

# A Spectrally Efficient Macrodiversity Handover Technique for Interference-Limited IEEE 802.16j Multihop Wireless Relay Networks

Jamil Sultan, Norbahiah Misran, Mahamod Ismail, and Mohammad Tariqul Islam

**In this paper, we propose an efficient macrodiversity handover (MDHO) technique for time-division-based interference-limited IEEE 802.16j multihop wireless relay networks. In the proposed MDHO, when the diversity set members of the mobile station (MS) are a base station (BS) and relay station (RS), the MS receives the signal transmitted by the BS in the first phase. During the second phase, it also receives the simultaneous transmissions of the BS and RS. Furthermore, when the diversity set members are two RSs or two BSs, the MS receives only the simultaneous transmissions of the diversity set members. The superiority of the proposed MDHO is validated using analytical and simulation results. The performance analysis metrics are the average downlink (DL) carrier to interference and noise ratio (CINR), the average DL spectral efficiency, and the average service outage probability. Evaluation results show that the proposed MDHO significantly outperforms the conventional MDHO. The CINR gain achieved using the proposed MDHO is 4.71 dB compared to the conventional MDHO.**

**Keywords:** Macrodiversity handover, multihop relay, IEEE 802.16j, cochannel interference, AMC.

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Jamil Sultan (phone: +6 017 361 5772, email: jameel730@hotmail.com), Norbahiah Misran (email: bahiah@eng.ukm.my), and Mahamod Ismail (email: mahamod@eng.ukm.my) are with the Department of Electrical, Electronic, and Systems Engineering, Universiti Kebangsaan Malaysia, Selangor, Malaysia.

Mohammad Tariqul Islam (email: titareq@yahoo.com) is with the Institute of Space Science, Universiti Kebangsaan Malaysia, Selangor, Malaysia.  
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## I. Introduction

Recently, there has been increasing interest in multihop relaying as a promising cost-effective approach to significantly enhance the throughput and extend the coverage of future wireless broadband cellular networks such as IEEE 802.16e mobile WiMAX [1]-[3]. The IEEE 802.16j relay task group specified OFDMA physical layer and medium access control (MAC) layer enhancements for the IEEE 802.16 standard for licensed bands to enable the operation of relay stations (RSs) [4]. Since the wireless terminal cannot transmit and receive simultaneously at the same time and frequency [1], [5]-[8], the relay communication is organized in two phases. In the first phase, the source-to-relay communication takes place. In the second phase, the relay forwards the received information to the destination.

Handover is an essential component of mobile cellular communication systems. Mobility causes dynamic variations in link quality and interference levels in cellular systems, and sometimes requires a particular user to change its serving station. This change is known as a handover. The main target of a handover is to provide a continuous connection when a mobile station (MS) migrates from the air-interface of one base station (BS)/RS to the air-interface provided by another BS/RS. Carrier to interference and noise ratio (CINR) is a major metric of handover target selection in IEEE 802.16j [9] as well as in beyond 3G systems employing OFDMA [10]. Three handover methods are supported within the IEEE 802.16j standard: hard handover (HHO), fast access station switching (FASS), and macrodiversity handover (MDHO). The implementation of

HHO is mandatory, while FASS and MDHO are two optional modes.

In single-hop networks, there is basically only one kind of handover, and it is from one BS to another. In the multihop relay (MR) networks, in contrast, there are also handovers between BS and RS within the same or different cells and between two RSs which can also be within the same or different cells. Hence, handover occurs frequently, and overhead of handovers becomes extremely high. Cho and others [11] introduced various handover scenarios in multihop cellular networks. Meanwhile, the effects of the RSs' deployment positions on the handover performance are also investigated in [11]. A handover method that reduces intercell handover and increases intracell handover has been proposed in [12]. The aim in [12] was to reduce the high signaling overhead and latency caused by intercell handover compared to intracell handover. Yang and others [13] proposed a handover protocol for de-centralized MR networks in which some management functions are delegated and performed by high capability RSs with the objective to reduce handover signaling delay and overhead. Lee and others [14] introduced a fast handover algorithm based on IEEE 802.16e systems.

The required changes in the MDHO and FASS handover procedures due to the deployment of RSs in the MR network infrastructure have been proposed in [15] for nine main classes of network topologies. The downlink (DL) performance of the HHO, FASS, and MDHO handover techniques in the time-division-based multihop wireless relay networks has been studied and evaluated in [16]. Sun and others [17] proposed a mechanism to transform the network topology and performance metrics, such as number of hops, antenna configurations, and/or mobile channel conditions, into a decisive factor for considering a handover.

In summary, most of the previous literature on the handover in MR networks has been devoted to evaluate the performance, to study the required handover procedure changes due to the RS' involvement, and/or to reduce the overhead and latency of HHO, FASS, and conventional MDHO. In the conventional MDHO, the MS receives only the simultaneous transmissions of the diversity set members whether the diversity set members are BS and RS, two RSs, or two BSs. In fact, in the conventional MDHO where the diversity set members are BS and RS, the signal transmitted by the BS in the first phase is not received by the MS even though the MS is idle in this phase.

However, cooperative relaying has emerged as a new form of diversity in wireless networks in which some terminals serve as relays for another terminal's transmission [5]-[8], [18], [19]. In [8], the MS overhears transmission from a BS to an RS to achieve higher spatial diversity gain or higher spatial multiplexing gain. Even though these works studied diversity in

multihop networks, the main interest of using multihop concepts is not in cellular networks but in ad hoc networks. To the authors' knowledge, most of the previous works on cooperative relaying have been carried out in a single cell noise-limited environment and for fixed users with BS and RSs as the diversity set members. Furthermore, since cooperative relaying is not limited to the overlapped coverage areas of the access stations, cooperation may increase the resource consumptions.

