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Study of Radio Resource Sharing for Future Mobile WiMAX Applications with Relays

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Abstract— **WiMAX (802.16e) is technically capable of offering city-wide broadband connections to a high number of mobile terminals. The technology has strong industrial support, however a number of challenges remain to be resolved. Major concerns include battery life for mobile terminals, balancing support for high velocity and high data-rate, and increasing area coverage. Relay technology is a promising approach to address these challenges. Due to limited radio resources, it is necessary to consider radio resource efficiency. This paper presents a de-tailed analysis of relay efficiency with and without resource sharing. To enhance spectral efficiency, a directional distributed relaying architecture is proposed for interference elimination and avoidance.**

Keywords- mobile WiMAX, smart antenna, multi-hop, relay directional distributed, MIMO, interference avoidance

I. INTRODUCTION

In general, WiMAX (Worldwide Interoperability for Microwave Access) is a metropolitan access technique, which not only provides wireless access, but also expands the cover-age of wired networks. This facilitates network access for re-mote or suburban areas. In 2004, the IEEE 802.16d standard [1] was published for Fixed Wireless Access (FWA) applications. In December 2005 the IEEE ratified the 802.16e [2] amendment, which aimed to support Mobile Wireless Access (MWA) with seamless network coverage. Consequently, as 802.16e is commercialized, WiMAX will become a promising scheme to evolve FWA to MWA. At present there is particular interest in mobile WiMAX, since this offers data transfer rates that exceed those of current 3G. The mobile WiMAX air inter-face adopts Scalable Orthogonal Frequency Division Multiple Access (SOFDMA) for improved multi-path performance in non-line-of-sight (N-LoS) environments.

WiMAX is well-known for long distance transmissions and high data capacities. However, power and spectral efficiency is key to successful deployment. It is well-known that radio relay deployment achieves both coverage enhancement and capacity improvement [3] [4]. Relaying is a promising approach that tackles many of the challenges faced by mobile WiMAX and is currently under development as IEEE 802.16j project [5]. It is being seriously considered for early deployment to promote success in the broadband wireless market. However, radio resource efficiency is a major challenge for relay systems. Radio resource sharing (taking interference issues into account) is a requirement of 16j. To meet these goals, smart antennas must play a key role in the system design. Mobile WiMAX can exploit this smart antenna based friendly OFDMA relaying technology. Also, by combining flexible channelization with Adaptive Modulation and Coding (AMC), it enables mobile WiMAX technology to improve both system coverage and capacity with high power and spectrum efficiency.

This paper gives a thorough analysis of relay efficiency together with a proposal of a directional distributed relaying architecture for highly efficient radio resource sharing. This architecture is based on both interference cancellation and interference avoidance for high data throughput with reduced demands on radio resource.

The paper is organized as follows: Section II provides a definition and analysis for effective system capacity gain. Section III presents a theoretical analysis of interference aspects and then proposes a directional distributed relaying architecture. Section IV presents case studies based on the use of a site-specific ray-tracing model over a realistic urban environment. Finally, the paper is concluded in section V.

II. EFFECTIVE EFFICIENCY OF MULTIHOP RELAY

A relay-based WiMAX system is considered to guarantee the Quality of Service (QoS) of cellular transmission, especially at cell-edge. Generally, relays can be applied in either a single relaying or a multi-hop architecture. Ideally, *n*-hop relay requires *n* radio resources to avoid interference between each hop. However, this might reduce the system spectral efficiency. Without loss of generality, the normalized effective system spectral efficiencies can be defined as

$$TDD : \textit{Effective system efficiency} = \frac{\text{System data throughput}}{\text{Total site time period allocated}}$$

$$FDD : \textit{Effective system efficiency} = \frac{\text{System data throughput}}{\text{Total site frequency allocated}}$$

There are two approaches to ensure the effective efficiency. One is to increase the system data throughput, such as employing high level AMC. Another is to reduce the radio re-source applied to the system. With a limitation of employing higher level AMC schemes (e.g., ¾ rate 64QAM in WiMAX standard), radio resource efficiency becomes a key challenge and radio resource sharing has to be considered for a relay deployment.

