Efficient Cooperative Diversity Schemes and Radio Resource Allocation for IEEE 802.16j

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***Abstract*—This paper studies various cooperative diversity schemes for Orthogonal Frequency Division Multiple Access (OFDMA)- Time Division Duplex (TDD) based two-hop cellular networks in low mobility scenarios, where the instantaneous channel state information is available at the base station. A user scheduling and radio resource allocation technique is developed in order to efficiently integrate various cooperative diversity schemes for the emerging IEEE 802.16j based systems. The analysis of the system with this scheduler shows that a simple cooperative diversity scheme which dynamically selects the best scheme between conventional relaying and direct transmission is promising in terms of throughput and implementation complexity. The conventional relaying refers to the scheme where the destination relies solely on the signals received through the relay.**

Keywords: AMC, cooperative diversity, IEEE 802.16e, IEEE 802.16j, OFDMA, relay, scheduling, throughput

I. Introduction

The Orthogonal Frequency Division Multiple Access (OFDMA) based IEEE 801.16e standard has been developed to provide high data rate coverage to the mobile users in a cell with an approximate coverage radius of 8 km [1]. The emerging IEEE 802.16j standard is currently being developed for increasing the coverage area of the IEEE 802.16e standard via the deployment of fixed or nomadic relay terminals. This paper provides design and analysis for the physical and Medium Access Control (MAC) layers of the emerging IEEE 802.16j standard.

Since wireless terminals cannot transmit and receive simultaneously at the same time and frequency, relaying requires at least two phases. In the first phase source-to-relay ($S \rightarrow R$) communication takes place and the second phase is used for the relay to forward the received information to the destination. The two phase communication causes multiplexing loss since each data block is transmitted twice. Hence, scheduling and radio resource allocation in multi-hop cellular networks need modifications on conventional scheduling algorithms designed for the single-hop networks. This is due to the fact that the end-to-end performance including the effect of multiplexing loss should be considered rather than only Signal-to-Noise-Ratio (SNR) or individual link throughput. The multi-hop cooperation schemes must be used only when they can provide end-to-end throughput greater than that of direct transmission, i.e., without (w/o) relay.

Although the performance of wireless relay networks is thoroughly studied from an information theoretic point-of-view, the work on the relative performance of various cooperative diversity schemes in a practical multi-user scenario is limited. In [2], the cooperative relay transmissions are used whenever the relay can correctly decode the packets that are transmitted by the source terminal. This causes throughput loss if higher throughput is provided with the direct transmission w/o relaying. In [3], end-to-end link adaptation and link selection methods have been developed for a single user in an Orthogonal Frequency Division Multiplexing (OFDM) Time Division Duplex (TDD) based wireless relay network. The literature for scheduling of the users in a wireless relay network considers the design either from information theoretic point of view or based only on SNR conditions which does not consider the multiplexing loss inherent in relaying (e.g., [4]–[7]). The emerging IEEE 802.16j standard may allow w/o relay transmissions in the second phase. However, the current standard does not specify how the radio resource allocation will be done [8]. It is claimed in [9] that it is computationally too complex to do the radio resource allocation together with path selection[1] for each sub-channel. We use the path selection algorithm devised in [3] which removes such additional complexity of path selection for each sub-channel.

In this study, we propose a radio resource allocation and scheduling algorithm for two-hop wireless relay networks. When a user's SNR condition for a given sub-channel remain unchanged during the whole frame, the optimal transmission scheme[2] for a given sub-channel will not change. For example, if a user is scheduled w/o relay in the first phase, that user should be scheduled w/o relay in the second phase as well. For optimal operation, our scheduler may choose to use the w/o relay transmissions in the second phase. Such decision is done for each sub-channel. Based on the scheduler proposed, we analyze the relative performance of various cooperative diversity schemes such as cooperative transmit diversity, cooperative receive diversity and cooperative selection diversity and discuss their advantages and disadvantages in the context of the emerging IEEE 802.16j based wireless relay networks.

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[1]i.e., selection of the path with or w/o relay.
[2]either with relay or without relay

II. System Model

As the relay network, we consider IEEE 802.16j based two-hop cellular network. The w/o relay system corresponds to the single hop IEEE 802.16e based cellular network. A single cell with multiple users and multiple fixed relays is considered. We consider low mobility users. Hence, we assume that the channel gains of each sub-channel remain unchanged during one frame, which consists of a certain number of OFDM symbols. A sub-channel is comprised of multiple contiguous sub-carriers with approximately equal instantaneous SNR levels. Hence, each sub-channel can be modeled as a flat fading channel with a given SNR, determined by the flat fading condition at the sub-carriers.