In this study, we propose an efficient MDHO technique for time-division-based interference-limited multihop wireless relay networks. In the proposed MDHO, when the diversity set members are BS and RS, the MS receives the signal transmitted by the BS during the first phase. During the second phase, it also receives the simultaneous transmissions of the BS and RS. On the other hand, the proposed MDHO performs similarly as the conventional MDHO whenever two RSs or two BSs are the diversity set members of the MS. To the best of the authors' knowledge, the proposed MDHO has not been addressed in the literature yet. The performance evaluation in this study is carried out for multicell interference-limited environment and for users with high mobility speeds. The performance analysis metrics are the average DL CINR, the average DL spectral efficiency, and the average service outage probability.

The rest of this paper is organized as follows. Section II describes briefly the simulated handover techniques of IEEE 802.16j. The baseband channel and signal models are described in section III. The simulation model is described in section IV. The simulation results and discussions are presented in section V. Finally, the conclusions are provided in section VI.

**Notation:** The term  $E[\cdot]$  denotes the expectation operator. The superscript  $*$  stands for conjugate operation, and the subscript  $i$  where  $i \in \{1, 2\}$  represents the phase index. The term  $\mathcal{CN}(0, a)$  represents a circularly symmetric complex Gaussian random variable with zero mean and variance  $a$ .

## II. Simulated Handover Techniques

In this section, we briefly describe the simulated handover techniques of IEEE 802.16j multihop relay networks.

### 1. Hard Handover

In HHO, the MS communicates only with one BS/RS at any one time. A connection with an old serving BS/RS is broken before the connection to a new target BS/RS is established. Handover is executed after the signal strength from the target station exceeds the signal strength from the current serving station. The HHO is the simplest scheme for the practical operation since it is only based on signal strength from different

BSs/RSs.

## 2. Fast Access Station Switching

For an MS and a BS that support FASS, the MS and the BS maintain a list of the access stations that are involved in FASS with the MS. This list is called a diversity set. The access station can be a BS or RS. The MS continuously monitors the access stations in the diversity set and defines an anchor station. The anchor station is the only BS/RS of the diversity set that MS communicates with for all uplink and downlink messages including management and traffic connections. The anchor station can be changed from frame to frame depending on access station selection scheme.

## 3. Macrodiversity Handover

For an MS and a BS that support MDHO, the diversity set is maintained by the MS and BS similarly as in FASS. The MS communicates with all access stations in the diversity set. Since the MR network infrastructure includes the RSs, different intracell and intercell MDHO scenarios can occur which can be further classified into two main cases: case 1 and case 2. Case 1 comprises the MDHO scenarios in which BS and RS are the diversity set members of the MS. Case 2 corresponds to the MDHO scenarios in which the diversity set members are two RSs or two BSs. In this study, the diversity set size is assumed to be 2. We highlight here that the diversity set members in case 1 and case 2 of the proposed MDHO are similar to those in case 1 and case 2 of the conventional MDHO, respectively.

### A. Case 1 of Conventional MDHO

Only RS receives the transmission of the BS during the first phase. In the second phase, both BS and RS transmit synchronously to the MS by using the same radio resource. At the end of the two phases, the MS combines the signals received from BS and RS via maximal-ratio combining (MRC). Since the MS does not receive any signal during the first phase, the modulation and coding scheme (MCS) in each phase is adjusted independently.

### B. Case 1 of Proposed MDHO

Both MS and RS receive the transmission of the BS during the first phase. In the second phase, both BS and RS transmit synchronously to the MS by using the same radio resource. At the end of the two phases, the MS combines the signals received during the first phase and the second phase using MRC. Since the MS receives during both phases in this case, the same MCS should be used over the two phases.

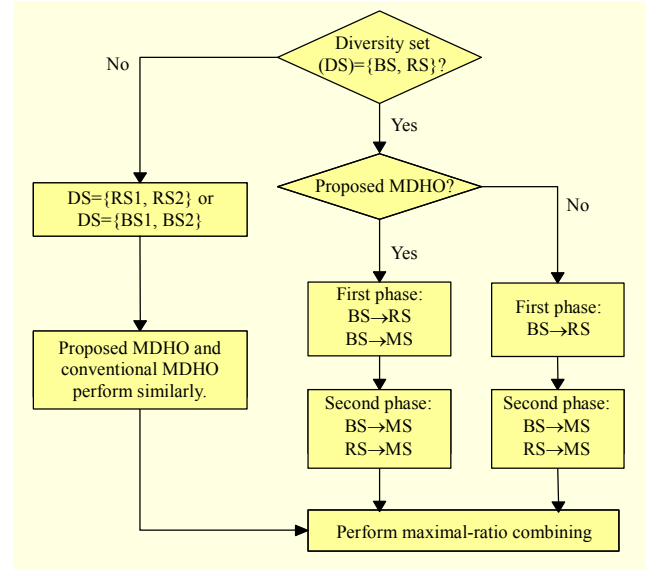


Fig. 1. Transmission sequences of conventional and proposed MDHO techniques. A → B denotes data communications between terminals A and B.

### C. Case 2 of Conventional MDHO and Proposed MDHO

In this case, the diversity set consists of two RSs, such as RS1 and RS2, or two BSs, such as BS1 and BS2. However, the proposed MDHO and the conventional MDHO perform similarly in this case. If the diversity set members are RS1 and RS2, the transmission sequences are as follows. In the first phase, RS1 and RS2 receive the transmission of the BS, whereas, in the second phase, both RS1 and RS2 transmit synchronously to the MS by using the same radio resource. At the end of the two phases, the MS combines the signals received from RS1 and RS2 via MRC. As the MS does not receive any signal during the first phase, the MCS in the first phase and the second phase are adjusted independently according to the average received CINR at the RS and the MS, respectively. However, when the diversity set members are BS1 and BS2, both BS1 and BS2 transmit simultaneously to the MS by using the same radio resource. The MS combines the signal received from BS1 and BS2 using MRC.

Figure 1 summarizes the transmission sequences of the conventional MDHO and the proposed MDHO during the two phases.