In order to measure the efficiency of relay deployment, we introduce an effective system capacity (C_{eff}), which is intended to leverage link level capacity gain and system capacity gain. Assume there are total s mobile stations (MSs) be allocated and there are p users within the s users that are transmitted through multi-hop relay, the C_{eff} can be expressed as

$$C_{eff} = \sum_{i=1}^{s-p} C_i^{BS} + \frac{\sum_{j=1}^{p} C_j^{RS}}{N_{rc}}, \quad (1)$$

where, N_{rc}, C^{BS} and C^{RS} denotes number of radio resource employed by relaying, the capacity without relaying (base station (BS) access capacity), and the capacity with relaying (relayed capacity) respectively. For simplicity, we assume that the links of BS-RS (relay station) and/or RS-RS are ideal for transmission without introducing any impacts on the performance of the last stage of RS-MS (no 'bottle neck' problem). Therefore, effective relay efficiency can be derived as

$$\xi_c = \frac{\sum_{i=1}^{s-p} C_i^{BS} + \left(\sum_{j=1}^{p} C_j^{RS} \right) \Big/ N_{rc}}{\sum_{k=1}^{s} C_k^{BS}}. \quad (2)$$

It can be seen in (2), there are several different kinds of trade-off for the relay efficiency. From a system-level point of view, the effective relay efficiency should be $\xi_c \geq 1$. In case of $\xi_c < 1$, radio resource sharing needs to be considered. However, the resource sharing could introduce interference. If no prior channel knowledge at the transmitter is available, then the theoretic channel capacity for a Multiple-Input Multiple-Output (MIMO) system with M transmit and N receiver antennas is given by [6]

$$C = \log_2 \det\left[\mathbf{I}_n + \frac{1}{M} \cdot \frac{P_s}{P_I + P_n} \cdot \mathbf{H}\mathbf{H}^* \right] \quad (bps/Hz), \quad (3)$$

where, P_s, P_I and P_n are the powers of received signal, interference and noise, respectively; $\mathbf{I}_n$ is $M \times N$ identity matrix and $\mathbf{H}$ is the normalized channel matrix which is considered to be frequency independent over the signal bandwidth, and '*' denotes transpose conjugate. With (3), (2) can be re-written as in (4) for downlink case.

$$\xi_c = \frac{\sum_{i=1}^{s-p} \log_2 \det\left[\mathbf{I}_{n,i} + \frac{1}{M_i} \cdot \frac{P_{S,i}^{BS}}{P_{I_c,i} + \sum_{ii=1}^{l_i^{RS}} P_{I_c,i,ii}^{RS} + P_{n,i}} \cdot \mathbf{H}_i \mathbf{H}_i^* \right] + \left(\sum_{j=1}^{p} \log_2 \det\left[\mathbf{I}_{n,j} + \frac{1}{M_j} \cdot \frac{P_{S,j}^{RS}}{P_{I_c,j} + P_{I_c,j}^{BS} + \sum_{jj=1}^{q_j^{RS}} P_{I_c,j,jj}^{RS} + P_{n,j}} \cdot \mathbf{H}_j \mathbf{H}_j^* \right] \right) \Big/ N_{rc}}{\sum_{k=1}^{s} \log_2 \det\left[\mathbf{I}_{n,k} + \frac{1}{M_k} \cdot \frac{P_{s,k}^{BS}}{P_{I_c,k} + P_{n,k}} \cdot \mathbf{H}_k \mathbf{H}_k^* \right]} \quad (4)$$

In (4), P_S^{BS} and P_S^{RS} represents the signal power from BS and RS; $P_{I_c}^{BS}$, $P_{I_c}^{RS}$ and P_{I_c} denotes Co-Channel Interference (CCI) power from BS, RS and any other resources (e.g., from other cells); l_i^{RS} denotes the number of RSs which use the same radio resource as that of the i^{th} user (BS-MS); q_j^{RS} represents the number of RSs which use the same radio resource as that of the j^{th} user (RS-MS). From (4) we can draw attentions to the impacts of interference and radio resource usage. Increasing either interference ($P_{I_c}^{BS}$, $P_{I_c}^{RS}$ and P_{I_c}) or N_{rc} could reduce the relay gain. On the other hand, reducing N_{rc} could increase the P_{I_c}, $P_{I_c}^{BS}$ and $P_{I_c}^{RS}$. Furthermore, for MIMO transmission the channel correlation is an important fact to be considered, which will be discussed in the next section.

