

Backhaul Network Based on WiMAX with Relays - System Level Performance Analysis

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Abstract—In this paper we present the system level performance analysis of the backhaul network based on WiMAX [1] with relays. The considered wireless communication system has hexagonal cellular structure, each cell containing a central base station (BS), one or more associated relay stations (RS), all serving the plurality of subscriber stations (SS). The base stations and the relay stations may share the same time-frequency resources when serving subscribers in accordance with various relaying modes having different reuse factor and leading to different level of interference in the deployment. The performance analysis of different relaying modes is presented in this paper. The methodology of individual mode assignment for each subscriber and frame composition is presented along with the analysis of geographical distributions of subscribers' preferable relaying modes. Finally, the total cell throughput is evaluated for the case of optimal subscribers' assignment to different relaying modes. We show that suggested adaptive relaying technique gives significant increase in the total cell throughput and spectral efficiency.

Keywords— *Wireless networking, relay, relaying mode, frame structure, interference environment, MEMBRANE, WiMAX*

I. INTRODUCTION (HEADING 1)

Wireless relaying is one of the most promising techniques that mobile communication systems may use to improve coverage and link quality of the cell-edge users. In combination with other modern techniques, such as multi-antenna space-time signal processing [2] and adaptive scheduling algorithms [3], relays may also give significant improvement in spectral efficiency and total cell throughput. Multiple relays per one base station create the possibility to use them in a number of different ways, leading to different system performance characteristics. The MEMBRANE (Multi-Element Multihop Backhaul Reconfigurable Antenna Network) project investigates the above mentioned techniques and aims to design an efficient multi-antenna multihop wireless backhaul network capable providing high throughput and coverage with acceptable delay performance. In this paper we investigate a cellular wireless communication system for the cases of one and two relays in each cell sector, with one- or two-hop transmissions. This relatively simple deployment however offers many opportunities for system adaptation and performance optimization. For example, some SS may take advantage of overhead-free direct communication with the BS, whereas others may benefit from backhauling data through the RS due to better link quality. In the section 2 we define the set of basic relaying modes, and in section 3 we introduce the

methodology of performance comparison of different relaying modes. Based on this methodology we also develop the algorithm for individual selection of relaying modes for subscribers and for frame composition. The frame structure suitable for adaptation of relaying modes is also proposed. Sections 4 and 5 respectively present the simulated deployment scenarios and the simulation methodology. The results of system-level performance analysis presented in section 6 show the great potential for system throughput improvement that may be achieved with the help of suggested relaying techniques.

II. BASIC RELAYING MODES

The relay stations may be used in several ways, each way having its specific properties. For example, one may want to split transmission of the BS and the RS in time to reduce the interference in the deployment. On the other hand simultaneous operation of BS and RS enables reuse of spectral resources thus improving the system throughput, but increase of interference in the deployment may limit this improvement.

To simplify the investigation of all possible combinations of BS and RS usage we define a set of 'basic relaying modes'. A basic relaying mode tells which station (BS or RS) serves the subscriber and whether other stations (BS or RS) are used at the same time to serve some other subscribers. Each basic relaying mode is assumed to be arranged in a separate time interval, and in this interval all BS and RS of the deployment follow the rules of the relaying mode. This approach simplifies modeling the interference environment and therefore evaluating the spectral efficiency of subscriber's operation. From the frame structure point of view, this approach may be interpreted as each basic relaying mode implemented in a specific zone of a frame, zones divided in time from each other and are synchronized between different cells. Below we describe the basic relaying modes for the case of one relay per sector (see Fig. 1).

1) BS-only mode

Subscribers operating in this mode are set to operate directly with the BS; relay stations are not used in any cell. In this mode the useful signal is the signal of the BS in the sector the SS is associated with, and the interference comes from all other BS sectors of the deployment including other sectors of the BS the SS works with.

2) RS-only mode

Subscribers operating in this mode are set to operate through the relay station of a sector. Therefore the useful signal for a SS is the signal from serving RS and the interfering signals are signals from all other RS.

3) BS+RS/BS mode

Subscribers operating in this mode are served by the BS, however, it is assumed that the RS serves other subscribers at the same time. Therefore from the subscribers' viewpoint this results in additional interference from the Relay Stations. From the entire system viewpoint this mode has advantage of reuse of the spectrum within the cell sector because different subscribers send/receive different data to/from BS and RS at the same time.

4) BS+RS/RS mode

Subscribers operating in this mode are served by the RS, but it is assumed that the BS serves some other subscribers at the same time. From subscribers' viewpoint this leads to additional interference from the Base Stations, and from the entire system viewpoint this mode takes advantage of spectrum reuse between different subscribers served by the BS and by the RS.