## III. Baseband Channel and Signal Model

In this analysis, it is assumed that the RS uses decode-and-forward (DF)<sup>1)</sup> where the signal received from the source terminal is demodulated and decoded before retransmission.

<sup>1)</sup> Note that this study can be extended to the case where forwarding schemes other than DF are used by the RS.

The source is a BS, while the destination is an MS. The diversity set members are assumed to be perfectly synchronized, and the MS is assumed to be equipped with multiple receive antennas [20]. The complex-valued constellation point transmitted by the source terminal at a given subcarrier during phase  $i$  is denoted as  $x_i$ . The mean and the variance of  $x_i$  are equal to  $E[x_i]=0$  and  $E[|x_i|^2]=1$ , respectively, for  $i=1, 2$ .<sup>2)</sup>

## 1. Baseband Channel

Let  $h_{SR,i}$ ,  $h_{SD,i}$ , and  $h_{RD,i}$  denote the channel coefficients of a given subcarrier during phase  $i$  for source-to-relay ( $S \rightarrow R$ ), source-to-destination ( $S \rightarrow D$ ), and relay-to-destination ( $R \rightarrow D$ ) links with variances  $\sigma_{SR}^2$ ,  $\sigma_{SD}^2$ , and  $\sigma_{RD}^2$ , respectively. The term  $\sigma_{AB}^2$  accounts for path loss and lognormal shadow fading of  $A \rightarrow B$  link. Since the shadow fading changes very slowly, the average channel coefficients are assumed to remain fixed during the first phase and the second phase. At a given subcarrier,  $n_{R,i} \sim \mathcal{CN}(0, I_{R,i})$  and  $n_{D,i} \sim \mathcal{CN}(0, I_{D,i})$  capture the effects of the additive white Gaussian noise (AWGN)-plus-interference samples observed during phase  $i$  at the relay and the destination terminals, respectively.  $E_S$  and  $E_R$  denote the fixed transmit signal power at a given subcarrier of the source and relay terminals, respectively. Since the handover is based on the large scale fading and due to the mobility of users, only the average CINR is of particular interest. Hence, at a given subcarrier, the average CINR of  $S \rightarrow R$ ,  $S \rightarrow D$ , and  $R \rightarrow D$  links are given by  $\bar{\gamma}_{SR,1} = \sigma_{SR}^2 E_S / I_{R,1}$ ,  $\bar{\gamma}_{SD,i} = \sigma_{SD}^2 E_S / I_{D,i}$ , and  $\bar{\gamma}_{RD,2} = \sigma_{RD}^2 E_R / I_{D,2}$ , respectively.

## 2. Input-Output Relations for Considered Handover Techniques

In this subsection, the input-output relations and the average post-processing CINR are derived for the considered handover techniques. The conventional MDHO is essentially a derivative of the proposed MDHO. We shall, therefore, first provide the input-output relations and derive the average post-processing CINR for the proposed MDHO and then specialize to the conventional MDHO. The average CINR is then provided for FASS and HHO.

### A. Case 1 of Proposed MDHO

The signal received at the destination terminal in the first phase is given by

$$y_{SD,1} = \sqrt{E_S} h_{SD,1} x_1 + n_{D,1}. \quad (1)$$

<sup>2)</sup> The subscripts 1 and 2 denote the first phase and second phase, respectively.

The signal received at the relay terminal in the first phase is given by

$$y_{SR,1} = \sqrt{E_S} h_{SR,1} x_1 + n_{R,1}. \quad (2)$$

Assuming that the relay terminal correctly decodes the signals transmitted by the source terminal during the first phase; the signals received at the destination terminal from the source and relay terminals during the second phase are

$$\begin{aligned} y_{SD,2} &= \sqrt{E_S} h_{SD,2} x_2 + n_{D,2}, \\ y_{RD,2} &= \sqrt{E_R} h_{RD,2} x_1 + n_{D,2}. \end{aligned} \quad (3)$$

Assuming that the MS has perfect knowledge of channel coefficients  $h_{SD,i}$  and  $h_{RD,2}$ , the MS performs perfect MRC wherein the weight of each diversity branch is the conjugate of the branch channel coefficient normalized to the noise-plus-interference variance of that branch [21]. Thus, the signal at the output of the maximal-ratio combiner can be given by

$$y_{MRC} = \frac{\sqrt{E_S} h_{SD,1}^*}{I_{D,1}} y_{SD,1} + \frac{\sqrt{E_S} h_{SD,2}^*}{I_{D,2}} y_{SD,2} + \frac{\sqrt{E_R} h_{RD,2}^*}{I_{D,2}} y_{RD,2}. \quad (4)$$

Hence, at a given subcarrier, the average post-processing CINR obtained at the MS after MRC can be derived from (4) as

$$\bar{\gamma}_{\text{post}}^{\text{PropMDHO1}} = \bar{\gamma}_{SD,1} + \bar{\gamma}_{SD,2} + \bar{\gamma}_{RD,2}. \quad (5)$$

It should be noted that the relationship between  $\bar{\gamma}_{SD,1}$  and  $\bar{\gamma}_{SD,2}$  can be given by

$$\bar{\gamma}_{SD,2} = \rho \bar{\gamma}_{SD,1}, \quad (6)$$

where  $\rho = I_{D,1} / I_{D,2}$  is the ratio of the variance of the noise-plus-interference during the first phase to the variance of the noise-plus-interference during the second phase.

In this case, for both first phase and second phase, the MCS is determined based on  $\min\{\bar{\gamma}_{SR,1}, \bar{\gamma}_{\text{post}}^{\text{PropMDHO1}}\}$ .

