Achieving Maximum System Throughput with Cooperative Relaying: A Case Study of IEEE 802.16j Multi-Hop Relay

Hyun-Seok Ryu, Heesoo Lee, Jae-Young Ahn, and Chung Gu Kang

Abstract: **Various types of cooperative relaying (CR) schemes exhibit different levels of throughput and outage performance because of their inherent trade-off between diversity gain and opportunity cost; in other words, the overhead that is associated with cooperation. This article attempts to answer whether cooperative communication is beneficial or not from the system-level viewpoint and furthermore, if it is, how its average throughput can be maximized while maintaining the target outage rate. In order to improve throughput at the required outage performance, we propose a unified selection criterion to deal with different levels of combining gain and opportunity cost associated with each scheme, which allows for the employment of different CR schemes for various positions of the mobile station. Our system-level simulation results for an IEEE 802.16j multi-hop relay confirm the varying levels of trade-offs among different CR schemes and furthermore, show that CR will be a useful means of maximizing the average throughput for a multi-hop relay system as long as each type of the cooperating scheme is carefully selected, depending on the position of the mobile stations.**

Index Terms: **Cooperative relaying (CR), IEEE 802.16j, system level simulation.**

I. INTRODUCTION

Multi-hop relay (MR) systems are considered to be a useful means of enhancing the coverage, throughput, and capacity of mobile wireless broadband networks, e.g., IEEE 802.16e mobile wireless metropolitan area network (WMAN), [1]–[3]. The coverage and throughput gains can be leveraged to reduce the total deployment cost for a given system's performance requirement and thereby improve the economic viability of those systems. Furthermore, it aims to facilitate in-band relaying without resorting to an additional frequency assignment for the relay link or the deployment of optical fiber. The IEEE 802.16j MR task group [4] is one particular example of standardization activities towards a relay-enhanced cellular system (RECS), which enables the exploitation of such advantages by specifying time division duplex (TDD)-based orthogonal frequency division multiple access (OFDMA) physical and medium access control layer enhancements to the IEEE 802.16 standard for licensed bands [5], [6].

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The throughput enhancement in an MR system is mainly attributed to the improvement of the carrier-to-interference-and-noise ratio (CINR) for mobile stations (MSs) around the relay stations (RSs) in areas remote to the base station (BS) where the data rate must be significantly reduced. Furthermore, the bandwidth efficiency can be maximized by dividing the coverage area into subcells, each of which is covered by a RS. By fully reusing the radio resources in all these subcells, the overall system capacity can be maximized. In spite of a significant gain throughout with the frequency reuse approach, co-channel interference becomes harmful to the MSs in the vicinity of neighboring RSs. Therefore, the performance limitation of a MR system can be properly understood only by investigating the throughput gain subject to the required level of service outage rate.

Recently, cooperative relaying has been considered to be a useful means of achieving diversity gain [7]–[10]. In particular, many different types of cooperative relaying (CR) schemes are specified in [2] and [3], which transmit information over multiple routes and then, combine the signals received from them or select one of them. From a physical-layer point of view, the spatial diversity of multiple nodes (cooperative diversity), possibly combined with the distributed space-time code, will always be useful for reducing the outage events incurred by the severe co-channel interference in the vicinities of the adjacent RSs.

From a system-level point of view, however, cooperation is not always beneficial, since it may require the cooperating nodes to lose its own transmission opportunities, i.e., reducing the overall bandwidth efficiency. Since all these CR schemes are different in their combining gains and resource requirements, there exists a different level of trade-offs in the average throughput and outage performances among them. In order to improve throughput while maintaining the required outage performance in the system, we propose a selective strategy in cooperation, which allows for the employment of different CR schemes that, depend on the position of the MSs throughout the cell coverage. In particular, a unified selection criterion is provided to deal with different levels of combining gain and opportunity cost associated with each scheme. It will serve as a typical example of a cross-layer design that incorporates the physical-layer property of cooperative diversity into upper-layer resource management.

We present the system-level simulation results to confirm the varying levels of trade-offs among different CR schemes and to show that the overall system throughput and outage performance can be fully enhanced with the proposed approach. Unlike most previous considerations for a point-to-point performance, our analysis is mainly focused on understanding the best possible system-level performance that can be achieved by cooperative

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relaying. To our best knowledge, there is no existing work evaluating the system-level performance in the cooperative relaying context, especially with an adaptive selection criterion. In [11], a minimum transmission-time criterion is proposed to determine whether each node with low data rate selects either direct transmission or transmission through a high data rate helper node in an IEEE 802.11 wireless local area network (WLAN). In contrast with the work proposed in [11], our work intends to deal with an underlying link-level performance inherent to the cooperative diversity in the relay-enhanced cellular network.

This paper is organized as follows. In Section II, we describe the preliminary simulation results for multi-hop relaying without cooperation. In Section III, we provide an overview of various types of cooperative relaying schemes in IEEE 802.16j. We propose a unified selection criterion for selective cooperative relaying in Section IV. Then, in Section V, we show the system level simulation results. We conclude the paper with a summary in Section VI.

II. PRELIMINARY RESULTS FOR MULTI-HOP RELAYING

In this article, we consider IEEE 802.16j MR standard, which is an enhancement to the OFDMA/TDD-based mobile wireless broadband access system, by employing multi-hop relay stations. This standard specifies the different modes of CR schemes, including a multi-hop relay capability, while maintaining the backward compatibility with the existing IEEE 802.16e WMAN standard [5], [6].

