverage extension in such networks.

The rest of this paper is organized as follows. In the next section, we discuss related work. In Section III, we present the system model including SINR analysis and fading channel. In Section IV, we propose a simple scheduling scheme in order to serve the SSs in a fair manner. Numerical results and analysis are shown in Section V. Section VI concludes the paper.

II. RELATED WORK

Researchers have recently started investigating the benefits of using relays in multihop WiMAX systems. In [2], the authors show an analytical approach for dimensioning cellular multihop WiMAX networks that are based on OFDM technology. They analyzed the network capacity by placing RSs at the border of the

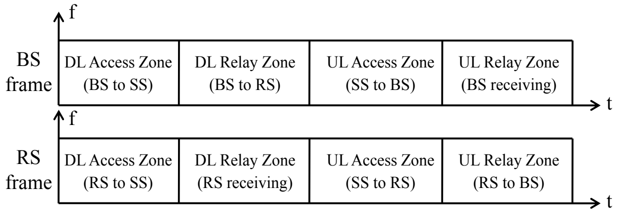


Fig. 1. Non-transparent mode frame structure [1].

BS's transmission range for the coverage extension scenario. However, the scheduling problem, i.e., assigning transmission opportunities to each link in the network in order to maximize a certain objective function was not considered. Several studies have considered the problem of scheduling for OFDMA based WiMAX networks [3], [4]. The authors in [3] show that the tiling (two-dimensional time×frequency) structure of an OFDMA frame results in a high combinatorial complexity of the scheduling problem, and therefore propose approximation algorithms to solve the problem. The work in [4] studies the proportional fair scheduling problem while taking into account the frequency selectivity and multiuser diversity. By using the proposed scheduling algorithm in [4], the authors showed that RSs can significantly increase coverage at the expense of mean throughput.

The mean throughput degradation is a major drawback of using RSs since RSs consume more resources compared to direct communications. However, frequency reuse and frequency planning schemes can be incorporated to enhance network throughput. The work in [5] shows that relays further reuse the already used channels in a controlled manner to prevent co-channel interference. As depicted in Figure 1, the 802.16j amendment allows BS and RSs to transmit to their associated SSs simultaneously during the access zone time frame. Thus, a frequency reuse scheme can be applied only for this access zone period.

In contrast to previous related work, we analyze coverage extension by placing RSs outside of the BS's transmission range, and consider network cost in comparison to a BS only scenario while taking into account mean throughput. We also incorporate a frequency reuse scheme into our detailed system model while considering the most relevant characteristics of IEEE 802.16j systems. Although we only address downlink analysis, all our schemes can be easily extended to the uplink scenario.

III. SYSTEM MODEL

A. Cellular Scenario

The considered network consists of several cells each served by a fixed central BS. Each cell has a three-tiered MMR network architecture comprised of a base station (BS), relay stations (RSs), and subscriber stations (SSs). The BS is responsible for providing the air interface to the SSs and is the only network entity that is connected to the backhaul network. The main responsibility of an RS is to relay data between the BS and the SSs. Although the standard allows for RS to RS connections, in this paper we assume that the SSs are at most two hops from the BS, i.e., the SSs can connect to the BS either directly or through one RS. All nodes in the network are assumed to be equipped with a single antenna and operate in half-duplex mode, i.e., any terminal cannot transmit and receive simultaneously. The parameters used for the analysis are listed in Table I.

TABLE I
SIMULATION PARAMETERS

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

B. SINR Analysis

WiMAX supports a variety of modulation and coding schemes (MCS) according to channel variation. When the channel is good, a 64 QAM modulation and a 5/6 convolutional coding scheme can be applied to achieve a high data rate. For IEEE 802.16, there are 7 different physical layer data rates specified by the standard [6], denoted as $C_1, C_2, ..., C_7$. Each data rate can be realized only if the SINR is above a certain threshold $\overline{\gamma} = \{0, \overline{\gamma}_1, \overline{\gamma}_2, ..., \overline{\gamma}_7, \infty\}$. That is, when the received SINR is in the range between $\overline{\gamma}_m$ and $\overline{\gamma}_{m+1}$, data rate C_m is achievable. The set of thresholds can be determined by bit error rate expression for M-QAM [7]. This approximation provides a closed-form expression for the link spectral efficiency of M-QAM as a function of the SINR and bit error rate:

TABLE II
SINR THRESHOLD SET

MCS	Downlink Data Rate C_m[Mbps]	Spectral Efficiency S_m[bps/Hz]	Threshold $\overline{\gamma}_m$[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

$$S_m = \log_2\left(1 + \frac{1.5\gamma}{-\ln 5P_b}\right), \tag{1}$$

where S_m is the spectral efficiency, γ is SINR, and P_b is bit error rate. Table II shows the values of the threshold set $\overline{\gamma}$ when P_b is 10^{-6}. For a given the transmission power P_t, the received signal power P_r is given by $P_r = \frac{G_t G_r P_t}{L}$, where G_t, G_r, and L represent the transmitting antenna gain, receiving antenna gain, and the path loss of the channel. The path loss model used in this analysis is the Erceg-Greenstein model [8], which is also recommended by the IEEE 802.16 working group. Using this model, the co-channel interference can also be calculated given the cluster size. Due to the assumption of TDD synchronized network system, only co-channel SSs interfere in UL, while neighboring BSs only generate interference in DL. In the following analysis, the received SINR is determined by:

$$SINR = \frac{P_r}{P_N + \beta P_I}, \tag{2}$$

where β is the number of co-channel cells of the first tier, P_N is the noise power, P_r is the received signal power and P_I is the interference signal power from a neighboring cell on the same frequency as the current cell.

C. Fading Channel

In addition to the propagation model, multipath fading may have a significant effect on reliable communications. With the assumption of a Rayleigh fading channel, the received SINR, γ , is an exponential random variable [9] with the following probability density function:

$$p(\gamma) = \frac{1}{\gamma^*}\exp\left(-\frac{\gamma}{\gamma^*}\right), \gamma \geq 0, \tag{3}$$

where γ^* is the average SINR. Therefore, the probability that a transmitter can achieve data rate C_m can be expressed as:

$$p(C_m) = \int_{\overline{\gamma}_m}^{\overline{\gamma}_{m+1}} \frac{1}{\gamma^*}\exp\left(-\frac{\gamma}{\gamma^*}\right) d\gamma. \tag{4}$$

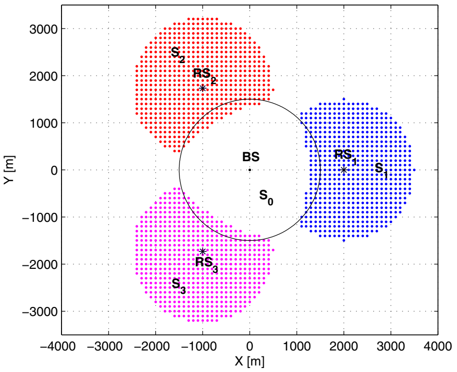


Fig. 2. A coverage extension scenario with three RSs placed outside the cell.

Consequently, the average achievable data rate, C_{ss} , can be computed by:

$$C_{ss} = \sum_{m=1}^{7} C_m \cdot p(C_m). \tag{5}$$

IV. THROUGHPUT ANALYSIS

In addition to parameters in Table I, we assume a reuse factor of 7, one sector per cell, and hilly terrains with heavy tree densities (terrain type A [8]). The cell radius, 1500m, is determined by the condition that the SINR value at an SS located at the cell edge is greater than the minimum threshold value in Table II, i.e., 9.1dB. As depicted in Figure 2, the BS is located at the center of the cell, three RSs are deployed to extend the cell coverage, and the SSs are distributed uniformly in the coverage area of the cell. The cell area is divided into four subsections denoted as S_0, S_1, S_2, and S_3. The SSs in subsection S_0 can receive data directly from the BS, while the SSs in subsection S_i should receive data from the BS via RS_i. If randomly chosen N SSs are receiving data from the BS within the same DL frame duration, i.e., there are N active SSs in a cell, the cell's maximum throughput can be computed by using the *conflict graph* model proposed in [10]. However, to maximize the cell throughput, when a subscriber link has a small capacity, it will not be scheduled. In other words, only the SSs connected with highest link capacities are scheduled to transmit resulting in the starvation of the SSs with small capacity links. To avoid this problem, we propose a simple scheduling scheme for serving the SSs in a fair manner. To achieve fairness, more time will be scheduled for SSs connected with lower link capacities.

We assume that the entire spectrum is allocated to each node whenever they are allowed to transmit, thus scheduling is done by assigning time slots to every node.

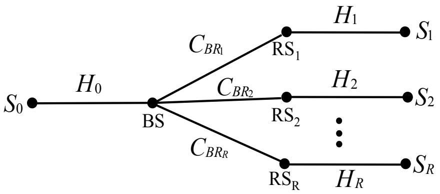


Fig. 3. A connectivity graph with R relay stations

In other words, the objective of our scheduling scheme is to determine time duration of access zone and time durations allocated to RSs in the relay zone such that every active SS will achieve the same throughput.