### B. Case 2 of Proposed MDHO

If the diversity set members are two RSs, that is, RS1 and RS2, the signals received at the relay terminals in the first phase are identical to that for case 1 and are, thus, calculated by (2). Assuming that RS1 and RS2 correctly decode the signals transmitted by the source terminal during the first phase, the signals received at the destination terminal during the second phase are given by

$$\begin{aligned} y_{R1D,2} &= \sqrt{E_R} h_{R1D,2} x_1 + n_{D,2}, \\ y_{R2D,2} &= \sqrt{E_R} h_{R2D,2} x_1 + n_{D,2}. \end{aligned} \quad (7)$$

Similarly, at a given subcarrier, the average post-processing CINR achieved at the MS after MRC can be derived as

$$\bar{\gamma}_{\text{post}}^{\text{case2r}} = \bar{\gamma}_{\text{R1D},2} + \bar{\gamma}_{\text{R2D},2}, \quad (8)$$

where  $\bar{\gamma}_{\text{RiD},2}$  is the average CINR of the  $\text{RSi} \rightarrow \text{MS}$  link.

In this case, the MCS is decided based on  $\min\{\bar{\gamma}_{\text{SR1},1}, \bar{\gamma}_{\text{SR2},1}\}$  in the first phase, whereas it is chosen based on  $\bar{\gamma}_{\text{post}}^{\text{case2r}}$  in the second phase, where  $\bar{\gamma}_{\text{SRi},1}$  is the average CINR of the  $\text{BS} \rightarrow \text{RSi}$  link.

However, if the diversity set members are two BSs, that is, BS1 and BS2, the average post-processing CINR at the MS after MRC can be derived as

$$\bar{\gamma}_{\text{post}}^{\text{case2b}} = \bar{\gamma}_{\text{S1D},2} + \bar{\gamma}_{\text{S2D},2}, \quad (9)$$

where  $\bar{\gamma}_{\text{SiD},2}$  is the average CINR of the  $\text{BSi} \rightarrow \text{MS}$  link.

In this case, the MCS is adjusted based on  $\bar{\gamma}_{\text{post}}^{\text{case2b}}$ .

### C. Conventional MDHO

The conventional MDHO is a subset of the proposed MDHO. Thus, the input-output relations, the average post-processing CINR, and the MCS's selection for case 2 of the conventional MDHO are exactly the same as that for case 2 of the proposed MDHO. Case 1 of the conventional MDHO is similar to that of the proposed MDHO except that the MS does not receive the signal transmitted by the BS during the first phase. Hence, at a given subcarrier, the average post-processing CINR for case 1 of the conventional MDHO achieved at the MS after MRC is derived as

$$\bar{\gamma}_{\text{post}}^{\text{ConvMDHO1}} = \bar{\gamma}_{\text{SD},2} + \bar{\gamma}_{\text{RD},2}. \quad (10)$$

In this case, the MCS is selected based on  $\bar{\gamma}_{\text{SR},1}$  in the first phase, whereas it is decided based on  $\bar{\gamma}_{\text{post}}^{\text{ConvMDHO1}}$  in the second phase.

### D. Fast Access Station Switching

In FASS, if the anchor station is a BS, the average CINR at the MS is equal to  $\bar{\gamma}_{\text{SD},2}$ . Otherwise, the anchor station is an RS and the average CINR at the MS is equal to  $\bar{\gamma}_{\text{RD},2}$ .

### E. Hard Handover

During HHO, if the MS is connected to the BS, the average CINR at the MS is equal to  $\bar{\gamma}_{\text{SD},2}$ . Otherwise, the average CINR at the MS equals  $\bar{\gamma}_{\text{RD},2}$ .

In the rest of this section, we present some numerical results to evaluate and compare the performance of the proposed MDHO and conventional MDHO. Since the proposed MDHO and conventional MDHO differ mainly in case 1, while they perform similarly in case 2, the performance comparison in this section is conducted for case 1 only using (5) and (10) derived in the previous subsections.

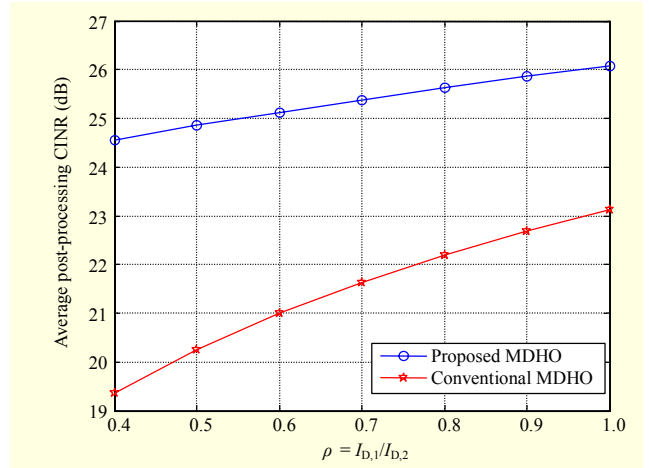


Fig. 2. Average post-processing CINR for proposed MDHO and conventional MDHO at  $\bar{\gamma}_{\text{SD},1} = 20$  dB and  $\bar{\gamma}_{\text{RD},2} = 8$  dB as a function of  $\rho$ .

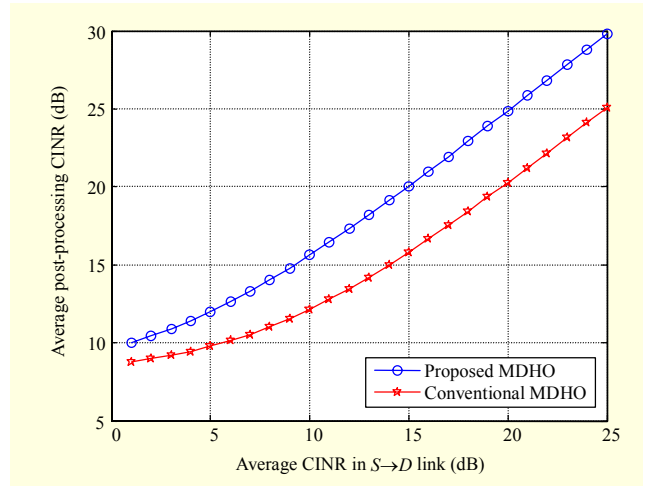


Fig. 3. Average post-processing CINR for proposed MDHO and conventional MDHO at  $\bar{\gamma}_{\text{RD},2} = 11$  dB and  $\rho = 0.5$  as a function of  $\bar{\gamma}_{\text{SD},2}$ .