For each sub-channel, the Channel State Information (CSI) regarding the instantaneous SNR in the source-to-destination ($S \rightarrow D$) link and the closest relay-to-destination ($R \rightarrow D$) link are fed-back by each user to the Base Station (BS). Such overhead is present in systems which use link adaptation such as Adaptive Modulation and Coding (AMC). Various CSI feedback algorithms can be used to reduce this overhead and are beyond the scope of this paper. Each Mobile Station (MS) is assigned to the Relay Station (RS) with the shortest distance to it. It is assumed that the relays are deployed at strategic locations in the cell such that the $S \rightarrow R$ links are very reliable and are in line of sight. This makes it practical for the relay to decode the signals received from the source with negligible error.

The relays use Decode-and-Forward (DF) where they demodulate, decode, re-encode and forward the signals received from the source terminal during the first phase. Repetition based relaying, where the relay repeats the information received from the BS is considered. For cooperative transmit and receive diversity schemes, this provides Hybrid-Automatic Repeat Request (ARQ) benefits. The MAC-Protocol Data Unit (PDU) packets are transmitted in Forward Error Correction (FEC) blocks where each block contains its cyclic redundancy check bits [10]. The receivers use cyclic redundancy check to check whether a block is received correctly or not. We assume that the probability of an undetected block error is negligible. The block is discarded if at least one bit in a block is received in error. ARQ is not implemented.

We use AMC for each sub-channel and for each frame based on the low complexity end-to-end link adaptation and selection method developed in [3]. The considered modulation modes are BPSK, QPSK, 16-QAM and 64-QAM. The considered FEC includes convolutional coding with the following code rates: 1/2, 2/3, 3/4, 5/6, 7/8 and 1 [11]. Each combination of the modulation and coding modes gives one AMC mode. Since AMC is used, we keep the transmit power from the relays and the BS constant. All the terminals in the network are equipped with single antenna. We develop and use a modified version of Proportional Fair Scheduling (PFS) [12].

The throughput is defined as the number of payload bits per second per hertz and per channel use that are received correctly at the corresponding receiver.

Terminology and Notation: The following terminology is used throughout this paper. The term j, $j \in \{1, 2, ..., J\}$, denotes the sub-channel index in the frequency domain. The total number of sub-channels are denoted by J. The term u, $u \in \{1, 2, ..., U\}$, denotes the MS index.

In a point-to-point flat fading link with instantaneous SNR γ, the end-to-end throughput with AMC is given by $\rho(\gamma) = R(\gamma)(1 - p_e(\gamma))$. In this expression, it is assumed that the AMC mode which provides the highest throughput is selected. The term $R(\gamma)$ represents the nominal rate (in $b/s/Hz$) of the selected AMC mode based on γ. If the selected coding rate is η and the selected M-ary modulation mode can provide a maximum rate of M b/s/Hz, then $R(\gamma) = M \times \eta$. For example if the selected AMC mode is 16-QAM with coding rate $\eta = 1/2$, then $R(\gamma) = \frac{4}{2}$ b/s/Hz. For SNR γ, $p_e(\gamma)$ represents the block error rate with the selected AMC mode. The * operator denotes the complex conjugate operation. We define the coverage area with radius r, as the area where the user throughput is above 0.5 b/s/Hz with probability p.

Baseband Channel, Interference and Noise Models: Assuming that the OFDMA system converts frequency selective fading into frequency flat fading at each sub–carrier, the fading at each sub-carrier is modeled as Rayleigh flat fading random variable. The terms $\gamma_{SR,j}$, $\gamma_{SD,j}$ and $\gamma_{RD,j}$ denote the instantaneous (i.e., short term average) SNRs at sub–channel j of the $S \rightarrow R$, $S \rightarrow D$ and $R \rightarrow D$ links, respectively. These channel coefficients include the path loss and fast fading effects. For each sub-channel, we assume a block fading channel which remains constant within the sub-carriers of a given sub-channel.

III. Cooperative Diversity Schemes

For all the cooperative diversity schemes considered, the transmission for each user in each phase occurs at a given sub-channel j.