III. Relay Efficiency without Radio Resource Sharing

Without radio resource sharing, the system deployment is applying each radio resource on each link, including BS-RS, BS-MS, RS-RS and RS-MS. For clearer demonstration, we start with a simple relay deployment for a Single-Input-Single-Output (SISO) system and with a single user. We define a relay SNR-gain as $G_{SNR} = SNR_{relay} - SNR_{access}$, where the SNR_{relay} and SNR_{access} is the signal to noise ratio of the last hop between RS and MS (shorten as relay-SNR) and the BS-access link (directly between BS and MS, shorten as access-SNR) respectively. Fig. 1 shows that the relay efficiency is not linearly increased with the G_{SNR}, and for a certain required efficiency the G_{SNR} varies according to the SNR_{access}. Fig. 1 also indicates that the requirement of the relay SNR-gain is much low if the SNR_{access} is low, e.g., while SNR_{access} is -10 dB, the relay SNR-gain only needs about 3.1 dB for 100% of relay efficiency. However, more than 10 dB relay SNR-gain is required for the SNR_{access} of 10 dB in order to maintain reasonable relay efficiency.

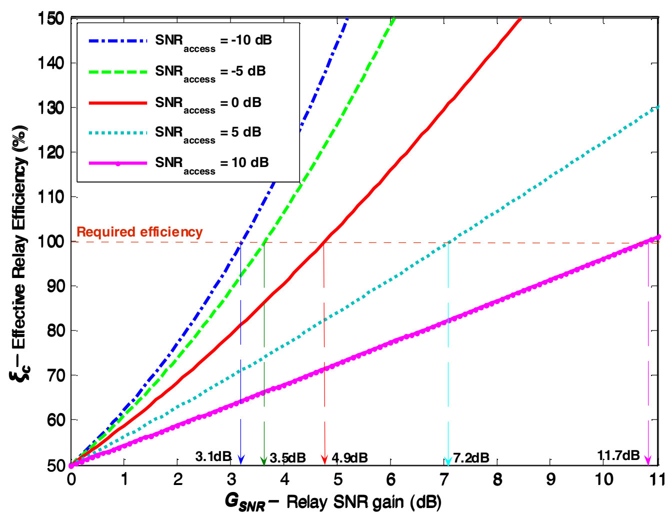


Figure 1. Analysis of relay SNR-gain required for high relay efficiency (2-hop with two radio resource, no resource sharing)

For multihop (hop number great than 2), the required relay SNR-gain becomes even higher. Some examples are shown in Table 1. The required relay SNR-gain is almost linearly increased with the increase of hop numbers.

TABLE 1 COMPARISON OF MULTIHOP REQUIRED RELAY SNR-GAIN AT EFFICIENCY OF 100%

	SNR_{access} = 0 dB	SNR_{access} = 5 dB
2-hop	4.86 dB	7.17 dB
3-hop	8.45 dB	13.53 dB
4-hop	11.76 dB	19.76 dB

Similarly to this and by using (4), a comparison of required relay SNR-gain for different MIMO configurations is depicted in Fig.2. It is interesting to see that MIMO is more efficient for relay deployment. Compared to a SISO system, MIMO requires less relay SNR-gain to achieve higher relay efficiency. More antennas can produce even higher relay efficiency. This implies that MIMO with relay could form an effective solution for both system efficiency and capacity. Note that the MIMO channels for this study are uncorrelated.

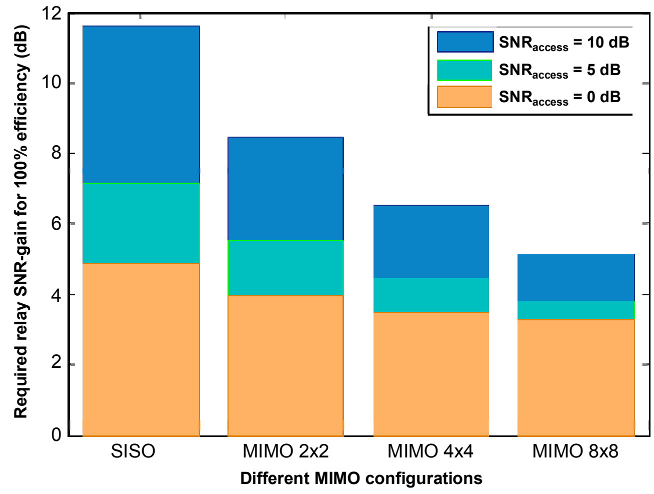


Figure 2. Comparison of required relay SNR-gain for different MIMO configurations (2-hop with two radio resource, no resource sharing)