Figure 2 presents the average post-processing DL CINR of the proposed MDHO and conventional MDHO with  $\bar{\gamma}_{\text{SD},1} = 20$  dB and  $\bar{\gamma}_{\text{RD},2} = 8$  dB for different values of  $\rho$ . The results in Fig. 2 show that the proposed MDHO can significantly improve the average post-processing CINR compared to the conventional MDHO. However, the performance difference between the proposed MDHO and conventional MDHO decreases as  $\rho$  increases. This is because the interference in the first phase closes to the interference in the second phase, and thus the difference between  $\bar{\gamma}_{\text{SD},1}$  and  $\bar{\gamma}_{\text{SD},2}$  decreases as  $\rho$  increases. Furthermore, the proposed MDHO achieves the lowest CINR gain over the conventional MDHO at  $\rho = 1$ , which also



corresponds to the noise-limited environment.

In Fig. 3, we fix  $\bar{\gamma}_{RD,2} = 11$  dB and  $\rho = 0.5$  and plot the average post-processing CINR as a function of  $\bar{\gamma}_{SD,2}$ . The results in this figure show that the proposed MDHO has better average post-processing CINR compared to the conventional MDHO. The proposed MDHO offers a significant CINR gain of as much as 4.71 dB over the conventional MDHO. The maximum CINR gain of the proposed MDHO over the conventional MDHO is achieved when  $\bar{\gamma}_{SD,2}$  is much stronger than  $\bar{\gamma}_{RD,2}$ . This is due to the fact that when  $\bar{\gamma}_{SD,2}$  is much stronger than  $\bar{\gamma}_{RD,2}$ , the  $\bar{\gamma}_{SD,1}$  becomes the dominant link according to (6) which, as a result, increases the gain of the proposed MDHO over the conventional MDHO. An interesting observation from Fig. 3 is that when  $\bar{\gamma}_{RD,2}$  is much stronger than  $\bar{\gamma}_{SD,2}$ , the CINR difference between the proposed MDHO and the conventional MDHO is small. In fact, when  $\bar{\gamma}_{RD,2}$  is much higher than  $\bar{\gamma}_{SD,2}$ , the  $R \rightarrow D$  link becomes the dominant link, while the effects of the  $S \rightarrow D$  links are marginal and thus the difference between the two MDHO techniques is small.

#### IV. Simulation Model

Performance evaluation is carried out using a system-level simulator developed in MATLAB. We consider the downlink of IEEE 802.16j TDD-OFDMA-based interference-limited two-hop wireless relay network that consists of seven hexagonal cells with a wrap-around structure. The cell radius is 1,400 m. Each cell has one BS located at its center and six fixed RSs. Each RS is located on the line that connects the center of the cell to one of the six cell vertices at a 2/3 position between BS and cell boundary. We assume that 30 MSs are distributed uniformly throughout each cell and move along a direction randomly selected in each frame. Meanwhile, the full-buffer traffic model is considered wherein each MS always has data to send or receive in the buffer [22]. The MDHO and FASS algorithm is implemented as described in 3GPP TR 25.922 [23] with a diversity set size of 2. The MDHO threshold used to add an access station to the diversity set is 3 dB. The effective isotropic radiated powers (EIRPs) from the BS and RS are fixed as 57 dBm and 45 dBm, respectively. Perfect time and frequency synchronizations are assumed. The mobile WiMAX system profile defined by WiMAX Forum is used as a reference [24], [25].

The system operates at a carrier frequency of 2.5 GHz. Frames have 5 ms duration. The scalable OFDMA mode with 1,024 subcarriers and a system bandwidth of 10 MHz are considered. A basic resource allocation unit is given by a

Table 1. Modulation and coding schemes' parameters.

MCS	Modulation	Code rate	Spectral efficiency (bps/Hz)	Required CINR (dB)
1	BPSK	1/2	0.5	3.0
2	QPSK	1/2	1	6.0
3	QPSK	3/4	1.5	8.5
4	16-QAM	1/2	2	11.5
5	16-QAM	3/4	3	15.0
6	64-QAM	2/3	4	19.0
7	64-QAM	3/4	4.5	21.0
8	64-QAM	5/6	5	23.0
9	64-QAM	1	6	28.0

subchannel, defined as a set of 48 subcarriers selected by the diversity mode in order to provide frequency diversity and average the intercell interference. In this case, the CINR of each subchannel is determined by taking the average of all corresponding subcarriers. Each user is allocated one subchannel.

We use adaptive modulation and coding (AMC) for each subchannel and for each frame which requires channel state information (CSI) at the BS. The AMC is done at the BS in order to have centralized control. Due to the mobility of users with high speeds, the channel changes rapidly, and thus using the instantaneous CINR as CSI is not feasible. In fact, in this study, we use the average CINR as CSI to decide on the appropriate MCS. For each subchannel, however, it is assumed that the CSI is accurately estimated at the MS and the RS and fed back to the BS at the end of each uplink subframe using the fast feedback channel quality indicator channel. Based on the received CSI, the BS determines the MCS suitable for each of the  $S \rightarrow R$ ,  $S \rightarrow D$ , and  $R \rightarrow D$  links. It is also assumed that no delay or transmission errors can occur in the feedback channel. The required CINR to achieve a target bit error rate of  $10^{-6}$  and the spectral efficiency for the simulated MCSs are given in Table 1. It should be noted that the spectral efficiency in this study is the average correctly received information-bits/sec/Hz (bps/Hz) of the MCS used to deliver the data to the MS. For instance, if the achieved average CINR of the MS is 20 dB, 64-QAM with code rate of 2/3 is selected according to Table 1, and hence the spectral efficiency in this case is  $6 \times (2/3) = 4$  bps/Hz.

