Link Adaptation and Selection Method for OFDM Based Wireless Relay Networks

Başak Can, Hiroyuki Yomo, and Elisabeth De Carvalho

Abstract: **We propose a link adaptation and selection method for the links constituting an orthogonal frequency division multiplexing (OFDM) based wireless relay network. The proposed link adaptation and selection method selects the forwarding, modulation, and channel coding schemes providing the highest end-to-end throughput and decides whether to use the relay or not. The link adaptation and selection is done for each sub-channel based on instantaneous signal to interference plus noise ratio (SINR) conditions in the source-to-destination, source-to-relay and relay-to-destination links. The considered forwarding schemes are amplify and forward (AF) and simple adaptive decode and forward (DF). Efficient adaptive modulation and coding decision rules are provided for various relaying schemes. The proposed end-to-end link adaptation and selection method ensures that the end-to-end throughput is always larger than or equal to that of transmissions without relay and non–adaptive relayed transmissions. Our evaluations show that over the region where relaying improves the end-to-end throughput, the DF scheme provides significant throughput gain over the AF scheme provided that the error propagation is avoided via error detection techniques. We provide a frame structure to enable the proposed link adaptation and selection method for orthogonal frequency division multiple access (OFDMA)–time division duplex relay networks based on the IEEE 802.16e standard.**

Index Terms: **Adaptive modulation and coding (AMC), amplify and forward (AF), CRC, decode and forward (DF), orthogonal frequency division multiplexing (OFDM), relay, throughput.**

I. INTRODUCTION

Multiple–antenna techniques achieved with co–located antennas, referred to as multiple-input multiple-output (MIMO) techniques, lead to an increase in the spectral efficiency of the wireless communication systems and have been extensively analyzed in the literature (e.g., [1]–[4]). MIMO techniques offer tremendous advantages such as spatial diversity, spatial multiplexing, beam-forming, space division multiplexing, interference suppression, etc. [2]. Cooperative wireless communications on the other hand have attracted a lot of attention as techniques which offer advantages similar to that of MIMO techniques even without co–located multiple antennas at a terminal [5]–[10]. In cooperative wireless communications, the information from a source is forwarded by one or several relay station(s) (RS(s)) to a destination. Since the wireless terminals cannot transmit and receive using the same radio resource [6]–[12], the communication is organized in two phases. A phase for the reception at the RS from the source terminal (first–phase) and a phase for the transmission from the RS, i.e., forwarding, to the destination terminal (second–phase) are needed. The destination terminal can obtain cooperative diversity (akin to spatial diversity) benefits via appropriately combining the received signals from the source and relay terminals. If the source–to–relay ($S \rightarrow R$) and relay–to–destination ($R \rightarrow D$) distances are smaller than the source–to–destination ($S \rightarrow D$) distance, then the path loss in the $S \rightarrow R$ and the $R \rightarrow D$ links are smaller than that of $S \rightarrow D$ link. In such a case, the destination terminal can further benefit from the reduced end-to-end path loss.

Amplify and forward (AF) and decode and forward (DF) are two main forwarding schemes which have been extensively used in cooperative wireless communications. An RS using the AF scheme amplifies and forwards (without decoding) the signal which is received from the source [7]. An RS using the DF scheme decodes, re–encodes, modulates and forwards the signal which is received from the source [7]. The performance of cooperative diversity with the AF and DF schemes depends on the signal to interference plus noise ratio (SINR) of the $S \rightarrow R$, $S \rightarrow D$, and $R \rightarrow D$ links [13]. The performance achieved with the DF scheme depends strongly on the ability of the RS to decode the received signal from the source terminal correctly. If there are errors in the decoding at the RS, then forwarding via DF causes error propagation. However, this situation can be avoided simply by detecting the erroneously received packets via cyclic redundancy check or similar measures and forwarding only when the packets are correctly received. Such a scheme is referred to as simple—adaptive decode and forward (AdDF) based relaying [12]–[14]. With this scheme, the end-to-end throughput is limited by the $S \rightarrow R$ link condition. The end-to-end throughput refers to the throughput delivered to the destination, i.e., a mobile station (MS). With AF, the noise at the RS is amplified and further propagated. For simple–AdDF, the adaptive modulation and coding (AMC) mode decision should take into account the SINR at the relay as the signal needs to be decoded correctly with high probability at the relay. However, for AF, the AMC mode decision can be based on the post-processing SINR at the destination, which might be larger than the SINR at the relay.

Erkip *et al.* analyzed adaptive modulation for coded cooperative systems achieved with DF based relaying in [13]. The coded cooperation scheme considered in [13] uses the RS whenever it can correctly decode the transmitted packets. This means that, when the detection error at the RS is negligibly small, then relaying is almost always used. However, if the SINR condition in the direct link allows a sufficiently high AMC mode, then direct transmission might outperform relay based transmission even if the $S \rightarrow R$ link condition is very good.[1] This is due

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[1] We prove this statement in the following sections of this paper.