However, MIMO channel correlation is a detrimental effect on the performance of a MIMO system [7]. In order to study the impacts of MIMO channel correlation, a correlation variable is introduced into (3). When the channel is random (stochastic), the capacity is random, too. The mean (ergodic) capacity can be defined as [8]

$$\langle C \rangle = \left\langle \log_2 \det\left[\delta_{ij} + \frac{\rho}{M} \cdot r_{ij} \right] \right\rangle \quad (bps/Hz), \qquad (5)$$

where δ_{ij} and ρ is Kroneker's delta and the signal to noise ratio, $\langle \bullet \rangle$ is the expectation over the channel matrix, r_{ij} is the 'instantaneous' correlation matrix for the i-th receive antenna and j-th transmit antenna, as

$$r_{ij} = \sum_k h_{ik} h_{jk}^* . \qquad (6)$$

where h_{ij} denotes the element of $\mathbf{H}$. As (5) takes correlation into account at both transmit and receive ends, (3) can be re-written as

$$C = \log_2 \det\left[\mathbf{I}_n + \frac{1}{M} \cdot \frac{P_s}{P_I + P_n} \cdot \mathbf{R} \right] \quad (bps/Hz), \quad (7)$$

where $\mathbf{R}$ is the normalized channel correlation matrix whose components are given by (6).

We set up three extreme scenarios: 1) the BS-MS link is correlated but the RS-MS link is uncorrelated; 2) both the BS-MS and RS-MS links are correlated with the same correlation values, and 3) the RS-MS link is correlated but the BS-MS link is uncorrelated.

The effective relay efficiency *vs.* channel correlation value can be plotted by using (7) and (4), as shown in Fig. 3. For this specific example of 2x2 MIMO, we deliberately set both the SNR_{access} and the relay SNR-gain to 6 dB, since these produce 100% effective relay efficiency while both BS-MS-link and RS-MS-link are uncorrelated. For the first scenario, the relay improves the link channel properties and consequently improves the relay efficiency. In contrast, for the third scenario the correlated RS-MS link degrades the relay efficiency severely. However, it is interesting to see the second scenario, which shows that the high channel correlation (correlation value > 0.6) could destroy the relay gain and dramatically decrease the relay efficiency.

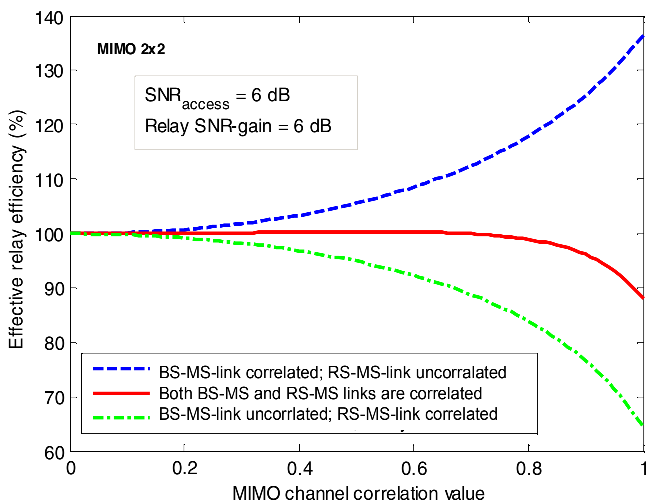


Figure 3. Channel correlation impacts on relayed MIMO system

Fundamentally there are two basic requirements for the MIMO relay application, which are the relay SNR-gain and the MIMO channel condition. MIMO channel spatial correlation has harmful impact, especially on high order MIMO transceivers. Therefore, SNR and MIMO correlation are both required to be taken into account for the MIMO relaying applications.

IV. Relay Efficiency with Radio Resource Sharing and Directional relay architecutre

Without resource sharing, relay requires high relay SNR-gain and plenty of radio resources. Due to the scarcity of radio resource, higher efficient relay deployments should support radio resource sharing. It is essential to develop criteria for sharing and techniques to balance relay efficiency and system performance.

With resource sharing, the critical issue is the interference introduced into the system. Fig. 4 illustrates the impact of the interference on the relay efficiency based on a SISO system with 2-hop. It is clearly shown that a high SIR is required if the access-SNR is high.