##### 1. Propagation and Interference Models

The suburban macrocellular environment is assumed. The relay link between the BS and the RS is assumed to be reliable

and in line-of-sight (LOS), while the access links between the BS and the MS and between the RS and the MS are in non-LOS (NLOS). The LOS assumption can be practically realized by placing RSs at a carefully selected location, such as on the roof of a building. We consider the LOS and NLOS COST231 W-I models for the desired and interfering relay links, respectively [26]. On the other hand, we consider the COST231 Hata model for the NLOS access links between the BS and the MS and between the RS and the MS [27], [28].

Shadowing is modeled as a lognormal random variable with zero mean and standard deviations of 8 dB for the access links and 3.4 dB for the relay links. The temporal correlation of the shadowing is modeled with a decorrelation distance of 20 m [22].

In this study, only the cochannel interference is taken into account in the performance evaluation. An orthogonal allocation scheme is considered in which no subchannels can be shared among the MSs directly served by the BS and those served by RSs. Thus, we assume zero intracell interference and that only intercell interference exists. It is assumed that all subcarriers are assigned in every cell at the same time. During the first phase of all handover techniques, the interference at a given subcarrier  $k$  comes from BSs only. During the second phase of MDHO and at a given subcarrier  $k$ , the access links intercell interference may be due to either the simultaneous transmissions of BS and one of the RSs, simultaneous transmissions of two RSs, transmission of BS only or transmission of RS only. This interference depends on the allocation of subcarrier  $k$  in the other cell. For FASS, the interference is similar to that for MDHO except that there are no simultaneous transmissions during the second phase; and the interference comes from either the BS or RS. For HHO, the interference comes from either the BS or RS from all surrounding cells. As far as the relay link is concerned, the intercell interference is caused by the transmissions of the cochannel BSs. In order to model the intercell interference for MDHO, FASS, and HHO, the interference model developed in [29] is adapted.

Thus, the average total interference of each subcarrier  $k$  for a HHO user  $u$  can be written as

$$I_{\text{total},u}^k = \sum_{j \in \Phi_j} I_{j,u}^k + P_N, \quad (11)$$

where  $I_{j,u}^k$  is the average interference caused by cell  $j$  to user  $u$  at subcarrier  $k$ ,  $\Phi_j$  is the set of interfering cells, and  $P_N$  is the receiver noise.

However, when user  $u$  is in MDHO or FASS, the average total interference of each subcarrier  $k$  can be expressed as

$$I_{\text{total},u}^k = \sum_{j \in (\Phi_j - \Phi_{\text{DS}})} I_{j,u}^k + P_N, \quad (12)$$

where  $\Phi_{\text{DS}}$  denotes the cells of the diversity set members of user  $u$ .

## 2. Implementation Aspects for the Proposed MDHO

The proposed MDHO is mainly operated on the BS. Thus, all BSs should be fully aware of the topology (number of hops) of the access stations constituting the diversity set of the MS in order to schedule the diversity set members and the MS accordingly. The topology information may be exchanged within the RS network entry procedures using ranging request/response messages. The BS is also aware of the topology information update due to events such as mobility. However, the BS might obtain or update the topology information of its associated RSs, directly or indirectly, through wireless relay links. In contrast, for BS to BS communications, the topology information might be obtained over the backbone network [4]. The BS scheduler then allocates the radio resources (symbol in the time domain and subchannel in the frequency domain) to the diversity set members and the MS depending on the MDHO scenario. Both the RS and the MS are notified of the allocated resources. In order to maintain the current MS configurations so that the IEEE 802.16e compliant MSs can handover seamlessly, existing standard procedures are used to inform the MS about its allocated data regions during the first phase and/or the second phase. In fact, in case 1 of the proposed MDHO, in order to notify the MS of its data regions, the BS can use the DL medium access protocol (DL-MAP) information elements (IEs) considered in the IEEE 802.16e standard for MDHO and multiple-input multiple-output (MIMO) which is denoted as Macro\_MIMO operation [30]. Thus, the BS uses the Macro\_MIMO\_DL\_Basic\_IE ( ) and MIMO\_in\_another\_BS\_IE ( ) defined for Macro\_MIMO operation to notifying the MS. However, in case 2 of the proposed MDHO as well as in case 1 and case 2 of the conventional MDHO, the BS uses the DL-MAP IEs considered in the standard for the MDHO to notify the MS of the allocated data regions. In fact, the HO\_Anchor\_Active\_DL\_MAP\_IE ( ) and HO\_Active\_Anchor\_DL\_MAP\_IE ( ) messages are used for the MS notification.

## V. Results and Discussion

Figure 4 illustrates the average percentage of users in case 1 of MDHO and the average percentage of users in case 2 of MDHO from the total number of users at different MS speeds. The combination of the percentages of case 1 and case 2 represents the percentage of users in the MDHO regions or the total MDHO probability. As can be seen from Fig. 4, the total MDHO probability increases as MS speed increases. In

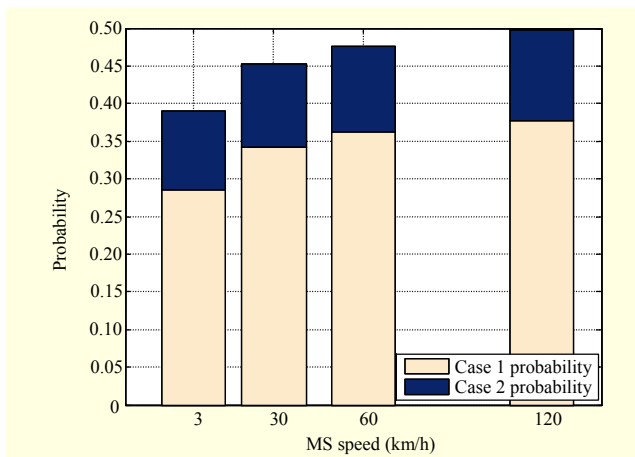


Fig. 4. Percentages of users being in case 1 and case 2 of MDHO from the total number of users at different MS speeds.