By analogy, for the cell having two RS per sector the following basic relaying modes may be defined. Reuse 1 modes are BS-only, RS1-only and RS2-only; reuse 2 modes are BS+RS1/BS, BS+RS1/RS1, BS+RS2/BS, BS+RS2/RS2, RS1+RS2/RS1 and RS1+RS2/RS2; reuse 3 modes are BS+RS1+RS2/BS, BS+RS1+RS2/RS1 and BS+RS1+RS2/RS2 as illustrated in Fig. 2.

III. COMPOSITE RELAYING MODES AND FRAME FORMING

Having defined the set of basic relaying modes, we now need to assign relaying modes to each subscriber in the cell so as to maximize the overall spectral efficiency in the cell. One obvious way to achieve this is to set each SS to operate in the relaying mode where it gets the best spectral efficiency.

Since some of the relaying modes take advantage of the spectrum reuse, the spectral efficiency metric used for selection must account for the reuse factor of the relaying mode. To simplify accounting for the reuse we made the following assumption in our simulations. Subscribers assigned to particular basic relaying mode get the resource quantity (e.g. the number of slots of some fixed size) proportional to the reuse factor of this basic relaying mode. For example each subscriber operating in BS-only and RS-only modes gets one slot per frame, whereas subscribers operating in BS+RS/BS, or BS+RS/RS get 2 slots per frame. If reuse 3 mode is used, then SS of this mode get 3 slots per frame. This assumption leads to very simple method of accounting for reuse in the effective spectral efficiency. The effective spectral efficiency is defined as per-subscriber SE multiplied by the reuse factor. We believe this approach does not lead to unfair resource allocation since

BS only		BS+RS / BS	BS-RS overhead
	RS only	BS+RS / RS	

Figure 1. Possible frame structure supporting multiple relaying modes. Horizontal dimension shows time division of relaying modes; vertical dimension shows various spectrum reuse schemes used by BS and RS.

SS operating in higher reuse modes suffer from greater interference and therefore have smaller per-SS spectral efficiency.

A. Frame forming procedure

Now we have the single criterion that may be used for assignment of reuse 1 as well as higher reuse basic relaying modes to each SS. Therefore we may now perform distribution of subscribers over the relaying modes. However, the following consideration should be taken into account. If for some subscribers it is preferable to operate in higher reuse mode (e.g. BS+RS/BS), then there must be other subscribers for which it is preferable to operate in complementary relaying mode (e.g. BS+RS/RS). Otherwise for some of SS that would like to take advantage of the spectrum reuse the reuse does not happen, which obviously affects the overall spectral efficiency in the deployment. Therefore to take the full advantage of the spectrum reuse some additional steps may be needed. One way is to make longer allocations for stations operating in the higher reuse mode having fewer subscribers than assigned to complementary modes. However, this may lead to unfair resource allocation. Another way that we use in this paper is to force "redundant" subscribers that do not have partners operating in the complementary relaying modes to operate in reuse 1 mode with the Base or Relay station according to their initial preferences. For example, if more subscribers are preferable to operate in BS+RS/BS rather than in BS+RS/RS, then some of subscribers are moved from BS+RS/BS mode to BS-only mode.

B. Composite relaying modes

Composite relaying modes are constructed of one or more basic relaying modes. The set of basic relaying modes selected for inclusion into composite modes determines the flexibility and efficiency of optimization of SS relaying modes.

1) Division mode

For one RS per cell sector case the subscribers choose between the BS-only and the RS-only basic relaying modes. Since all modes are of reuse 1, no additional relaying modes appear upon frame forming. For two RS per sector, subscribers choose between the BS-only, RS1+RS2/RS1 and RS1+RS2/RS2 modes. Therefore upon frame forming RS1-only or RS2-only modes may appear in the basic relaying mode set in addition to the two aforementioned modes.

BS only			BS+RS1/BS	BS+RS2/BS		BS+RS1+RS2 / BS	BS-RS1 overhead
	RS1 only		BS+RS1/RS1		RS1+RS2/RS1	BS+RS1+RS2 / RS1	BS-RS2 overhead
		RS2 only		BS+RS2/RS2	RS1+RS2/RS2	BS+RS1+RS2 / RS2	

Figure 2. Possible frame structure supporting multiple relaying modes. Horizontal dimension shows time division of relaying modes; vertical dimension shows the spectrum reuse schemes used by BS and one or two RS.