For the general case, when R RSs are deployed and N SSs are active in a cell, the cell area is divided into $R+1$ subsections denoted as S_0, S_1, ..., S_R, and the number of active SSs in each subsection can be denoted as n_0, n_1, ..., n_R respectively, i.e., $N = n_0 + n_1 + ... + n_R$. We denote with λ_0 and λ_1, ..., λ_R the time fraction of the access zone and time fractions allocated to RS_1, RS_2, ..., RS_R in the relay zone respectively. Thus, the following equation is satisfied:

$$\lambda_0 + \lambda_1 + \cdots + \lambda_R = 1. \tag{6}$$

Let us also denote with C^i_j and t^i_j the link capacity of the j^{th} active SS ($j = 1, ..., n_i$) with its parent node and the time duration allocated to the j^{th} active SS in subsection S_i ($i = 0, ..., R$) respectively. The SSs located in the same subsection have to share the access zone, i.e., $\lambda_0 = t^i_1 + t^i_2 + ... + t^i_{n_i}$. In each subsection S_i, the throughput of each node should be equal for fairness:

$$C^i_1 t^i_1 = C^i_2 t^i_2 = \ ... \ = C^i_{n_i} t^i_{n_i}, \quad i \in \{0, 1, ..., R\}. \tag{7}$$

Equation (7) assures fairness within subsection S_i. The throughput per node can be controlled by the time fractions λ_1, ..., λ_R allocated to the RSs in order to achieve absolute fairness. We define the average data rate (H_i) of subsection S_i as the sum of the throughput of active nodes' in S_i divided by the total time duration of access zone:

$$H_i = \frac{n_i C^i_1 t^i_1}{t^i_1 + t^i_2 + ... + t^i_{n_i}}, \quad i \in \{0, 1, ..., R\}. \tag{8}$$

Using (7), we can eliminate times t^i_j in (8):

$$H_i = \frac{n_i}{\frac{1}{C^i_1} + \frac{1}{C^i_2} + \cdots + \frac{1}{C^i_{n_i}}}, \quad i \in \{0, 1, ..., R\}. \tag{9}$$

Figure 3 shows a simplified connectivity graph with each subsection's average data rate H_i. Let C_{BR_1}, C_{BR_2}, ..., C_{BR_R} denote the link capacities between BS and RS_1, RS_2, ..., RS_R respectively. To ensure that every active SS can achieve the same amount of throughput regardless of their associated link capacities, more time is scheduled for the subsection that has a smallest throughput per node. In other words, it is necessary to reduce the other subsections' throughput per node by decreasing time fractions allocated to RSs. Therefore, only the subsection that has the minimum throughput per node can fully use resources during the access zone λ_0, while the rest of subsections excluding S_0 are constrained by the link capacities C_{BR_1}, C_{BR_2}, ..., C_{BR_R}. Thus, the following equation should be satisfied for absolute fairness:

$$\frac{\lambda_0 H_x}{n_x} = \frac{\lambda_1 C_{BR_1}}{n_1} = \frac{\lambda_2 C_{BR_2}}{n_2} = \ ... \ = \frac{\lambda_R C_{BR_R}}{n_R}, \tag{10}$$

where H_x and n_x are the average data rate and the number of active SSs of S_x that has minimum throughput per node, the second term represents the throughput for nodes in S_1, the third term represents the throughput for nodes in S_2, etc. Only S_0 is not constrained by the relay zone transmissions since every SS in S_0 are directly connected with the BS. Therefore, unless S_0 has minimum throughput per node, the active SSs in S_0 can achieve a higher throughput since they can fully use resources during λ_0 without any constraint. If we use (10) to substitute for λ_i in (6), λ_0 can be expressed as:

$$\lambda_0 = \frac{1}{\frac{n_1}{n_x}\frac{H_x}{C_{BR_1}} + \frac{n_2}{n_x}\frac{H_x}{C_{BR_2}} + \cdots + \frac{n_R}{n_x}\frac{H_x}{C_{BR_R}} + 1}. \tag{11}$$

After determining λ_0 from (11), the time fractions λ_1, ..., λ_R can be easily computed using (10). Consequently, the cell throughput can be computed by:

$$\begin{aligned} \textit{Cell Throughput} = & \lambda_0 H_0 + \lambda_1 C_{BR_1} + \lambda_2 C_{BR_2} + \\ & + \cdots + \lambda_R C_{BR_R}. \end{aligned} \tag{12}$$

The first term represents the sum of the throughput of active SSs in S_0, the second term represents the sum of the throughput of active SSs in S_1, etc.