A. Cooperative Transmit Diversity–1

The MS and RS listen to the transmission of the BS during the first phase. In the second phase, both BS and RS transmit simultaneously to the MS. Such transmission scheme can realize an effective Multiple-Input-Multiple-Output (MIMO) channel provided that the same AMC mode is used over the two phases. This requires the two phases to have equal duration. BS and RS use cooperative-space-time coding in the form of Alamouti scheme [13]. The transmission sequence of the BS and the RS during the two phases is presented in [3]. After the two phases end, the MS space-time decodes the signals received during the two phases. Assuming that the RS decodes the transmitted symbols by the BS correctly, the post–processing instantaneous SNR at each sub-channel j achieved after space time decoding at the MS is equal to [3]

$$\gamma_{post,j}^{coopTxDiv1} = 2\gamma_{SD,j} + \gamma_{RD,j}.$$

Hence, second order diversity can be achieved for each symbol transmitted by the BS.

Since we assume that the $S \rightarrow R$ link can support the highest rate AMC mode with negligible decoding error, we choose the AMC mode for a given sub-channel j based on

$\gamma_{post,j}^{coopTxDiv1}$. With such link adaptation at a sub-channel j, the end-to-end throughput per channel use is given by [3]

$$\rho_j^{coopTxDiv1} = 0.5\rho(\gamma_{post,j}^{coopTxDiv1}) \quad (1)$$

The factor of 0.5 accounts for the fact that the same AMC mode needs to be used over the two phases of transmissions to achieve a cooperative-MIMO channel.

B. Cooperative Transmit Diversity–2

The cooperative diversity–2 is a subset of cooperative diversity–1. The main difference is that, the MS does not exploit the signal received during the first phase. Therefore, the AMC mode in each phase can be chosen independently and the two phases do not have to have equal duration. The AMC mode to be used in the first phase is chosen based on $\gamma_{SR,j}$ for each sub-channel j. For the second phase, the AMC mode for each sub-channel j is chosen based on the post–processing SNR given by [3]

$$\gamma_{post,j}^{coopTxDiv2} = \gamma_{SD,j} + \gamma_{RD,j}. \quad (2)$$

When the $S \rightarrow R$ link is reliable, the duration of the first phase can be shorter than that of the second phase as a higher rate AMC mode can be used. This compensates, to a certain extent, for the multiplexing loss caused by the two phased relay transmission. With this link adaptation at sub-channel j, the end-to-end throughput per channel use is given by [3]

$$\rho_j^{coopTxDiv2} = \frac{\rho(\gamma_{SR,j})\rho(\gamma_{post,j}^{coopTxDiv2})}{R(\gamma_{SR,j}) + R(\gamma_{post,j}^{coopTxDiv2})}. \quad (3)$$

C. Cooperative Receive Diversity

In the first phase of cooperative receive diversity scheme, the source transmits at a particular AMC mode while both the relay and the destination receive. In the second phase, the relay repeats with the same AMC mode and the BS remains silent. After Maximum Ratio Combining (MRC), the MS achieves cooperative receive diversity. Even if this scheme can achieve the same post processing SNR as that of cooperative transmit diversity–2, it suffers from a potentially higher multiplexing loss due to the need for identical AMC modes and hence equal–duration phases. Hence, cooperative receive diversity cannot outperform cooperative transmit diversity–2.

D. Cooperative Selection Diversity

With conventional relaying, the $S \rightarrow R$ transmissions occur in the first phase. The destination chooses not to receive during the first phase. In the second phase, only the relay transmits. The destination relies solely on the signals received via the $R \rightarrow D$ link. With cooperative selection diversity scheme, BS dynamically chooses between conventional relaying and direct transmission. When the BS chooses to use conventional relaying, the post–processing SNR at the MS is equal to $\gamma_{RD,j}$, otherwise it is equal to $\gamma_{SD,j}$. For the first phase of conventional relaying, the AMC mode is determined based on $\gamma_{SR,j}$ and for the second phase based on $\gamma_{RD,j}$. Hence, the end-to-end throughput with conventional relaying is given by [3]

$$\rho_j^{conv} = \frac{\rho(\gamma_{SR,j})\rho(\gamma_{RD,j})}{R(\gamma_{SR,j}) + R(\gamma_{RD,j})} \quad (4)$$