In order to understand the throughput and outage performance characteristics, we first explain a basic resource management model, that includes the resource allocation schemes specific to the MR system. Then, we investigate the preliminary system-level performance results for two-hop relaying without any cooperative diversity effect in a cellular OFDMA-TDD system.

A. System Model

Fig. 1 illustrates a frame structure for a non-transparent scenario [2], [3]. It is especially designed for a two-hop scenario with a single frequency assignment (FA). Each TDD frame is divided into downlink and uplink intervals, each of which is further divided into an access zone for the MS (i.e., used for the BS→MS[1] and RS→MS links) and a relay zone for the RS (i.e., used for the BS→RS link). One main characteristic of this particular frame structure is that the access zone is shared with all MSs that are communicating directly with a multi-hop relaying BS (MR-BS) or indirectly via RSs. For the non-transparent scenario in which some MSs might not be able to receive the MAP message[2] directly, the bandwidth allocation results must be also relayed. Therefore, two different MAPs for the MS must be transmitted in the downlink: One for the MS that is directly served by the MR-BS and the other for the MS that is served by the RS. For the simplicity of the presentation, we denote the former as MAP and the latter as RS-MAP. Furthermore, there

[1] A→B means that data is transmitted from A to B.

[2] MAP is one of the MAC management messages specified in IEEE 802.16 standard that notifies resource allocation results, determined by a packet scheduling algorithm in the BS, to the MSs.

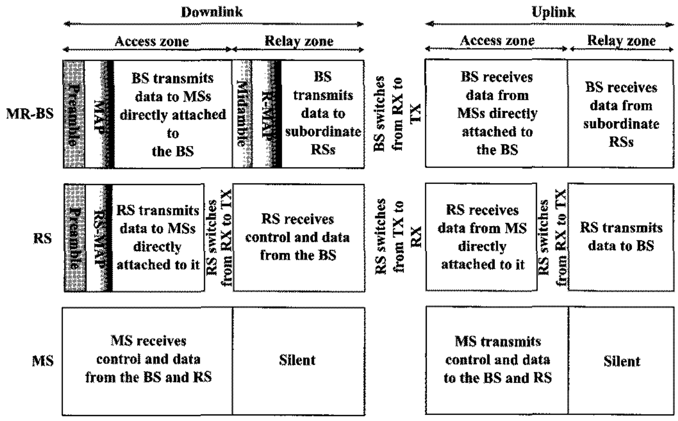

Fig. 1. MR frame structure: Non-transparent case [2], [3].

must be another MAP for the relay zone, as the corresponding resource is orthogonally allocated by multiple RS's. This is referred to as R-MAP [2], [3].

In the current discussion, we focus on a downlink of an IEEE 802.16e standard-based OFDMA-TDD system with 720 useful subcarriers over a nominal bandwidth of 8.75 MHz in 2.3 GHz [5], [6]. Each 5 ms frame is composed of 42 OFDM symbols. For the asymmetric characteristics of typical internet traffic, we assume a downlink/uplink ratio of 27:15, i.e., 27 symbols for a downlink subframe and 15 symbols for a uplink subframe. Two symbols are assigned to the preamble and mid-amble in the downlink, and the rest of the symbols, except for some that are used for MAP information, are assigned to the data burst. Note that the size of the MAP varies with the number of active users. R-MAP and RS-MAP will turn out to be a critical source of overhead in association with CR.

A basic resource allocation unit is given by a subchannel, e.g., it is defined as a set of 48 subcarriers selected either by a diversity mode or a band adaptive modulation and coding (AMC) mode. The boundary between the access and relay zones must be determined dynamically because it depends on the traffic load. Furthermore, depending on the frequency reusability over the access zones of the downlink, we consider two different allocation schemes: The overlapped and orthogonal allocation schemes. The orthogonal allocation scheme corresponds to the case in which no subchannels are reused over the access zone, i.e., no subchannels can be shared among the MSs directly served by the MR-BS and those served by RSs. However, the overlapped allocation scheme corresponds to the case for in which all subchannels are reused over the access zone are shared among all MS's throughout the cell coverage, whether the MS is directly served by the MR-BS or not. In fact, it would be the most bandwidth-efficient since the frequency resource is fully reused by every RS and BS in each cell. While allowing for the maximization of the bandwidth efficiency, however, it tends to suffer from co-channel interference, which reduces the overall system throughput, and furthermore, induces outage events around sub-cell edges as well as the boundary of each cell. On the other hand, as far as a relay zone is concerned, all corresponding subchannels are orthogonally divided for RSs, and thus, they are not subject to any co-channel interference.

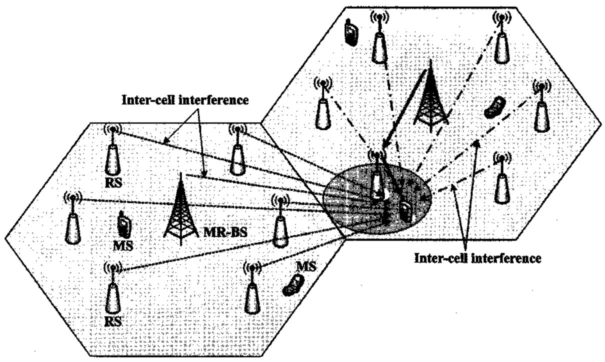

Fig. 2. Co-channel interference model for a simple two-hop relay system in a multi-cell environment.