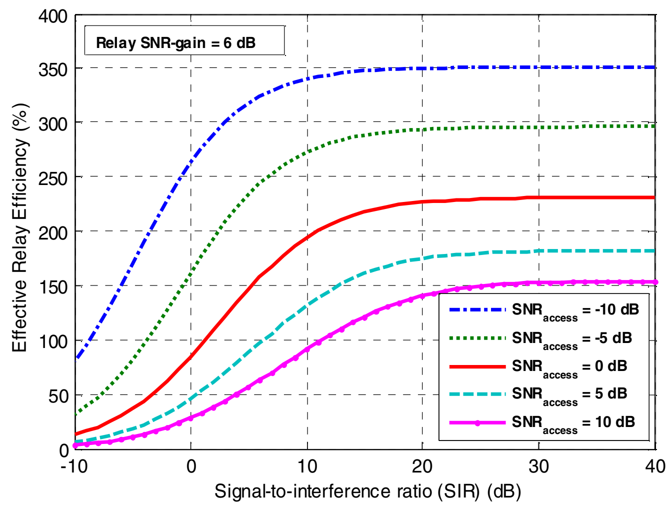


Figure 4. Analysis of relay SIR required for high relay efficiency

Fig.5 presents the impacts of interference on MIMO system. We have set two thresholds: one is 100% efficiency (which is required for the minimum SIR value). Another one is the 200% efficiency which means that the relay deployment doubles the capacity of the direct BS-MS link without relay. More interesting phenomena are that, the MIMO is more tolerant to interference compared to the SISO system. For example, the SISO system requires SIR 4 dB more than the 8x8 MIMO.

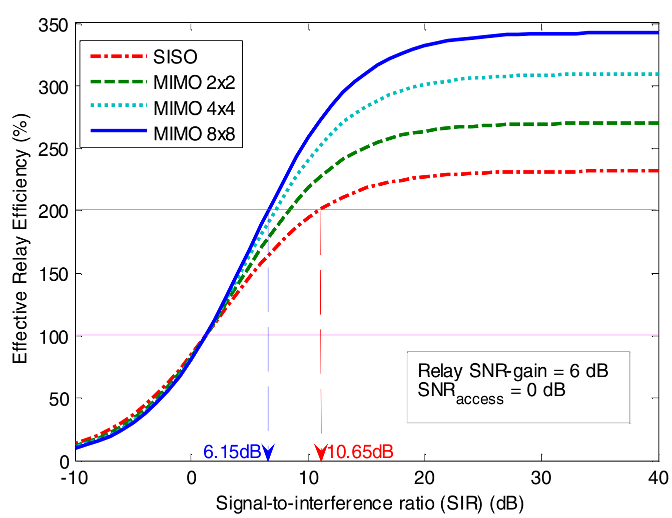


Figure 5. Impact of interference on relayed MIMO system

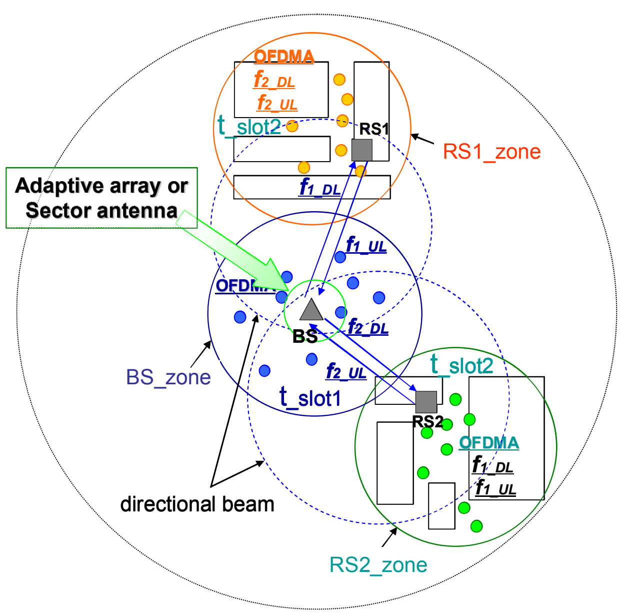
So far, we have studied the relay deployment both with and without resource sharing. For clearer comparison between these two different deployments, here we pick up a very typical example as shown in Table 2 (referred to Fig. 5 and Fig. 1). In this instance, SNR_{access} of 0 dB means that it is difficult for the MSs to directly communicate with their BS. The relay SNR-gain is set to 6 dB. For this setup, the possible maximum system capacity (achieved by the relay with sharing) is 4.8 times the capacity of the direct access link between BS to MSs, which doubles the capacity of the relay without sharing. Therefore, it has highly potential benefits for relay deployments considering radio resource sharing.