The end-to-end throughput with cooperative selection diversity is then given by

$$\rho_j^{coopSDiv} = \max\{\rho_j^{conv}, \rho(\gamma_{SD,j})\} \quad (5)$$

E. Adaptive Cooperative Diversity Scheme

Adaptive cooperative diversity scheme chooses the best scheme (in terms of end-to-end throughput) among direct transmission and the aforementioned cooperative diversity schemes. If the two schemes have the same performance the one with less complexity is selected. We order the schemes with increasing complexity as follows: direct transmission, conventional relaying, cooperative transmit diversity–2 and cooperative transmit diversity–1 [14]. This adaptive scheme chooses coherent signal combining at the MS only when it can increase the end-to-end throughput as compared to both conventional relaying and w/o relay schemes. Hence, it can reduce the complexity at the receiver while maximizing the end-to-end throughput.

IV. Scheduling and Radio Resource Allocation for Multi-hop Cellular Networks

The scheduling and the radio resource allocation are performed at the BS. For each Down-Link (DL) frame $k \in \mathbb{N}$, they are developed as the following. The BS uses a look-up table developed for point-to-point flat fading links with given SNR conditions. For each instantaneous SNR γ with resolution of 0.1 dB, the look-up table stores the throughput $\rho(\gamma)$ and the AMC mode which provides the highest throughput. For each sub-channel j and for each user (i.e., MS) u, the BS calculates the post–processing SNR with the relay, i.e., $\gamma_{u,j}^{post}$. Let $\gamma_{SD,u,j}$ denote the instantaneous SNR the user u experiences on a sub-channel j in the $S \rightarrow D$ link. The BS plugs in $\gamma_{SD,u,j}$, $\gamma_{SR,j}$ and $\gamma_{u,j}^{post}$ to the look-up table and reads the corresponding throughput and nominal rate for each of them. Then, for each cooperative diversity scheme under consideration, it calculates the end-to-end throughput with the relay, i.e., $\rho_{u,j}^{with-relay}$, by the end-to-end throughput equations presented in Section III. Let $\rho_{u,j}^{direct} = \rho(\gamma_{SD,u,j})$ define the throughput that user u can obtain on sub-channel j w/o relay. For each user and for each sub-channel, the BS first decides on to relay or not by

$$\rho_{u,j} \quad = \quad \max\{\rho_{u,j}^{direct}, \rho_{u,j}^{with-relay}\}. \quad (6)$$

For each user u on sub-channel j, the w/o relay transmission is chosen if $\rho_{u,j} = \rho_{u,j}^{direct}$ otherwise the relayed transmission is chosen. For each sub-channel j, the BS calculates the PFS metric for each user according to [12][3]

$$PFS_{u,j} = \frac{\rho_{u,j}}{\overline{\rho}_u[k-1]}. \quad (7)$$

The term $\overline{\rho}_u[k-1]$ represents the past average throughput of user u at DL frame $k-1$. Then, for each sub-channel, the BS

[3]Park et al. analyze the PFS in [12] for single-hop wireless networks.

schedules the user who has the maximum PFS metric [12], i.e.,

$$\hat{u} = \underset{u \in \{1,2,\ldots,U\}}{\arg\max} \left\{ \frac{\rho_{u,j}}{\overline{\rho}_u[k-1]} \right\}. \tag{8}$$

Once the users are scheduled, the past average throughput for each user is updated by using a low pass filter with a time constant of T slots. This update is done according to

$$\overline{\rho}_u[k] \quad = \quad \frac{(T-1)\overline{\rho}_u[k-1] + \sum_{j=1}^{J}(c_{u,j}\rho_{u,j})}{T}. \tag{9}$$

The term $c_{u,j}$ is equal to one if user u is scheduled on sub-channel j, otherwise it is equal to zero. The time constant T adjusts the level of fairness of the scheduler. T should be long enough to provide fairness to the users.

The designed scheduler and radio resource allocation provide both cooperative diversity and multi-user diversity. For a given user, it guarantees that the end-to-end throughput will always be greater than or equal to that of w/o relay and fixed relaying where relays use the whole frequency band in the second phase.