B. Preliminary Simulation Results for Two-Hop Relaying

We assume that 10 mobile users are uniformly distributed throughout each cell. We deploy six RS's in each cell, located around a BS at a position two-thirds between the BS and the cell boundary. The corresponding co-channel interference is illustrated in Fig. 2. For simplicity of the exposition, only two neighboring cells are shown, but we will consider a 19-cell wrap-around structure in the simulation. The transmit powers of BS and RS are limited to 20 W and 10 W, respectively. Meanwhile, we consider a full buffer traffic model, i.e., each BS or RS always has packets to transmit in the buffer. A simple round-robin packet scheduling algorithm is employed to determine which MS is served in each interval. All other simulation models, including the cellular lay-out and wireless channel model, are referred to [12] and [13].

The average system throughput is computed by taking the average of data rates for all MS's in each cell without allocating the radio resource to those that cannot meet the required CINR to support the minimum modulation and coding set (MCS) level (i.e., quadrature phase shift keying (QPSK) 1/12). Herein, service outage rate is the probability that the MS is subject to an outage event. The event occurs in the following two cases: First, since the BS→MS or RS→MS link cannot guarantee the minimum MCS level, the BS cannot allocate the resource to the MS. Second, even whilst the BS transmits a data burst to the MS by using the scheduled resource, the MS cannot decode the data burst due to erroneous reception. Fig. 3 compares the average system throughput and outage performance of the direct transmission (i.e., without relaying) with that of two-hop relaying for the different resource allocation schemes. Here, the boundary between access and relay zones is determined to maximize the average system throughput for the given traffic scenario, which turns out to be 16:11 (access zone symbols:relay zone symbols) and 14:13 for orthogonal and overlapped allocations, respectively.

In all cases, it is clear that there is improvement in the average throughput performance with the two-hop relay. Furthermore, the relay-enhanced system with overlapped allocation always performs the best. It corresponds to almost as much as an 80% and 31% improvement over direct transmission in average throughput with the overlapped allocation and orthogonal allocation, respectively. Improvement in the overlapped allocation is mainly attributed to fully reusing the frequency in every RS [12]. Furthermore, the better quality of received signal from a close-by RS improves the per-user data rate in the cell edges for both overlapped and orthogonal allocations.

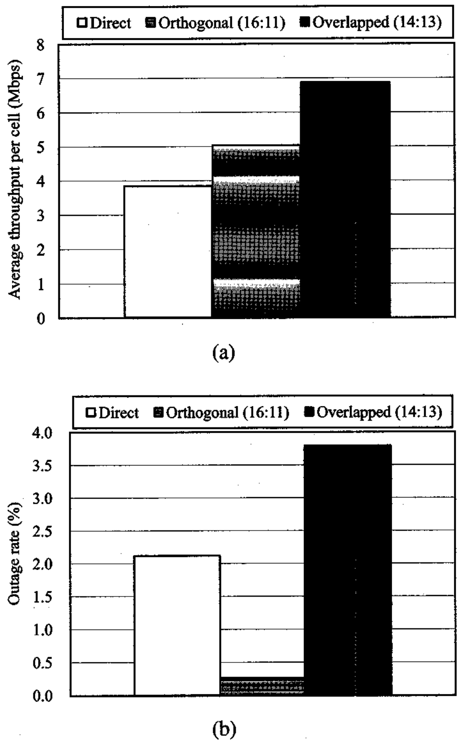

Fig. 3. Average system throughput and outage performance: Direct transmission vs. two-hop relaying: (a) Average system throughput and (b) service outage rate.

In Fig. 3(b), however, we note that the MR relay with overlapped allocation suffers from a higher outage rate than others. This is attributed to the fact that the aggressive frequency reuse in every RS incurs significant outage events around a boundary of neighboring RSs. In fact, this particular observation makes multi-hop relaying less useful in practice. In the sequel, we investigate how the key physical-layer property of cooperative diversity can be exploited to combat the degradation in outage performance while improving the system throughput of two-hop relaying with overlapped allocation.

III. COOPERATIVE RELAY: OVERVIEW

As described in Section II, two-hop relaying provides a primitive form of cooperative communication, through which a single two-hop route is formed between MR-BS and MS. To make a concise presentation, the two-hop relaying is referred to as simple relaying (SR). Meanwhile, a more advanced form of cooperative relaying is to transmit information over multiple-relay paths and then, to estimate the transmitted information at the receiver by combining or selecting the signals received over multiple routes. CR can be achieved by sending signals across different transmit antennas of a BS and RSs within a cell during the transmission of a burst to a particular MS. It is similar to the macro-diversity effect with neighboring BSs. For example,

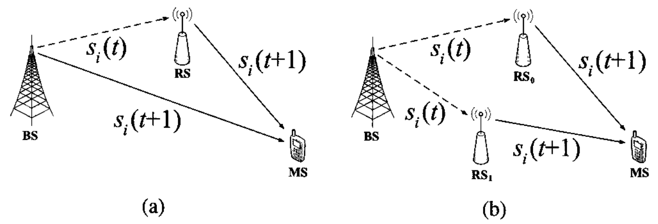

Fig. 4. CSD: (a) One-RS cooperation and (b) two-RS cooperation.

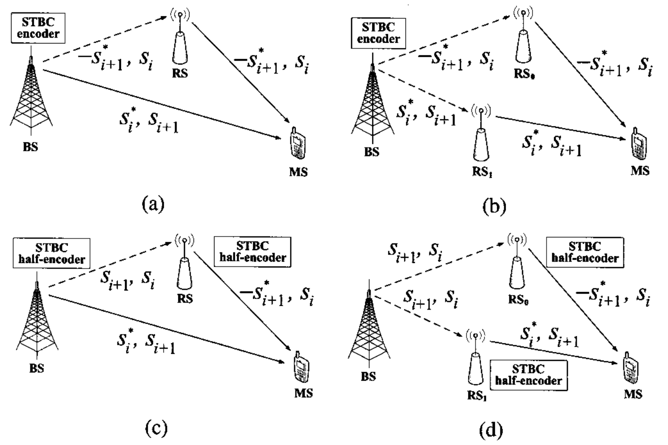

Fig. 5. CTD: (a) Full encoding: One-RS, (b) full encoding: Two-RS, (c) half encoding: One-RS, and (d) half encoding: two-RS.