TABLE 2 COMPARISON OF SISO RELAY WITH AND WITHOUT SHARING

Relay SNR-gain = 6 dB; SNR_{access} = 0 dB; SISO					
	Achieved efficiency	Requirements	Link relayed capacity	System capacity	**Possible max sys capacity**
Without sharing	120%	N/A	$2.4C_{access}$	$2.4C_{access}$	$\mathbf{2.4C_{access}}$*
Full sharing*	120%	SIR = 2 dB	$1.2C_{access}$	$2.4C_{access}$	$\mathbf{4.8C_{access}}$

*'Full sharing' means resource sharing rate equals one.
C_{access} represents the capacity of access link from BS to MS without relay

As discussed previously, the main concern on the sharing scheme is the interference. In order to support high efficient WiMAX, a relaying system should have a suitable topology to fully take advantage of spatial separation and effective resource assignment [2]. For this purpose, a directional distributed relaying architecture with a paired radio-resource transmission scheme is proposed and depicted in Fig. 6.



f – radio resource; DL – down Link; UL – Up Link; zone – coverage area
f_{1_DL} – downlink radio resource of pair-1, so on

Figure 6. Directional distributed relaying with paired radio-resource

In the above figure, the radio resource (*f*) can be either frequency, time slot or fractional frequency (e.g., subchannels in OFDMA). The transmission in the BS_zone is the same as that of 802.16e. For relaying transmission, a paired transmission is applied, where BS forms two directional beams or uses two sector antennas to make transmission with RS1 and RS2 simultaneously. We also use two paired radio resources: f_{1_DL} - f_{1_UL} and f_{2_DL} – f_{2_UL}. The first pair of f_{1_DL} - f_{1_UL} is applied to BS-RS1 and RS2_zone; the second pair of f_{2_DL} – f_{2_UL} is applied to BS-RS2 and RS1_zone. It is clear that the radio resources are shared between RSs and MSs, where each end-user employs only one pair of radio resource, on average, for UL and DL.

By this sharing scheme, the interference can be easily controlled at the BS and the RS. There are only two sets of interference in this relay configuration, as illustrated in Fig. 7. The interference between BS and MS-groups can be detected and controlled by the BS. Firstly the BS could employ an adaptive array for spatial separations. Secondly, since the power from each MS of each MS-groups is known to the BS, interference avoidance can be applied between the two groups by the BS. Furthermore, this kind of interference should be small. This is due to the BS allocating the MSs through a relay, which means that the relay SNR-gain should be much higher than the SNR_{access} level. Another source of interference between RSs can be canceled by array processing (including sector antenna) at the RSs.

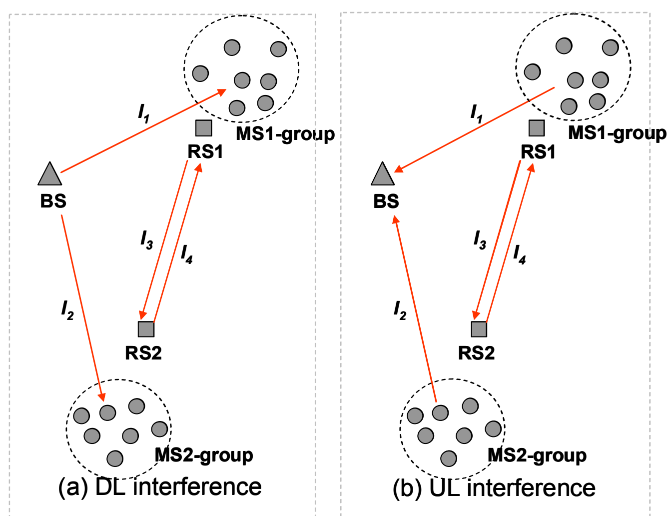


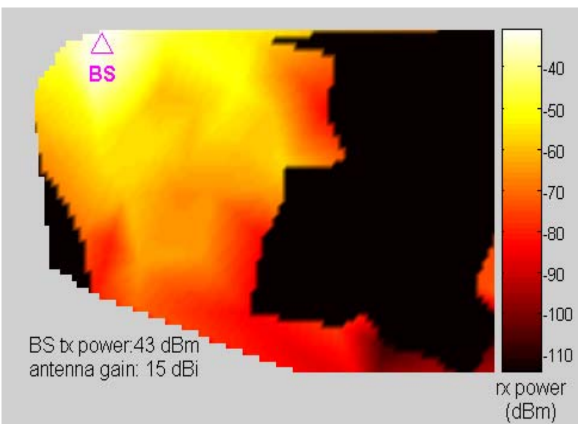
Figure 7. Interference illustration for the directional distributed relaying

The proposed topology is fully compatible with the existing 802.16e since there is no modification required at MSs. Varied deployments under the same concept are also feasible but they might produce different interference mode. In fact, the interference mode and its impacts on system performance are highly dependent on the application environment, which is not easy for a statistic study.