TABLE II. SYSTEM LEVEL SIMULATOR PARAMETER SUMMARY

Parameter name	Value	Units
Reuse	1x3x1	(Cell x Sector x Frequency)
Cell radius	1000	m
Carrier frequency	2.3	GHz
Channel model	SCM-Urban Macrocell	
Pathloss model	COST 231	
<i>BS/RS parameters</i>		
Height, Δh_{BS}	10	m
Rms power/sector	42	dBm/sector
BS/RS Antenna	70 / omni	deg
HPBW	15 / 0	dB
BS/RS Antenna Gain	2	dB
Cable Loss	4	dB
Receiver noise	10	wavelengths
Antenna spacing		
<i>SS parameters</i>		
Rms power	20	dBm
Height, Δh_{SS}	1.5	m
Antenna Gain	omni	
MS receive noise	6	dB
MS Antenna spacing	0.5	wavelengths

2) *Simultaneous mode*

For one RS per sector subscribers chose between BS+RS/BS and BS+RS/RS modes. Upon frame forming, BS-only or RS-only modes may appear in the basic relaying mode set. For two RS per sector subscribers choose between the reuse 3 basic modes. Upon frame forming any of reuse 1 modes may appear in the basic relaying mode set.

3) *Hybrid relaying*

This is the most flexible relaying mode that takes advantage of all available basic relaying modes for given number of RS per sector.

IV. RELAY DEPLOYMENT SCENARIOS

The choice of appropriate deployment scenario is very important for analysis of the benefits that relay stations bring to the system. One way to use relays is to cover the areas of high SS density. On the other hand, relays may be used to improve

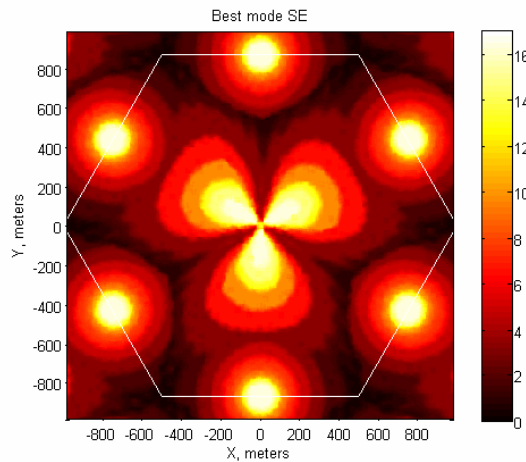


Figure 3. Distribution of SS' effective spectral efficiency over a cell for hybrid relaying mode.

performance in low-SINR areas thus equalizing the receive conditions of SS in the deployment. For evaluation purposes, it is assumed that all SS are uniformly distributed over the cell area; therefore their performance is mainly affected only by the factors such as path loss, shadow fading and antenna patterns of BS, RS and SS.

Two deployment scenarios were considered; in the first case each sector of a BS had one RS placed in the broadside of sectors' antennas. In the second case two relays per BS sector were deployed symmetrically. From the symmetry considerations, we assume that optimal RS positions are identical for every cell and sector, and optimal RS angular positions are symmetrical with respect to the BS sector antenna broadside (in case of symmetrical antenna patterns). The displacement of relay stations for the first and for the second deployment scenarios can be understood from Fig. 3 and Fig. 5 respectively.

V. SIMULATION METHODOLOGY

As the base platform for wireless relay-enabled communication system we have chosen the WiMAX 802.16e [1] technology. The WiMAX OFDMA standard is currently evolving to enable support of relay stations.

The methodology of simulations is the following. A number of subscriber stations are uniformly distributed within hexagonal grid of base stations and relay stations. For each SS in the center cell, the SINR (signal to noise plus interference) values are estimated for each frequency subchannel taking into account the interfering signals in the same subchannel. Based on the estimated SINR values using the PHY-layer abstraction model, the subscriber's spectral efficiency is determined for each subchannel. Simulation conditions, such as environment parameters and BS/RS/SS properties are summarized in the Table I.

The spectral efficiency is measured for links between SS and the BS or RS depending on which station it communicates with. The average effective spectral efficiency over the cell was

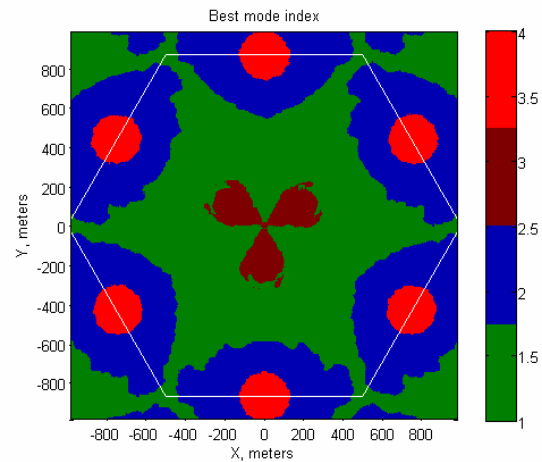


Figure 4. Map of relaying modes in hybrid relaying. Colors correspond to: 1 – BS-only; 2 – RS-only; 3 – BS+RS, BS active; 4 – BS+RS, RS active.