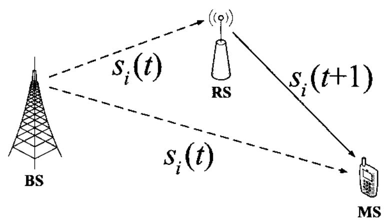

Fig. 6. CRD.

three different types of CR modes are considered in [2] and [3]: Cooperative source diversity (CSD), cooperative transmit diversity (CTD), and cooperative hybrid diversity (CHD).

Figs. 4, 5, and 6 present the examples for the various types of CR schemes. Note that all these schemes work in two phases: The first phase is illustrated with the dotted line and the second phase with the solid line. For CSD, the antennas simultaneously transmit the same signal using the same time-frequency resource as in an OFDMA system. Referring to Fig. 4, one or two-RS transmits the same signals over two different paths, which are summed up in front of the RF stage. Assuming that the channel gains of RS→MS links for RS_0 and RS_1 are given by h_{RS_0-MS} and h_{RS_1-MS}, respectively, for the case of the CSD scheme with two RSs shown in Fig. 4(b), the normalized received signal to noise ratio (SNR) at a MS is given as

$$\gamma_{MS}^{(CSD)} = \frac{|h_{RS_0-MS} + h_{RS_1-MS}|^2}{N_0} \tag{1}$$

where N_0 means variance of white Gaussian noise.

The CTD scheme exploits space time block code (STBC)-encoded signals across the transmit antennas using the same time-frequency resource. As illustrated in Fig. 5, one or two-RS can be involved in CTD. Depending on whether STBC encoding is required at the RS, these schemes are broadly categorized into *full encoding* and *half encoding*. For the full encoding case, the BS has a full STBC encoder, while RS just relays the encoded symbols (see Figs. 5(a) and 5(b)). For the half encoding case, an individual RS is involved with STBC encoding in cooperation with the BS or the other RS as shown in Figs. 5(c) and 5(d). For the case of the CTD scheme with two RSs, the normalized received SNR at a MS is given as

$$\gamma_{MS}^{(CTD)} = \frac{|h_{RS_0-MS}|^2 + |h_{RS_1-MS}|^2}{N_0}. \tag{2}$$

From (1) and (2), we note that the normalized received SNR of CTD might be better than that of CSD due to diversity gain. The CSD scheme has no diversity gain but can just achieve power gain. Thus, in this paper, we do not consider CSD in the CR schemes.

We also note that the one or two-RS cooperation case for CSD and CTD suffers from its own drawback: Either incurring unnecessary co-channel interference toward the neighboring cell or requiring an extra bandwidth. For one-RS cooperation, BS transmission in the second phase causes extra co-channel interference to the MS's in the neighbor cells. For the two-RS cooperation case, furthermore, CR involves extra bandwidth since a cooperating RS loses its own transmission opportunity. In other words, the diversity gain is obtained at the expense of an extra bandwidth that is required to provide another path. A combination of CTD and CSD schemes is classified as the CHD scheme.

Other than the three different modes of CR schemes specified in [2] and [3], another useful type of CR is a cooperative receive diversity (CRD) scheme [7]–[10]. As illustrated in Fig. 6, it is virtually the same as the SR scheme except that a signal overheard by MS in the first phase of relaying can be combined with the signal relayed by RS in the second phase. Since it relies only on the overheard source signal, no extra bandwidth other than signaling overhead is required to achieving the diversity gain. As two signals are received over different paths, they might be assigned with different MCS levels, which can still be combined using log-likelihood-ratio (LLR) values. For a given quality of the relay link, in fact, the combining gain is determined by the CINRs for the BS→MS and RS→MS links, denoted by γ_{BS-MS} and γ_{RS-MS}, respectively.

IV. SELECTIVE COOPERATIVE RELAYING SCHEME

A. Selective Cooperative Relaying: Overview

As an extra bandwidth is required for some CR schemes, there exists a trade-off between combining gain achieved by cooperation and overhead associated with the additional bandwidth. In fact, the level of combining gain depends on the relative position of MS with respect to the MR-BS and RS while the amount of overhead varies with the type of CR scheme. In other words, a CR scheme must be properly selected by considering the MS position, so as to maximize the overall system throughput. Toward this end, the trade-off can be evaluated in a unified manner. In order to quantify the trade-off effect, we first define an equivalent burst transmission rate (EBR). It represents the efficiency of

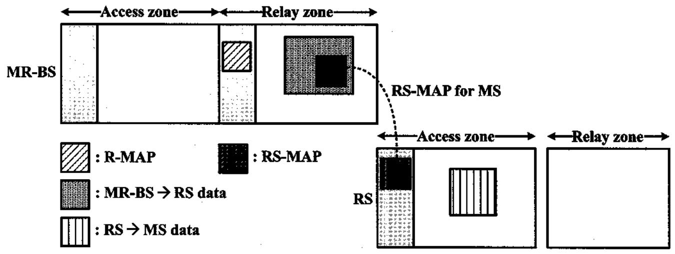

Fig. 7. Resource allocation illustration: SR.