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to the fact that relaying necessitates additional radio resources as compared to transmission without (w/o) relay. Hence, it is of utmost importance to consider the end-to-end throughput to decide on [15] proposed to make such a decision based on average channel conditions in the $S \rightarrow R$, $S \rightarrow D$, and $R \rightarrow D$ links. The design is made for flat fading channel conditions in the $S \rightarrow D$ and $S \rightarrow R$ links and a non fading line of sight channel condition in the $R \rightarrow D$ link. For the design rules to decide whether to use the relay or not, the authors claimed that due to high complexity simple decision rules cannot be developed to take into account small scale fading in all the links constituting a relay network. However, simple decision rules can be developed with the preparation of lookup tables which we provide in this paper. Such lookup tables allow decisions for the AMC modes to be used as well. In [16], Laneman *et al.* proposed a selection relaying scheme developed for frequency flat channels. The proposed scheme selects relaying only when the signal to noise ratio (SNR) in the $S \rightarrow R$ link is above a threshold which is determined solely by the channel capacity of the $S \rightarrow R$ link. When relaying is selected, either AF or DF based relaying is used. The channel conditions in the $R \rightarrow D$ and $S \rightarrow D$ links are not considered in the proposed selection relaying in [16]. As a hybrid forwarding scheme, the study in [17] proposed a hybrid space–time coding scheme for cooperative relaying via frequency flat channels. The relays perform DF based relaying if instantaneous SNR in the $S \rightarrow R$ link is high, otherwise relays use AF. In summary, the aforementioned works have not taken into account all the instantaneous fading coefficients in a relay network and the end-to-end throughput performance at the same time. Consequently, these link adaptation and selection mechanisms cannot guarantee that the end-to-end throughput performance is not worse than that of w/o relay and non–adaptive relayed transmissions where the relay is always used.

In this study, we propose an end-to-end link adaptation and selection method for orthogonal frequency division multiplexing (OFDM) based wireless relay networks. Relaying is selected (with the best forwarding scheme) only when it can improve the end-to-end throughput as compared to that of w/o relay transmissions. This selection is made according to the instantaneous SINR conditions of the links constituting the relay network. The forwarding schemes considered in this study are AF and simple–AdDF.[2] The proposed link adaptation and selection method dynamically selects the best transmission method at each sub-channel. A sub-channel is comprised of several contiguous subcarriers with approximately equal channel coefficients. Simple and efficient rules for

1. end-to-end link adaptation with AMC
2. link selection (transmission with or w/o relay)

are provided based on lookup tables. A frame structure to enable the proposed link adaptation and selection method in an orthogonal frequency division multiple access (OFDMA)–time division duplex (TDD) based cellular wireless relay network has been provided.

The structure of the paper is as follows. Section II describes the system model. In Section III, the end-to-end throughput performance of the simple–AdDF, AF, and w/o relay schemes are presented and compared to each other. We present our proposal for an end-to-end link adaptation and selection method for wireless relay networks in Section IV and show its superior performance. Conclusions and future works are drawn in Section V.

Notation: The superscripts ^{H} and * stand for transpose conjugate and conjugate operations, respectively. Bold uppercase letters represent matrices and bold lower case letters represent vectors. The term $\mathcal{E}$ denotes the expectation operation. The subscript i, $i \in \{1, 2, ..., N\}$, represents the subcarrier index where N represents the total number of sub-carriers in the OFDM system. The index n where $n \in \{0, 1, 2, ...\}$ represents the OFDM symbol index in time domain. The term $\mathcal{CN}(0, b)$ represents a zero mean circularly symmetric complex gaussian random variable with mean 0 and variance b.

II. SYSTEM MODEL

Our analysis is based on the following system model. An infrastructure based RS which is used exclusively for relaying is considered. The analysis in this study can be extended to multi–relay scenarios. We consider single antenna terminals and two–phase (i.e., two–hop) relaying. We consider downlink transmissions in a TDD-OFDM based cellular wireless relay network and we take IEEE 802.16e system as a reference [18]. The source is a base station (BS) and the destination is an MS. We consider mobile users with relatively low speed. For such users, the channel remains unchanged for the duration of a frame which consists of a certain number of OFDM symbols. Therefore, the link adaptations according to the obtained channel state information (e.g., instantaneous SINR) are feasible and effective. Hence, we consider transmissions with band–AMC mode of operation which requires channel state information at the BS [18]. Since users with relatively low speed are considered, we use instantaneous SINR as channel state information. The design of adaptation methods for high-mobility users requires further considerations, such as impact of imperfect channel state information, the form of channel state information to be used (e.g., [19]), etc. We decide on the AMC mode and the best transmission method per sub-channel. The throughput is defined as the number of payload bits per second per hertz that are received correctly at the corresponding receiver. We assume that a packet is discarded if at least one bit is in error. The receivers use cyclic redundancy check to detect packet errors where it is assumed that the undetected error probability is negligibly small [20]. The modulation schemes that are considered in this paper are: Binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM. The forward error correction (FEC) is considered in the form of convolutional coding with coding rates: "1 (no–coding), 1/2, 2/3, 3/4, 5/6, 7/8" [18]. We assume that during downlink subframe no feedback is provided by the MS since it is engaged in data reception. Before the second phase starts, the RS broadcasts information on which sub-channels it could detect the packets correctly and on which sub-channels it could not. This control signaling will only be needed for simple–AdDF based relaying. In Section IV, we show that this overhead