V. The Frame Structure

The frame structure developed in this study is shown in Fig. 1. In the figure, cooperative selection diversity based transmissions are considered. The users report their CSI to the BS using the fast feedback channel. Based on this CSI, the BS allocates the radio resources and schedules the users. It transmits in DL-MAP the information on which user is scheduled on which sub-channel and for each scheduled user whether relaying should be used or not. All the relays and users listen to this information. The duration of the second phase is fixed. If conventional relaying is selected for a given user, then the duration of the first phase at each sub-channel can be variable depending on the AMC mode chosen for the second phase. Since the $S \rightarrow R$ links have good channel conditions, the duration of the first phase at each sub-channel can be shorter than or equal to that of second phase. This leaves some free radio resources in the first phase and hence compensates to a certain extent for the multiplexing loss. These free radio resources can be used by the scheduler to accommodate additional $S \rightarrow D$ (w/o relay) transmissions. For conventional relaying or cooperative transmit diversity–2 schemes, the scheduler has the freedom to optimize the locations of the free radio resources and the radio resources to be used for the $S \rightarrow R$ transmissions. In such optimization, the priority should be given to $S \rightarrow D$ transmissions as fading will be more severe as compared to Line of Sight (LOS) $S \rightarrow R$ links. We do not consider these free radio resources.

VI. Performance Evaluation

In this section, we present performance evaluations using the scheduling and radio resource allocation described in Section IV. The average end-to-end throughput is calculated per channel use, i.e., the average is taken over the radio resources allocated to the users in order to provide conclusions that are not sensitive to the system parameters.

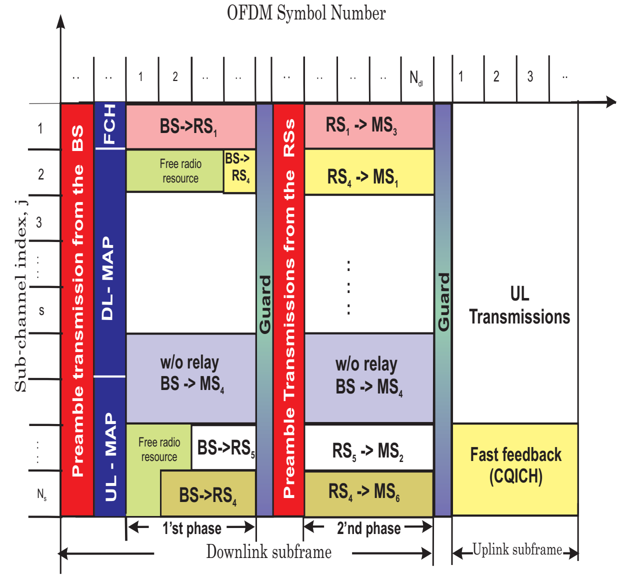

Fig. 1. Frame structure for low mobility users in two-hop cellular networks with infrastructure based relays. CQICH stands for the channel quality indicator channel provided in the IEEE 802.16e standard. $\{RS_1, RS_2, \ldots\}$ denote the different relays. Each color in each phase represents the transmission to a given user, i.e, MS_u.

A. Simulation Setup

An FEC block is comprised of 96 coded bits [15]. One sub-channel is comprised of 8 data sub-carriers and one pilot subcarrier over t consecutive OFDM symbols. The term $t,\ t \in \{2, 3, 6, 12\}$ represents the number of OFDM symbols required to transmit one FEC block. It depends on the selected modulation mode with AMC. The duration of the second-phase is fixed to 12 OFDM symbols. The first phase can use up to 12 OFDM symbols. The scalable OFDMA mode with 1024 sub–carriers with a system bandwidth of 10 MHz is considered [11]. A total of 60 users and 60 sub-channels have been simulated to create the multi-user environment. We consider users with speeds up to 7.7 km/h such that the 50% coherence time is greater than or equal to 10ms. The frames have 5 ms of duration [11]. The time constant T is set to 100 to provide fairness to the users.

For the $S \rightarrow R$ links the wireless channel model developed in [16], [17] is used with a path-loss exponent of 3 and a Rician K factor of 10. The selected model has a 90% coherence bandwidth of 17 sub-carriers. For the $R \rightarrow D$ and $S \rightarrow D$ links the Non-LOS (NLOS) channel model presented in [18] is used with a path-loss exponent of 3.5. The selected model has a 90% coherence bandwidth of 8 sub–carriers. These channel models allow us to assume a block fading channel which remains constant within a sub-channel. The total Effective Isotropic Radiated Power (EIRP) from the BS is fixed as 57.3 dBm. Since the relay terminals are simpler than a BS and transmit at lower power, we assume that the total EIRP from each relay station is fixed as 47.3 dBm [19]. The heights of the MSs, BS and RS are 1.5 m, 32 m and 10 m, respectively. Carrier frequency is 2.5 GHz. Based on these assumptions, path–loss at each link is calculated accordingly [16]. The effect of shadowing is not considered.