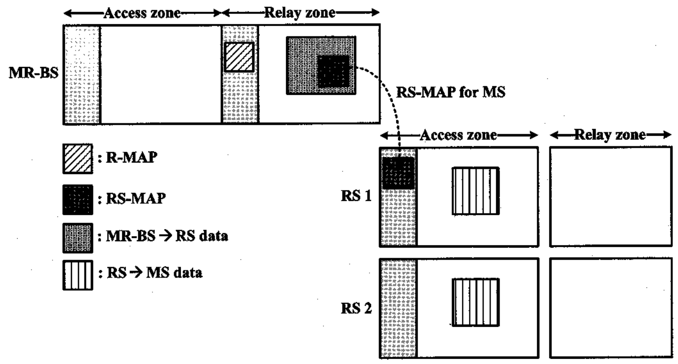

Fig. 8. Resource allocation illustration: CTD.

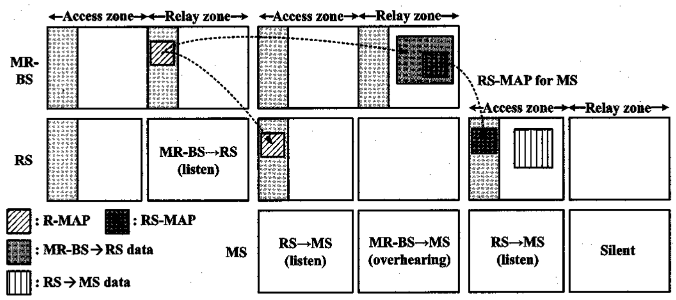

Fig. 9. Resource allocation illustration: CRD.

each CR scheme in terms of overhead associated with MAP and other signaling information along with the achievable transmission data rate. Our proposed approach is to employ the various types of CR schemes in a selective manner so that the overall system capacity may be maximized while maintaining the same level of outage performance as the existing scheme.

B. Equivalent Burst Rate

Let the size of data burst and the amount of associated overhead information be denoted by N_{burst} and N_{overhead}, respectively. The corresponding data rate will be determined by the CINR of an individual MS. Let $R(\gamma)$ be the maximum allowable data rate for the given CINR, γ. Consider the transmission times that are required when an individual radio resource transmits data and overhead information. Then, the EBR is the data rate that makes the sum of the individual transmission times over each link of the MR equal to that of an individual burst as a single burst. More specifically, the EBR, denoted by R_{eff}, is given as follows

$$\frac{N_{\text{burst}}}{R_{\text{eff}}} = \frac{N_{\text{burst}}}{R(\gamma_{\text{MS}})} + \frac{N_{\text{overhead}}}{R(\gamma_0)} \tag{3}$$

or

$$R_{\text{eff}} = \frac{N_{\text{burst}} R(\gamma_{\text{MS}}) R(\gamma_0)}{N_{\text{burst}} R(\gamma_0) + N_{\text{overhead}} R(\gamma_{\text{MS}})} \tag{4}$$

where γ_{MS} and γ_0 are the CINRs for data transmission and overhead bursts, respectively. The EBR can be interpreted as an indicator of the transmission efficiency that is achievable when all required resources are devoted to the transmission of the data burst.

As a different CR scheme is involved with the different amount of overhead associated with signaling and relaying, the corresponding EBR varies with the type of CR scheme. As an illustrative example, we refer to a SR scenario, which involves two different types of overhead, R-MAP and RS-MAP as shown in Fig. 7. Let $N_{\text{R-MAP}}$ and $N_{\text{RS-MAP}}$ denote the sizes of R-MAP and RS-MAP, respectively. Since MAP bursts are protected by the most robust MCS mode, e.g., QPSK modulation with a coding rate of 1/3 and a repetition factor of 4 in the mobile worldwide interoperability for microwave access (WiMAX) specification [5], [6], we assume that the corresponding data rate is always fixed by R_{MAP}. Furthermore, we assume that the CINRs measured for the BS→RS link and the RS→MS link are given by $\gamma_{\text{BS-RS}}$ and $\gamma_{\text{RS-MS}}$, respectively. The EBR for the SR scheme, $R_{\text{eff}}^{(\text{SR})}$, can be written as

$$\frac{N_{\text{burst}}}{R_{\text{eff}}^{(\text{SR})}} = \frac{N_{\text{R-MAP}}}{R_{\text{MAP}}} + \frac{N_{\text{burst}} + N_{\text{RS-MAP}}}{R(\gamma_{\text{BS-RS}})} + \frac{N_{\text{RS-MAP}}}{R_{\text{MAP}}} + \frac{N_{\text{burst}}}{R(\gamma_{\text{RS-MS}})}. \tag{5}$$

For the CTD scheme, a required bandwidth for data burst is doubled for the access link as shown in Fig. 8, since two RSs are involved, i.e., transmitting N_{burst} bits over each access link. Thus, $2N_{\text{burst}}$ bits are required for transmitting. Therefore, the EBR for the CTD scheme, $R_{\text{eff}}^{(\text{CTD})}$, is given by

$$\frac{N_{\text{burst}}}{R_{\text{eff}}^{(\text{CTD})}} = \frac{N_{\text{R-MAP}}}{R_{\text{MAP}}} + \frac{N_{\text{burst}} + N_{\text{RS-MAP}}}{R(\gamma_{\text{BS-RS}})} + \frac{N_{\text{RS-MAP}}}{R_{\text{MAP}}} + \frac{2N_{\text{burst}}}{R\left(\gamma_{\text{MS}}^{(\text{CTD})}\right)} \tag{6}$$

where $\gamma_{\text{MS}}^{(\text{CTD})}$ is a combined CINR from two RSs, which is given by (2).