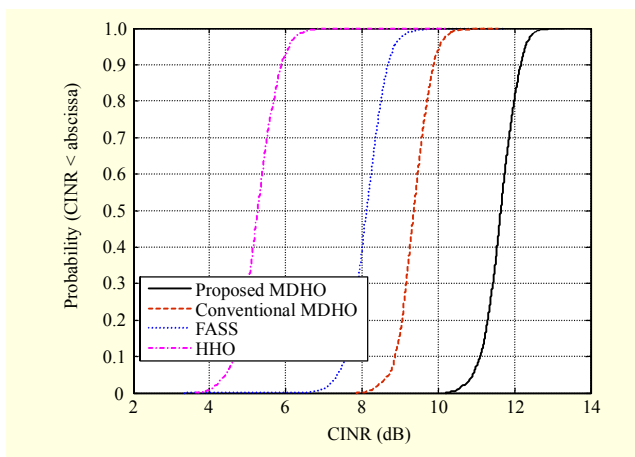


Fig. 5. CDF of average DL CINR at MS speed of 3 km/h.

addition, the percentage of case 1 is always much higher than the percentage of case 2. This could be explained by noting that the EIRP of the BS is much higher than that of RS and EIRP values are the same at RSs. Consequently, the BS has the highest priority to be included into the diversity set of the MS. However, as the MS speed increases, the MS crosses the overlapping cells coverage areas more frequently which increases the overall MDHO probability. Since case 1 represents most of the MDHO cases, any enhancement proposed to the case 1 will result in significant improvements to the performance of MDHO. This shows the importance of our proposed MDHO.

Figure 5 presents the CDF of the average DL CINR for the proposed MDHO, the conventional MDHO, the FASS, and the HHO techniques at an MS speed of 3 km/h. The results presented in Fig. 5 are taken for the users in the MDHO region only. In Fig. 5, it is clearly shown that the average DL CINR of the proposed MDHO is better than that of the conventional MDHO, the FASS, and the HHO. The median DL CINRs for

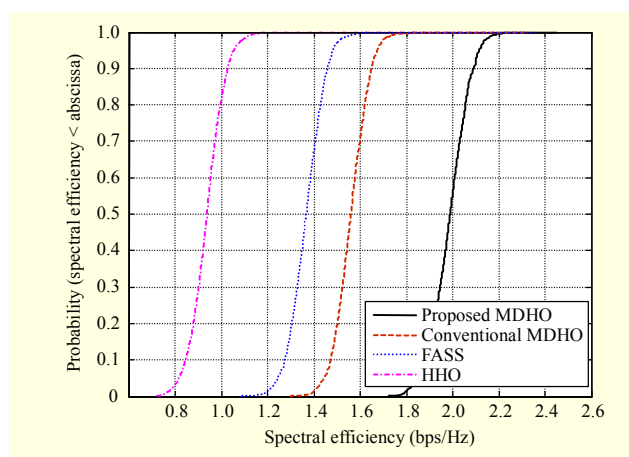


Fig. 6. CDF of average DL spectral efficiency at MS speed of 3 km/h.

the proposed MDHO, the conventional MDHO, the FASS, and the HHO are 11.64 dB, 9.36 dB, 8.12 dB, and 5.26 dB, respectively. The CINR gain of the proposed MDHO over the HHO is 6.38 dB whereas the CINR gain of the conventional MDHO over the HHO is 4.1 dB. Moreover, in order to have a fair comparison with the theoretical results presented in Fig. 3, for the users being in the case 1 of MDHO, the CINR gain of the proposed MDHO over the conventional MDHO is 3.11 dB. Comparing these simulation results with the theoretical results presented in Fig. 3, it is clear that, in both simulation and theoretical results, the proposed MDHO outperforms the conventional MDHO. However, the achieved simulation gain is lower than the maximum achieved theoretical gain because in the simulation the strongest access station in the diversity set and the interference ratio  $\rho$  depend on the locations of the MSs in the cells.

The CDF of the average DL spectral efficiency for proposed MDHO, conventional MDHO, FASS, and HHO at MS speed of 3 km/h is illustrated in the results of Fig. 6. The results presented in Fig. 6 are taken for the users in the MDHO region only. From this figure, we can find that the proposed MDHO provides the highest spectral efficiency among the considered handover techniques. In fact, the median DL spectral efficiency of the proposed MDHO, the conventional MDHO, the FASS, and the HHO are 1.99 bps/Hz, 1.56 bps/Hz, 1.37 bps/Hz, and 0.94 bps/Hz, respectively. The proposed MDHO offers spectral efficiency gains of as much as 0.43 bps/Hz, 0.62 bps/Hz, and 1.05 bps/Hz over the conventional MDHO, the FASS, and the HHO, respectively.

Figure 7 illustrates the probability of selecting an MCS with a specific spectral efficiency at a pedestrian MS speed of 3 km/h. The results in this figure are taken for all MSs. Clearly, for all handover techniques, the lower spectral efficiency MCSs are used more often than the higher spectral efficiency



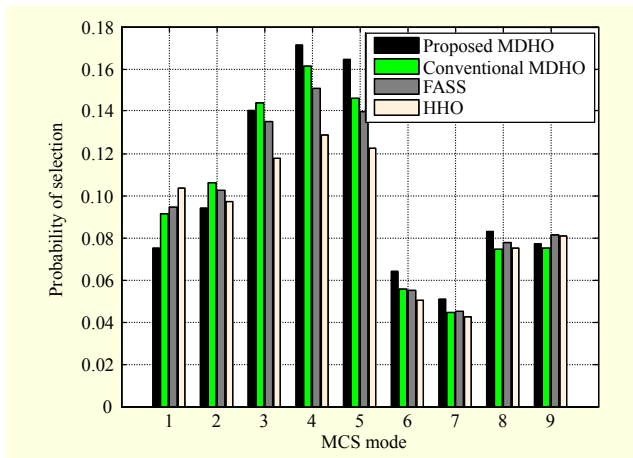


Fig. 7. Selection probability of different MCSs at MS speed of 3 km/h.