The BS is at the center of the cell. In accordance with the fixed infrastructure relay assumption, we choose to place the relays at favorable locations. All the relays are positioned symmetrically at a distance of 10.4 km to the BS. This way the relays improve the coverage and system throughput while still maintaining a reliable and high speed (using 64-QAM) link with the BS. The positions of the relays are marked with “x”.

B. Relative Performance Evaluation of the Cooperative Diversity Schemes

Our performance measures are the overall average throughput per channel use and the throughput gain for a single user at different positions in the cell. Average throughput gain of scheme A with respect to scheme B is defined as

$$\text{throughput\_gain(A,B)} = \frac{(\overline{\rho}^A - \overline{\rho}^B)}{\overline{\rho}^B} \times 100,$$

where $\overline{\rho}^A$ and $\overline{\rho}^B$ are the average throughput values of a single user at a given position in the absence of other users. As explained in Section IV, $\overline{\rho}^A$ is the average throughput of scheme A with the possibility of choosing direct transmission whenever it is necessary.

Fig. 2 shows throughput_gain(cooperative transmit diversity-2, w/o relay). We observe that around the BS, i.e., up to 6 km, the gain is zero. In this region direct transmission provides the highest end-to-end throughput. The relays must be placed outside of the coverage area of w/o relay system. With the current simulation setup, the direct transmission provides a coverage area with radius $r = 8.4$ km for $p = 0.95$. This verifies that the relay positions we select are suitable.

We also measured coverage area with radius r at probability p achieved by different schemes. The adaptive cooperative diversity achieves $r = 14.85$ km for $p = 0.7$ [4]. For $p = 0.7$, the adaptive cooperative diversity provides the highest coverage area. For $p = 0.95$, the cooperative transmit diversity–2 and adaptive cooperative diversity schemes provide the same coverage range which is 14.7 km. The cooperative selection diversity provides negligibly (1.4%) less coverage range as compared to that provided by cooperative transmit diversity–2.

In the presence of multiple users in the cell, Fig. 3 presents the overall average throughput per channel use as a function of the total number of relays in the cell. The average throughput is calculated within a range greater than 6 km and smaller than 14.85 km to the BS, which is the coverage area where relaying improves the performance compared to w/o relay system. As seen in the figure, in the average throughput sense, cooperative transmit diversity–2 and cooperative selection diversity outperform the cooperative transmit diversity–1 even though cooperative transmit diversity–1 provides the highest post processing SNR. Interestingly the cooperative selection diversity can perform as well as more complex diversity schemes such as adaptive cooperative diversity and cooperative transmit diversity–2. With 6 relays in the cell,

[4]In Figures 2, 4 and 5, the black circle has radius 14.85 km.

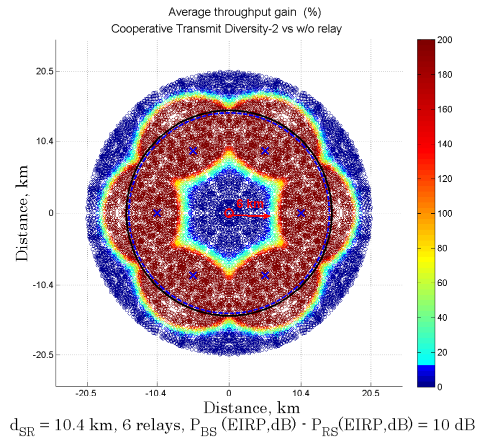

Fig. 2. Average throughput gain throughput_gain(cooperative transmit diversity-2, w/o relay) at different position in the cell. The gains greater than 200% are rounded to 200. (This figure should be printed in color for enhanced readability.)