Finally, for the CRD scheme, no additional bandwidth is required for cooperation, but there must be extra signaling right before MR-BS broadcasts the data bursts, so as to indicate that MS must overhear the R-MAP for locating the data burst that are relayed as shown in Fig. 9. The supportable data rate for MS is determined by combining the signals over the RS→MS and BS→MS links. If the CINRs for these links are given by $\gamma_{\text{BS-MS}}$ and $\gamma_{\text{RS-MS}}$, the corresponding data rate is denoted by $\widetilde{R}(\gamma_{\text{BS-MS}}, \gamma_{\text{RS-MS}})$. The EBR for the CRD scheme, $R_{\text{eff}}^{(\text{CRD})}$, is now given by

$$\frac{N_{\text{burst}}}{R_{\text{eff}}^{(\text{CRD})}} = \frac{2N_{\text{R-MAP}}}{R_{\text{MAP}}} + \frac{N_{\text{burst}} + N_{\text{RS-MAP}}}{R(\gamma_{\text{BS-RS}})} + \frac{N_{\text{RS-MAP}}}{R_{\text{MAP}}} + \frac{N_{\text{burst}}}{R\left(\gamma_{\text{MS}}^{(\text{CRD})}\right)}. \quad (7)$$

The factor of 2 for $N_{\text{R-MAP}}$ in (7) represents the additional overhead incurred by extra signaling for CRD.

C. Selection Criteria

At first, BS determines if MS will be connected directly with the BS or served by RS(s). In other words, the CINR achievable with a direct connection to BS and that with relaying are compared, and then, the station with the better CINR is selected. In the case that the better CINR can be achieved via RS, one of the possible CR schemes (i.e., the SR scheme, two-RS cooperated CTD with half-encoding (Fig. 5(d)), and CRD (Fig. 6)) will be employed. Secondly, the EBR is used to compare the efficiency of these CR schemes. In other words, the one with the largest EBR is selected. More specifically, comparing $R_{\text{eff}}^{(\text{CRD})}$ with $R_{\text{eff}}^{(\text{SR})}$ and $R_{\text{eff}}^{(\text{CTD})}$, CRD must be selected if

$$R_{\text{eff}}^{(\text{CRD})} > \max\left\{R_{\text{eff}}^{(\text{SR})}, R_{\text{eff}}^{(\text{CTD})}\right\} \quad (8)$$

which can be shown as

$$\frac{1}{R_{\text{MS}}^{(\text{CRD})}} < \min\left\{\frac{1}{R_{\text{MS}}^{(\text{SR})}} - \alpha, \frac{2}{R_{\text{MS}}^{(\text{CTD})}} - \alpha\right\} \quad (9)$$

where $C = N_{\text{R-MAP}}/N_{\text{burst}}R_{\text{MAP}}$. Similarly, CTD must be selected if

$$R_{\text{eff}}^{(\text{CTD})} > \max\left\{R_{\text{eff}}^{(\text{SR})}, R_{\text{eff}}^{(\text{CRD})}\right\} \quad (10)$$

which is shown as

$$\frac{1}{R_{\text{MS}}^{(\text{CTD})}} < \frac{1}{2}\min\left\{\frac{1}{R_{\text{MS}}^{(\text{SR})}}, \frac{1}{R_{\text{MS}}^{(\text{CRD})}} + \alpha\right\}. \quad (11)$$

We note that the constants, 2 in (9) and 1/2 in (11), represent the overhead associated with doubling a required bandwidth in CTD. Meanwhile, α corresponds to the overhead due to overhearing operation of CRD. Thus, if the data rate of CRD, including the associated overhead, is higher than that of SR and that of CTD with overhead, CRD should be selected. Similarly, if the data rate of CTD, including the associated overhead, is higher than that of SR and that of CRD with overhead, CTD should be selected.

V. SIMULATION RESULTS AND DISCUSSION

A. Simulation Model

An ideal hexagonal cell is assumed for each site while considering only 2 tiers of cells with respect to a reference cell in the center, i.e., considering a total of 19 cells in our simulation. Due to the finite number of cells, an accurate level of interference from all other cells cannot be captured in the model. In order to remove such a boundary effect, we consider a so-called wraparound structure, which allows for the capture of a more accurate level of inter-cell interference [2]. Each cell is fully loaded, and furthermore, all subcarriers are fully reused by BS and RS (i.e., overlapped allocation).

A path loss follows the WINNER model at a frequency band with a center frequency of 2.3 GHz [15]. A log-normal shadow fading model with a standard deviation of 8 dB is considered for large-scale fading [2]. Meanwhile, multi-path fading follows the International Telecommunication Union Radiocommunication Sector (ITU-R) M.1225 recommendation [16] for vehicular A model (VEH-A). An individual multi-path is subject to the independent Rayleigh fading, whose time-domain correlation is implemented by Jake's model [17]. In order to consider the channel mismatch effect subject to mobility, we assume that the channel feedback is delayed by two frames.

We assume that 10 mobile users are uniformly distributed throughout each cell. We deploy six RS's in each cell, located around a BS at a position two-thirds between BS and the cell boundary. For each MS, a candidate RS is selected by the CINR measured between MS and the candidate RS. In other words, the one or two RSs with the best CINR are selected for CR, depending on the CR schemes. Note that we do not take the traffic load in each RS into account, i.e., no load-balancing feature is incorporated into the RS selection scheme. The transmit power of BS and RS is limited to 20 W and 10 W, respectively. Meanwhile, we consider a full buffer traffic model, i.e., each BS or RS always has packets to transmit in the buffer. A simple round-robin packet scheduling algorithm is employed.