V. NUMERICAL RESULTS AND ANALYSIS

In this section we analyze cell coverage extension by varying both the location and number of RSs from a cost efficiency perspective. Moreover, we investigate the cell throughput with respect to the number of active SSs in a cell under our proposed scheduling scheme. In the considered network, both the BSs and RSs are assumed to use omni-directional antennas and each cell has between one and six RSs arranged in a circular pattern at the same distance from the BS. The communication link between BS and RSs is assumed to be line-of-sight (LOS). To

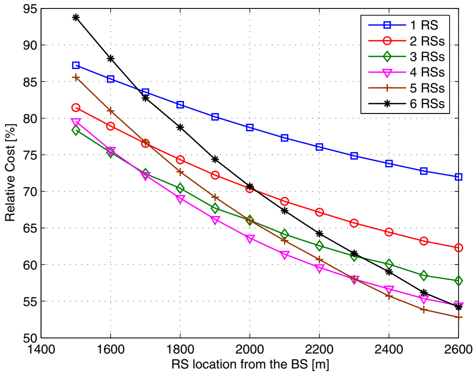


Fig. 4. Relative cost (as percentage of without-RS case) as a function of the RS location for different number of RSs per each cell.

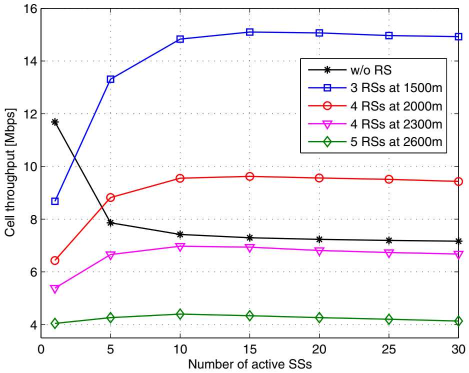


Fig. 5. Cell throughput as a function of the number of active SSs within a cell for different locations of RS.

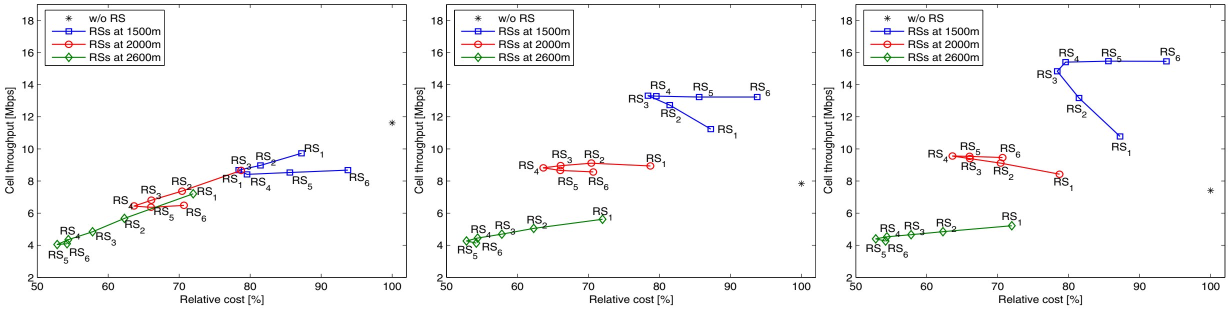
analyze the cost efficiency of using RSs, the cost of an RS is assumed to be 40% of the cost of a BS [11]. The total network service area is assumed to be covered by 100 cells when not using RSs, i.e., 100 BSs are needed to cover the total service area. However, if we extend each cell coverage area with RSs, the total number of cells that are needed to cover the service area will be reduced, thus leading to a reduced number of BS needed to cover the same area. For example, assume that when using two RSs, the area of a cell becomes $2\mathrm{km}^2$ and the total service area is $100\mathrm{km}^2$. The required total number of BSs and RSs are 50 and 100 respectively. The cost of this network is equivalent to the network that has 90 BSs without any RSs ($50 + 100 \times 0.4$). We consider this cost of the BSs and RSs in each scenario as the network cost. To observe the network cost comparison between cases with and without RSs, we define the relative cost parameter:

$$\textit{Relative Cost}[\%] = \frac{\text{Cost of network with RS}}{\text{Cost of network without RS}} \times 100. \tag{13}$$