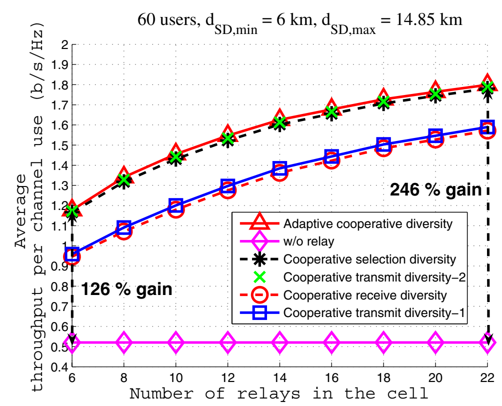

Fig. 3. Average throughput per channel use versus the number of relay stations in the cell. The minimum and maximum distance of the users to the BS are $d_{SD,min} = 6$ km and $d_{SD,max} = 14.85$ km, respectively.

the cooperative selection diversity enhances the throughput by 126% compared to w/o relay system. This gain increases as the number of relays deployed in the cell increases. In order to explain the conclusions of Fig. 3, in Fig. 4 we plot throughput_gain(cooperative transmit diversity-2, cooperative selection diversity). The cooperative transmit diversity–2 brings a throughput gain of around 25% in most of the region where throughput gain is significant. Such a gain can be seen over the region where the received SNR from the BS and the closest RS is comparable to each other. Over that region, the benefits of increased post–processing SNR compared to cooperative selection diversity becomes important. However, this region is only a small fraction of the overall coverage area and hence, the overall gain in the average throughput becomes insignificant. Furthermore, as the number of relays is increased in order to increase the throughput, this region gets smaller. Fig. 5 shows throughput_gain(cooperative transmit diversity-2, cooperative transmit diversity-1). The cooperative transmit diversity–1 can outperform the cooperative transmit diversity–2 only at distances far from both the BS and the closest RS. Due to high path-loss in this region, SNR gain becomes more important than the multiplexing loss. On the other hand, this region is small and outside the coverage area. Therefore it does

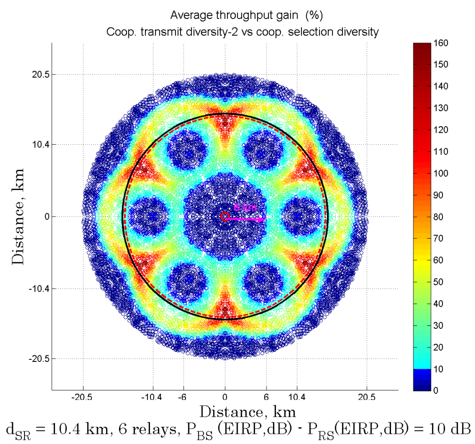

Fig. 4. Average throughput gain throughput_gain(cooperative transmit diversity-2, cooperative selection diversity) at different position in the cell. (This figure should be printed in color for enhanced readability.)

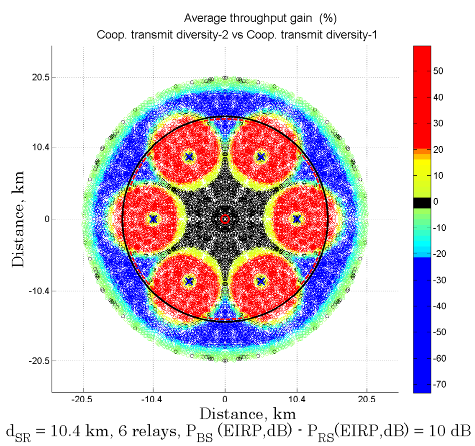

Fig. 5. Average throughput gain throughput_gain(cooperative transmit diversity-2, cooperative transmit diversity-1) at different position in the cell. (This figure should be printed in color for enhanced readability.)

not affect the overall average throughput and coverage. Therefore, in terms of the average throughput performance in the coverage area, adaptive cooperative diversity performs close to cooperative transmit diversity–2 and cooperative selection diversity.

VII. Conclusions and Future Works

In this study, efficient radio resource allocation and user scheduling techniques have been developed for the DL transmissions in a two-hop cellular network using the emerging IEEE 802.16j standard. The users are prioritized according to the end-to-end throughput with the best scheme among two hop or single hop transmission. The practical performance of various cooperative diversity schemes has been analyzed with the radio resource allocation and user scheduling techniques developed herein. We demonstrated that the cooperative selection diversity scheme is a promising cooperative diversity scheme compared to the other more complex cooperative diversity schemes which require coherent signal combining at the MS. The future works out of this study include: 1. Extension of the design and evaluation to the multi-cell environment 2. The design and evaluation for users with high mobility where radio resource allocation and scheduling should be based on long term average channel conditions. 3. The analysis and design with imperfect CSI. 4. Investigations on synchronization issues.