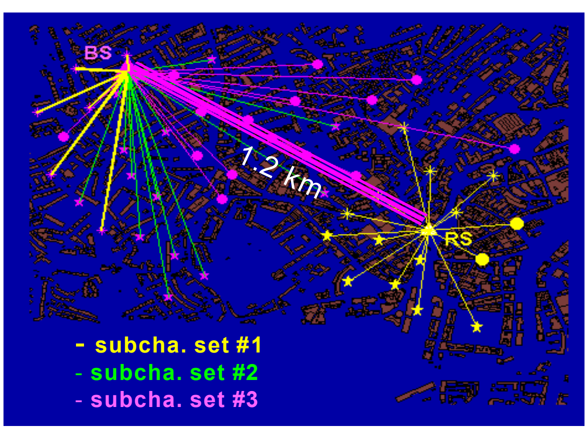
However, from our experience, for certain acceptable SIR level (e.g., 10 dB), it can be easily achieved by spatial separation in the relaying system. For achieving higher SIR (e.g., 10 dB to 25 dB), simple array processing (including sector antenna) might be required. In addition, interference avoidance can be adopted for further improvement of system performance. For a scenario with SIR greater than 25 dB, there will be much less impact on transmission. Use of ray-tracing enables to perform and prove this study, which will be described in the next section for a realistic environment and applications.

V. CASE STUDY OF RADIO RESOURCE SHARING

Our WiMAX relay system is based on the 512-FFT OFDMA air-interface and is operated with a 5 MHz bandwidth [4]. The scenario covers a region of central Bristol. Both BS and RS are deployed on tall local buildings, and MSs are distributed at ground street level with heights of 1.5 m over this geographic area, as shown in Fig. 8. The Effective Isotropic Radiated Power (EIRP) at BS and RS were 58 dBm and 38 dBm respectively (based on a 15 dBi antenna gain). Omni antenna is applied to the MS and a three 120^0 sector antenna is used at both the BS and the RS.



(a) BS coverage



(b) BS and RS radio resource location

Figure 8. WiMAX system coverage with relay over central of Bristol

Firstly, the raw Multi-Path Component (MPC) data is created using the ray tracing tool, which takes individual buildings, trees, corner and roof-top edges, terrain blocking and scattering into account. Then we use the ETSI specific antenna beam patterns (with side lopes) [9], which are spatially convolved onto the isotropic ray traced channel data.

Fig. 8(a) presents the distribution of received power. A coverage hole can be seen within this specific geographic area. Therefore, a RS is applied to extend the WiMAX coverage. With radio resource sharing, RS-MS and some BS-MS can be transmitted by same frequency resources simultaneously. For simplicity, we assume there are total three subchannel sets (as shown in Fig. 8(b)) and each subchannel set has 5 subchannels. Each subchannel set maps to 140 certain subcarriers and there are total 420 used subcarriers. When applying a RS, a certain subcarrier set has to be located to BS-RS link and transmitted by one sector. In this case, we define that three subchannels are used for the BS-RS link and two subchannels are for the BS-MS (which face to the RS) in the subcha. set #3. For all RS-MS and those BS-MS, where the antenna beam is steered away from the direction to the RS, they can share the subcha. set #1. The subcha. set #2 is used for those MSs which link to one BS sector (not face to the RS) and are located near to the RS, as shown in Fig. 8(b).

Fig. 9 presents the SINR contribution within the BS coverage hole under the assumptions above. As expected, RS improves the coverage, although users suffer CCI from the BS because of radio resource sharing. It shows that, without relay, there are about 60% of users have SINR value less than 15 dB. In contrast, only 10% occurs when relay is applied.