Note that the size of the overhead varies with the required number of bits for MAP information per MS. For example, a total of 120 bits is required for 10 users in each cell if $N_{\text{R-MAP}} =$ 12 bits. This corresponds to one orthogonal frequency division multiplexing (OFDM) symbol, and thus, 23 OFDM symbols are available for data transmission in mobile WiMAX [3]. If $N_{\text{R-MAP}}$ increases to 24, 48, and 96 bits, then the available number of data symbols is reduced to 21, 17, and 9. In other words, resource availability is mainly governed by the signaling overhead. We assume that a typical value of $N_{\text{R-MAP}}$ for mobile WiMAX ranges roughly between 24 and 48 bits [5], [6]. The data symbols are divided into access and relay zones with a given ratio. In the following simulation, the system-level performance is evaluated by varying $N_{\text{R-MAP}}$ as well as the access/relay zone ratio while assuming $N_{\text{R-MAP}} = N_{\text{RS-MAP}}$.

For the access link, the minimum required CINR levels for the given MCS follow the reference in Table 1 [12], [18]. Recall that the performance of the Alamouti's space-time code given in [14] is the same as that of the maximum ratio combining (MRC) scheme as long as full power is applied to each antenna. For a CTD scheme, therefore, the signals from two different RS's are combined to determine the MCS level with reference to the required CINR in Table 1. Since the same MCS must be applied to two different links associated with the cooperat-

[3] MAP bursts exploit QPSK with an effective coding rate of 1/12. Thus, a MAP burst with the size of 120 bits is encoded to 1440 bits. Then, 720 QPSK modulated symbols are mapped to 720 used subcarriers. Since 1 OFDM symbol consists of 720 used subcarriers, 1 OFDM symbol is required to transmit 120 bits size of MAP burst.

Table 1. MCS table for adaptive modulation and coding.

Downlink MCS		Required CINR (dB)
Modulation	Coding rate	
QPSK	1/12	−3.46
QPSK	1/6	−1.0
QPSK	1/3	1.73
QPSK	1/2	5.40
16-QAM	1/2	10.5
64-QAM	1/2	15.0
64-QAM	2/3	20.0
64-QAM	5/6	28.5

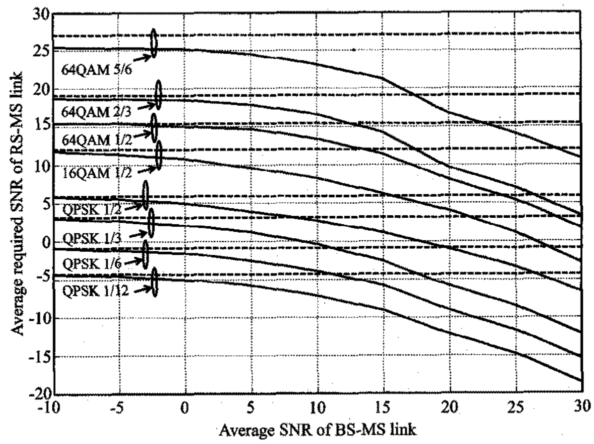

Fig. 10. 1% block error rate curves for CRD.

ing RS, the actual data rate will be determined by the one with the worse channel condition. Therefore, a simple MRC assumption in this paper will be overestimating the performance. For a CRD scheme, meanwhile, MCS is determined by the channel conditions of the BS→MS and RS→MS links. To simplify our analysis, we assume that the BS→RS link is always reliable enough to transmit at the maximum possible data rate, e.g., using 64-quadrature amplitude modulation (QAM) modulation with a coding rate of 5/6 in mobile WiMAX. MS performs LLR combining of the corresponding symbol over the BS→MS link and the other over the RS→MS link. Fig. 10 shows the 1% block error rate (BLER) curves for the different MCS levels when turbo code is applied to a block length of 256 bits with 2 iterations. These curves will be used to determine the minimum required CINR levels of the BS→MS and RS→MS links for the given MCS level. The dotted lines in Fig. 10 represent the reference values in Table 1. Note that the performance of CRD approaches to the reference values as the BS→MS link degrades.

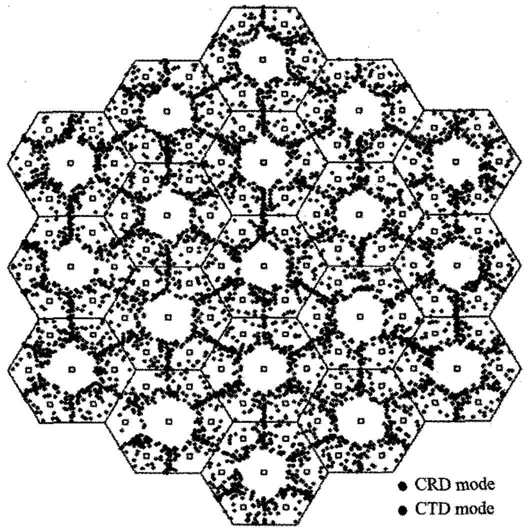

Fig. 11. The distribution of the MSs exploiting the proposed selection criteria.