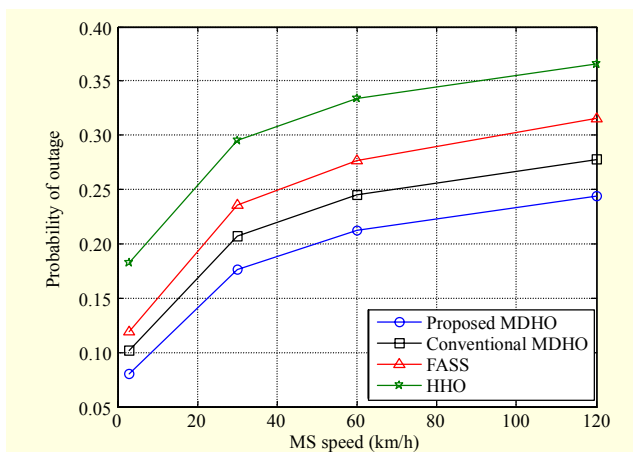


Fig. 8. Service outage probability vs. MS speeds.

MCSs. This is due to the various channel impairments experienced by the MSs in the interference-limited environment.

A service outage probability is defined as a probability that the received CINR does not meet the required CINR (3 dB from Table 1) to support the minimum MCS level (that is, BPSK with 1/2 coding rate). Figure 8 shows the average service outage probability of the various handover techniques at MS speeds of 3 km/h, 30 km/h, 60 km/h, and 120 km/h, having taken into account all MSs. The results in this figure show that the proposed MDHO has the lowest outage probability while the HHO has the highest outage probability. In addition, the outage probability increases as the MS speed increases. At a pedestrian MS speed of 3 km/h and for a total number of 210 users, about 38 users, 25 users, 21 users, and 17 users are in outage in case of HHO, FASS, conventional MDHO, and proposed MDHO, respectively. On the other hand, at a vehicular MS speed of 120 km/h and for a total number 210 MSs, about 77 users, 66 users, 58 users, and 51

users, are in outage in case of HHO, FASS, conventional MDHO, and proposed MDHO, respectively.

## VI. Conclusion

In this paper, we proposed an efficient MDHO technique for time-division-based interference-limited IEEE 802.16j multihop wireless relay networks. For each of the considered handover techniques, we derived the input-output relations and the average post-processing DL CINR. Evaluation results showed that the proposed MDHO significantly outperforms the conventional MDHO in terms of the average DL CINR, the average DL spectral efficiency, and the service outage probability. The proposed MDHO offers a CINR gain and a spectral efficiency gain of 4.71 dB and 0.43 bps/Hz, respectively, over the conventional MDHO; also, 6.38 dB and 1.1 bps/Hz, respectively, over the HHO. However, the performance gain of the proposed MDHO over the conventional MDHO increases as the CINRs in the  $S \rightarrow D$  links increase compared to that in the  $R \rightarrow D$  link, or the interference ratio  $\rho$  decreases. The lower spectral efficiency MCS modes are used more often compared to the higher spectral efficiency MCS modes. The focus of this paper was on the spatial diversity gain achieved by the proposed MDHO where the same data is transmitted during the two phases. However, the spectral efficiency could be further improved by considering the spatial multiplexing gain of the proposed MDHO that needs further investigation and is left for future work. Further investigations on the capacity of each handover technique should also be carried out. Finally, the enhancement in the system performance by using the proposed MDHO comes at the cost of increased complexity. This is due to the fact that in case 1 of the proposed MDHO, the MS needs to buffer the transmission of the BS occurs during the first phase to be diversity combined with the simultaneous transmissions of the BS and RS occur during the second phase. This incurs more processing and hence more battery power consumption compared to the conventional MDHO.

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**Jamil Sultan** received the BSc in electronic and communication engineering from the University of Technology, Iraq, in 1999. He received the MEng in computer and communication engineering from Universiti Kebangsaan Malaysia (UKM), Malaysia, in 2005. He is currently working toward the PhD in the Department of Electrical, Electronic, and Systems Engineering, UKM. His main research interests are mobile communication and wireless networking, particularly handover, power control, mobile WiMAX, and multihop relay networks.



**Mohammad Tariqul Islam** received the BSc and MSc in applied physics and electronics from the University of Dhaka, Bangladesh, in 1998 and 2000, respectively, and the PhD in telecommunication engineering from the Universiti Kebangsaan Malaysia (UKM), in 2006. He is currently working as an associate professor at the Institute of Space Science (ANGKASA), UKM. His research interests include the enabling technology for RF, antenna technology, smart antenna receivers, and MIMO systems.



**Norbahiah Misran** received her BEng in electrical, electronic, and systems engineering from the Universiti Kebangsaan Malaysia (UKM), in 1999. She completed her PhD in communication engineering at Queen's University, Belfast, UK, in 2004. She started her career as a tutor at the Department of Electrical, Electronic & Systems Engineering, UKM, in 1999. She has been a lecturer at the same university since 2004. She has been an associate professor at the UKM since 2009. Her major areas of research include antennas, RF design, wireless communication, and engineering education.



**Mahamod Ismail** joined the Department of Electrical, Electronics, and System Engineering, Universiti Kebangsaan Malaysia (UKM) in 1985 where currently he is a professor of communication engineering. He received the BSc in electrical and electronics from the University of Strathclyde, UK, in 1985, the MSc in communication engineering and digital electronics from the University of Manchester Institute of Science and Technology (UMIST), Manchester, UK, in 1987, and the PhD from the University of Bradford, UK, in 1996. He was with the first Malaysia Microsatellite TiungSat Team Engineers in Surrey Satellite Technology Ltd., UK for 9 months starting in June 1997. His research interests include mobile and satellite communication, and wireless networking, particularly radio resource management for next generation wireless communication networks. He is currently the Chair of IEEE Malaysia Section.