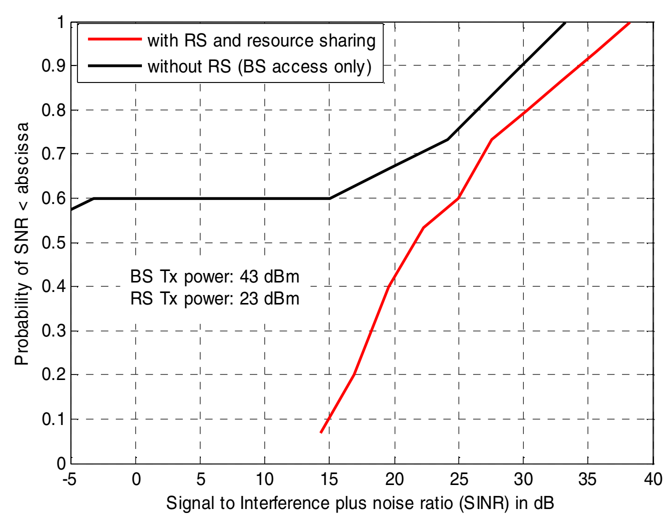


Figure 9. SINR in directional relaying system with radio resource sharing

Within the OFDMA PHY model, a Cyclic Prefix (CP) is applied in the system which equals to 1/8 of an OFDMA symbol. It ensures that up to 11.2 µs of delay spread can be tolerated. The OFDMA symbol time is 100.8 µs. Also, optimal AMC (between 1/2 QPSK, 3/4 QPSK, 1/2 16QAM, 3/4 16QAM, 2/3 64QAM and ¾ 64QAM) is applied. Fig. 10 compares system spectral efficiency (in Mbps/Hz) between three different system deployments, named as 'without RS', 'with RS but no sharing' and 'with RS and sharing'. Results indicate that, without relay only 1.14 Mbps/Hz throughput can be reached in this area (see Fig. 8). By using the directional relaying which reduce the interference by spatial separation, it enables the system to share the radio resource and hence increase the spectral efficiency. As shown in Fig. 10, about 58% capacity gain could be achievable without additional radio resource compared to the case of relaying without sharing, which has a spectral efficiency of 2.29 Mbps/Hz.

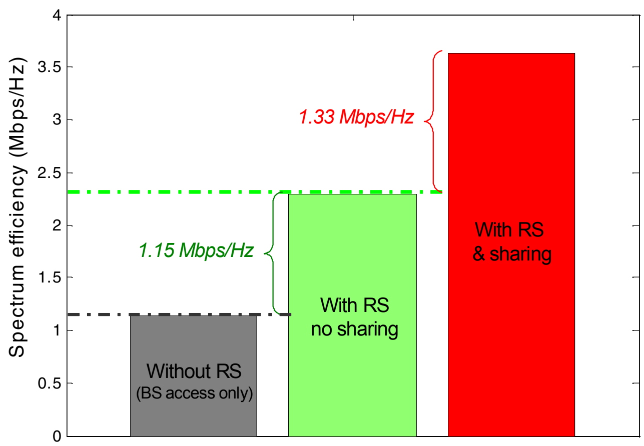


Figure 10. Spectrum efficiency comparisions of a SISO system

VI. Conclusions

This paper presents a study and analysis of effective relay efficiency, focusing on coverage and system capacity for mobile WiMAX. Even though it is well-known that relay deployment can achieve both coverage extension and performance enhancement, it is critical to investigate the trade-off between system efficiency and performance improvement.

For relay system without radio resource sharing, a higher relay SNR-gain is required, for instance, more than 10 dB relay SNR-gain is required for the access-SNR of 10 dB within a 2-hop relay system in order to maintain reasonable relay efficiency. This implies that the system might require higher transmit power on the RS. In contrast, radio resource sharing offers a highly potential benefit for the mobile WiMAX when relays are deployed. Firstly, the potential system efficiency can be doubled compared to the relay systems without resource sharing. Secondly, topology control is performed mainly at the BS and RS. Thirdly, it extends the applicability of adaptive antenna system (AAS) application for interference control, elimination and avoidance. In addition, results also indicate that the radio resource sharing scheme is more acceptable to a MIMO relaying, since the MIMO system is more tolerant to interference compared to the SISO system.

Furthermore, the study has shown that it is feasible to take advantage of both spatial separation and array processing. A directional distributed relay topology is proposed and results were presented for a realistic urban environment. Results show that, 58% capacity gain could be achievable without additional radio resource compare to the case of relaying without sharing. This proposal is fully backward compatible with the existing mobile WiMAX standard and in addition it achieves high system efficiency, performance improvements and coverage enhancement.

Acknowledgment

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