B. Simulation Results and Discussion

Fig. 11 captures the distribution of the MSs when the proposed selection criterion is applied to each cell. In this figure, the rectangle in the center and edge of each hexagonal cell denotes the BS and RSs, respectively. In order to examine the distribution of the MSs selecting the CRD and CTD schemes, the MSs that directly communicate with BS and choose the SR scheme are cleared. In fact, the MSs directly connected with the BS are located in the center circle of each cell and the MSs selecting the SR scheme are located in the boundary-circle of each cell. Meanwhile, we note that the CTD and CRD schemes are most effective when two independent signals to be combined are equally reliable, e.g., the MS located somewhere roughly in the middle of BS and RS for the CRD and in the middle of two cooperative RS's for the CTD. In other words, the diversity gain of CTD and CRD schemes varies with the position of the MSs and thus, their own effective merit will be attributed to the trade-off between diversity gain and opportunity cost associated with an individual scheme.

Fig.12 shows the average system throughput while varying the access and relay zone boundary for the given value of $N_{\text{R-MAP}}$. In the selective CR scheme, each MS selects one of the different CR schemes dynamically using the best EBR criterion. It is observed that there exists an optimum boundary for each case to maximize the average throughput. For example, the average throughput is maximized for the SR and selective CR schemes when the downlink is divided into access and relay zones by a ratio of 14:13, respectively. As expected for all the schemes, the average throughput decreases with $N_{\text{R-MAP}}$. In particular, it is found for CTD that the optimum boundary is affected mainly by the amount of overhead, $N_{\text{R-MAP}}$. It is also clear that CRD always outperforms SR, while CTD suffers from a dramatic throughput reduction caused by overhead incurred by extra bandwidth for cooperation. On the other hand, the selective CR and CRD show only a slight difference in their performance. The reason why the throughput performance of the selective CR is slightly inferior to that of CRD is that some MS's subject to the service outage can be now served by CTD, but their data rate tends to be low due to only a marginal improvement in CINR. For example, those at the boundary of two adjacent RSs mainly select CTD. This leads to the trade-off relation-

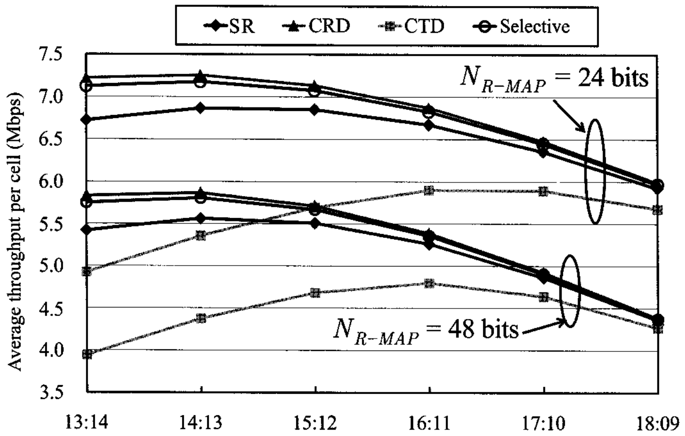

Fig. 12. Average system throughput for the different MAP size as the access/relay zone ratio varies.

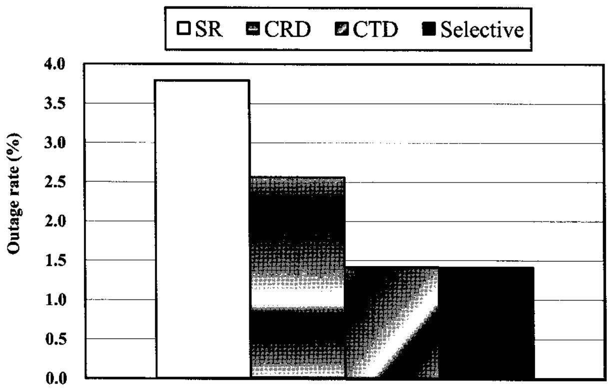

Fig. 13. Service outage rate.

ship between outage and throughput performance, which can be explained more clearly by investigating the outage rate for each scheme.

Fig. 13 shows the service outage rate for the different schemes with the same conditions as shown in Fig. 12. As expected, it is clear that the outage performance is improved over SR using the CR schemes. In particular, CTD outperforms CRD. In connection with the throughput performance in Fig. 12, we again find that there exists a trade-off relationship between the outage rate and throughput performance. Furthermore, the selective CR scheme shows the best outage performance. According to the results in Figs. 12 and 13, we conclude that the selective CR scheme provides the best trade-off capability, which also reveals the maximum possible achievable system throughput.

VI. CONCLUSION

Cooperative diversity is an effective means of reducing outage events, especially around the boundaries of two adjacent RSs or BSs. However, cooperation is not always useful, since some cooperative relay schemes, e.g., CTD, are effective only at the expense of losing their own transmission opportunities in the cooperating RSs. In this article, we have shown that each type of cooperative relay itself is already hampered either by outage or throughput performance, and furthermore, there is a trade-off characteristic between CTD and CRD.

Our preliminary analysis is mainly focused on understanding the best possible performance that can be achieved using cooperative relays. Our observation prompts us to devise a selective strategy that employs the different cooperative relay schemes in the varying positions of mobile stations. Since cooperation is not always useful, the system throughput can be maximized while warranting the outage performance, by selecting the specific relaying scheme only when it is beneficial in terms of system throughput. In conclusion, CR will be a useful means of maximizing the average throughput for a multi-hop relay system as long as each type of the cooperating schemes is carefully selected, depending on the position of the mobile stations.

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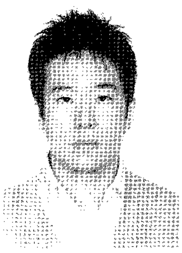

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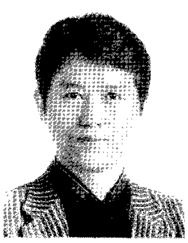

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