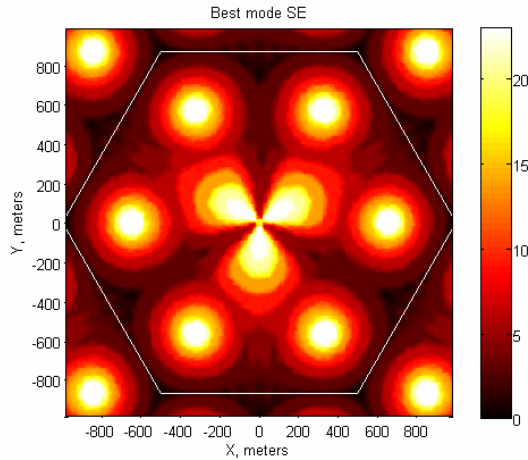


Figure 5. Distribution of SS' effective spectral efficiency over a cell for hybrid relaying mode in two relay per sector case.

TABLE I. AVERAGE SPECTRAL EFFICIENCY FOR DIFFERENT RELAYING MODES

Relaying mode	Average SE over a cell, bps/Hz
<i>Single relay station per a BS sector</i>	
BS-only	2.81
Division mode	3.74
Simultaneous mode	5.26
Hybrid relaying	5.29
<i>Two relay stations per a BS sector</i>	
BS-only	2.86
Division mode	5.94
Simultaneous mode	7.50
Hybrid relaying	7.86

evaluated for various basic and composite relaying modes.

When evaluating the average spectral efficiency over the cell, one should take into account the overhead transmission between the BS and the RS. This transmission is assumed to be performed in a separate time-division zone; the length of the zone is determined by the ratio of average spectral efficiency of subscribers served by the RS and the spectral efficiency of the BS-RS link. In our simulations we assumed that BS and RS communicate via strong line-of-sight channel, using highly-directive antennas, therefore achieving the maximal spectral efficiency of SISO link, limited only by the highest modulation and coding scheme applied in the system. In our case this was QAM64 modulation with the rate 5/6 convolutional turbo-code, having the spectral efficiency of 5 bps/Hz/sec.

VI. SIMULATION RESULTS

Resulting geographical distribution of effective spectral efficiency for the case of one RS per sector is shown in the Fig.3. It is seen that the regions of high spectral efficiency correspond to locations of BS and RS, and their shape is determined by the directivity patterns of the antennas of the BS and RS. The map of basic relaying modes for one RS per sector is shown in the Fig. 4. Resulting distribution of effective spectral efficiency and the map of preferable basic relaying modes for two RS per sector case are shown in Fig. 5 and Fig.

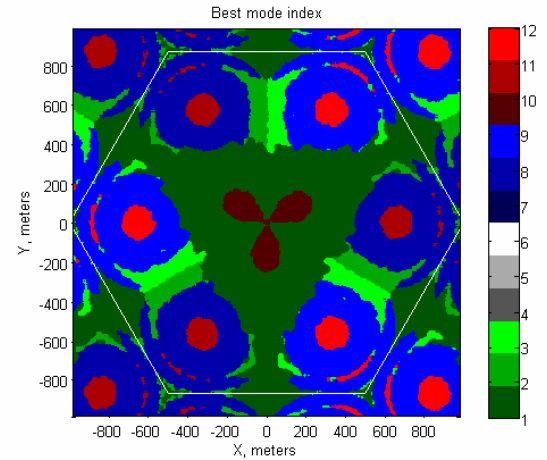


Figure 6. Map of relaying modes for 2-relay per sector case. Color legend: 1 – BS-only; 2 – RS1 only; 3 – RS2 only; 4 – BS+RS1, operating with BS; 5 – BS+RS1, operating through RS1; 6 – BS+RS2, operating with BS; 7 – BS+RS2, operating with RS2; 8 – RS1+RS2, operating through RS1; 9 – RS1+RS2, operating through RS2; 10 – BS+RS1+RS2, operating through BS; 11 – BS+RS1+RS2, operating through RS1; 12 – BS+RS1+RS2, operating through RS2.

6 respectively. Table II summarize average effective spectral efficiencies of various composite relaying modes for the cases of one and two relay stations per sector. One may notice that average SE for BS-only mode differs for one and two RS per sector case. This happens due to slightly different sets of SS for the two cases determined by different association of subscribers to cell sectors for these two cases.

VII. CONCLUSION

System level performance analysis of the backhaul network based on WiMAX with relays is presented in this paper. We have investigated the impact of various relaying modes on the spectral efficiency of the WiMAX with relays. We have developed the methodology of optimal assignment of relaying modes for each subscriber station in the deployment and showed the great increase of spectral efficiency that may be achieved by using the adaptation of the relaying modes to subscribers.

ACKNOWLEDGMENT

The IST MEMBRANE project is funded by the European Commission under 6th Framework Program.

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