References

[1] WiMAX Forum, "WiMAXs Technology for LOS and NLOS Environments," *WiMAX Forum White Papers*, August 2004.
[2] Z. Lin, E. Erkip, and M. Ghosh, "Adaptive Modulation for Coded Cooperative Systems," *IEEE 6th Workshop on Signal Processing Advances in Wireless Communications*, pp. 615– 619, June 2005.
[3] B. Can, H. Yomo, and E. De Carvalho, "Link Adaptation and Selection Method for OFDM Based Wireless Relay Networks," *Journal of Communications and Networks, Special issue on MIMO-OFDM and Its Applications*, June 2007. [Online]. Available: http://kom.aau.dk/~bc/
[4] M. Hu and J. Zhang, "Opportunistic Multi-Access: Multiuser Diversity, Relay-Aided Opportunistic Scheduling and Traffic-Aided Smooth Admission," *Mobile Networks and Applications, Kluwer Academic Publishers*, vol. 9, no. 4, 2004.
[5] G. Li and H. Liu, "Resource Allocation for OFDMA Relay Networks with Fairness Constraints," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, November 2006.
[6] I. Hammerstrom, M. Kuhn, and A. Wittneben, "Channel Adaptive Scheduling for Cooperative Relay Networks," *IEEE VTC, Fall*, vol. 4, pp. 2784–2788, 2004.
[7] F. Atay Onat, A. Adinoyi, Y. Fan, H. Yanikomeroglu, and J. S. Thompson, "Optimum Threshold for SNR-based Selective Digital Relaying Schemes in Cooperative Wireless Networks," *IEEE Wireless Communications and Networking Conference (WCNC)*, March 2007.
[8] The Relay Task Group of IEEE 802.16, "Draft Standard for Local and Metropolitan Area Networks: Part 16, Air Interface for Fixed and Mobile Broadband Wireless Access Systems, Multihop Relay Specification," IEEE, Tech. Rep., August 2007.
[9] M. Kaneko and P. Popovski, "Radio Resource Allocation Algorithm for Relay-aided Cellular OFDMA System," *Proceedings of IEEE International Conference on Communications*, June 2007.
[10] WiMAX Forum member organizations, "WiMAX System Evaluation Methodology," WiMAX Forum, Tech. Rep., September 2007.
[11] Wimax Forum, "Mobile WiMAX– Part I: A Technical Overview and Performance Evaluation," *WiMAX Forum White Paper*, June 2006.
[12] T. Park, O. Shin, and K. B. Lee, "Proportional Fair Scheduling for Wireless Communication with Multiple Transmit and Receive Antennas," *IEEE VTC, Fall*, vol. 3, pp. 1573– 1577, 2003.
[13] S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, October 1998.
[14] B. Can, M. Portalski, H. S. Lebreton, S. Frattasi, and H. Suraweera, "Implementation Issues for OFDM-Based Multihop Cellular Networks," *IEEE Communications Magazine, Technologies in Multi-Hop Cellular Networks*, September 2007.
[15] IEEE, "IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems; Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1," IEEE, Tech. Rep., 2006.
[16] IEEE 802.16 Broadband Wireless Access Working Group, "Channel Models for Fixed Wireless Applications," IEEE, Tech. Rep., July 2001.
[17] V. Erceg, L. J. Greenstein, S. Y. Tjandra, S. R. Parkoff, A. Gupta, B. Kulic, A. A. Julius, and R. Bianchi, "An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 7, pp. 1205–1211, July 1999.
[18] D. S. Baum, J. Hansen, J. Salo, G. Del Galdo, M. Milojevic, and P. Kyösti, "An Interim Channel Model for Beyond-3G Systems: Extending the 3GPP Spatial Channel Model (SCM)," *IEEE VTC, Spring*, vol. 5, pp. 3132 – 3136, 2005.
[19] M. Asa, D. T. Chen, and N. Natarajan, "Relay Strategy of Broadcast Messages in Mobile Multihop Relay," *IEEE 802.16 Presentation Submission Template (Rev. 8.3)*, no. IEEE C802.16mmr-06/008, January 2006.