Figure 4 shows relative costs when RSs are used to extend the cell coverage. Due to the fact that the RSs have high gain antennas and high transmission power (in comparison to those of the SS), the location of RS could be outside of the BS coverage. The maximum distance between BS and RS, 2600m, is determined by the condition that the SINR value of RS should be greater than the minimum threshold value 9.1dB. It is clear that the relative costs are decreasing as the locations of RSs from the BS increase since the extension of cell coverage leads to fewer required BSs and, hence, cost efficiency. However, increasing number of RSs is not always desirable from cost efficiency point of view. When RSs are placed at 1500m, the minimum relative cost is 78% when using the three RSs case, i.e., deploying more than three RSs at 1500m is not desirable as they are more costly. From 1700m to 2300m deploying four RSs is the optimal case, and five RSs is better for distance from 2400m to 2600m.

To evaluate the effect of RSs on the throughput of the SSs we will use our proposed simple scheduling scheme such that every active SS can achieve the same throughput regardless of its associated link capacity. From (5), given the distance between transmitter and receiver, the average achievable data rate can be computed. We consider this value as a link capacity. Therefore, whenever N active SSs are randomly placed within the cell, the cell throughput can be easily calculated by using (6)-(12). Figure 5 shows cell throughput as a function of the number of active SSs within a cell. To obtain average cell throughput value, we repeat simulation over 10,000 times in each scenario since N active SSs are randomly placed within a cell. We computed the 95% confidence intervals but do not show them as they are very small (smaller than the symbols used in the figure) and would clutter the graphs.

In the case without-RSs, the cell throughput decreases as the number of active SSs increases because as the number of SSs increase it is more likely to have SSs with small link capacities consuming a large fraction of the time in order to preserve fairness. On the other hand, the cases with-RSs show that cell throughput tends to increase with the number of active SSs. This increase demonstrates that the frequency reuse scheme has a positive impact on the cell throughput, i.e., a number of active SSs that are in each different subsection can receive data simultaneously. Moreover, the cases with-RSs illustrate that the cell throughput decreases as the placement of the RS is further away from the BS. When five RSs are placed at 2600m from the BS, the cell throughput is around 4Mbps, while when three RSs



(a) 1 active node (b) 5 active node (c) 10 active node

Fig. 6. Cell throughput as a function of relative cost for 1, 5, and 10 active SSs

are placed at 1500m, the cell throughput ranges from 8.6 to 15.3Mbps depending on the number of active SSs. Especially, when the locations of RSs are less than 2300m, the achievable cell throughput is always higher than without-RS case for more than one SS.

The effects of using RSs on both cost and throughput can be examined simultaneously. Figure 6 depicts the cell throughput as a function of relative cost for three different numbers of active nodes (1, 5, and 10). In each graph, three different RS locations and six different number of RSs are plotted. When there is only one active SS in a cell, the cell throughput when using RSs is always smaller than when not using RSs. The further the location of RSs from the BS the smaller the cost and cell throughput. In other words, the relative cost decreases as the cell coverage area increases at the expense of cell throughput. However, when there are five active SSs in a cell, cell throughput when using RSs can be much higher than when not using RSs due to frequency reuse. As shown in Figure 6(b), the cell throughput increases even as the relative cost decreases especially when number of RS is changing from one to three at the location of 1500m. This trend is also present in Figure 6(c). It is also noted that deploying more than three RSs at 1500m and four RSs at 2000m are not desirable from both throughput and cost points of view. Therefore, cost effective coverage extension without throughput degradation is always feasible by carefully choosing both location and number of RSs.

VI. Conclusion

In this paper we evaluate the performance of WiMAX networks enhanced with relays for the purpose of cost effective coverage extension. We present an accurate model for the link capacity of 802.16 MMR systems and propose a simple scheduling scheme for serving the SSs in a fair manner. Through simulation and numerical analysis, we make several fundamental observations about cost effective coverage in such networks. First, with good RS's antenna gain and power, the RSs can be deployed further away from the edge of the cell to maximize cell coverage (e.g., when five RSs are deployed at 2600m, the relative cost is only 53%). Second, we observe that the mean throughput of the cell can be affected by the number of active SSs as well as relative cost. The lower the relative cost the lower the cell throughput, however as the number of active SSs increases, a higher cell throughput can be achieved in some cases due to frequency reuse. Finally, we suggest some design guidelines so that network operators can achieve cost-effective coverage extensions without significant throughput degradation.

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