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[2] Note that more complex forwarding schemes other than AF and simple–AdDF can be included into the framework of link adaptation and selection for wireless relay networks.

is negligibly small in a practical system setting. With simple–AdDF based relaying, cooperative transmissions are done only for the packets that are correctly decoded by the RS.[3] We do not include any automatic repeat request (ARQ). We highlight that this study can be extended to include ARQ. Since AMC is used, the power control at the transmitters does not contribute to the throughput enhancement significantly [10], [21]. Hence, throughout this study, power control at the transmitters is not considered and the average transmit energy of the source and relay terminals per subcarrier is fixed and represented by E_S and E_R, respectively.

OFDM adds a cyclic prefix to each symbol to mitigate inter symbol interference caused by multi-path propagation. If the cyclic prefix is longer than the delay spread of the wireless channel, then frequency selective fading caused by multi-path propagation can be converted into frequency flat fading at each sub-carrier. Adding a cyclic prefix to achieve this causes a small reduction in total transmission rate. Since this reduction is the same for each scheme, we do not take it into account in the throughput.

A. Baseband Channel, Noise and Interference Models

Let $h_{SR,i}$, $h_{SD,i}$, and $h_{RD,i}$ represent the frequency domain channel coefficient of subcarrier i for $S \rightarrow R$, $S \rightarrow D$, and $R \rightarrow D$ links, respectively. Since a properly designed OFDM system converts frequency selective fading into frequency flat fading at each subcarrier, $|h_{SD,i}|$, $|h_{RD,i}|$, and $|h_{SR,i}|$ are modeled as Rayleigh flat fading random variables. These channel coefficients include the path loss, shadowing, and fast fading effects. At a given subcarrier i, $n_{R,i}[n] \sim \mathcal{CN}(0, N_o^R)$ and $n_{D,i}[n] \sim \mathcal{CN}(0, N_o^D)$ represent the additive white gaussian noise (AWGN) plus interference samples observed at the relay and destination terminals, respectively. In this study, the mobile(s) are scheduled on orthogonal radio resources. Hence, we assume zero intra-cell interference. The interference is assumed to be caused by other cells in the network and modeled as a complex Gaussian random variable which is independent than the AWGN. With this model, $\gamma_{SR,i} = |h_{SR,i}|^2 E_S/N_o^R$, $\gamma_{SD,i} = |h_{SD,i}|^2 E_S/N_o^D$, and $\gamma_{RD,i} = |h_{RD,i}|^2 E_R/N_o^D$ represent the instantaneous SINR conditions at subcarrier i of $S \rightarrow R$, $S \rightarrow D$, and $R \rightarrow D$ links, respectively.

B. The Considered Relaying Schemes

In this study, various relaying schemes such as cooperative–multiple input single output (MISO), cooperative–single input multiple output (SIMO), and cooperative–MIMO are considered to achieve diversity. A conventional relaying scheme is considered as well. An efficient end-to-end link adaptation method for each of these relaying schemes is presented.

B.1 Cooperative Transmit Diversity

To achieve cooperative transmit diversity, only the RS listens to the transmission of the BS during the first phase. In the second phase, both BS and RS transmit simultaneously by using the same radio resource. This way, a cooperative–MISO channel is observed at the MS. Hence, this scheme is referred to as cooperative–MISO scheme [7]. To achieve diversity, cooperative space time coding can be used by the BS and the RS terminals [7] and we use Alamouti space time coding [3]. This scheme achieved with DF based relaying does not necessitate two phases with equal duration since the MS does not exploit any signal transmitted in the first phase. Hence, we adjust the AMC mode for each phase independently. This leads to an efficient use of radio resources. For DF based relaying, the AMC mode per hop should only depend on the post processing SINR at the corresponding receiver node, i.e., either the RS or the MS. For AF based relaying, the decoding is done only at the MS at the end of two phases. Hence we choose the AMC mode according to the post processing SINR observed at the MS. The time divisioned transmission structure to achieve cooperative transmit diversity with Alamouti space-time coding is presented in Table 1. In the table, $x_{1,i}$ and $x_{2,i}$ represent the transmitted constellation points at subcarrier i. In the following Sections I-A and I-B, the input output relations with the cooperative transmit diversity is presented for both AF and simple–AdDF based relaying. The transmission sequence presented in Table 1 has been considered.

1.A) Input Output Relations with AF Based Relaying: In the first phase, the RS using AF based relaying first performs fast Fourier transform (FFT) operation. It amplifies the signal at each subcarrier and buffers for subsequent transmission in the second phase. During the second phase, the RS remodulates the signal at each sub-carrier with OFDM. Note that the amplification and forwarding could have been done before FFT operation. However in this case, link adaptation and selection cannot be done for each sub-channel. Let $s_{R,i}^{AF}$ represent the transmitted signal by the RS at subcarrier i and $\alpha_i = \sqrt{E_R}/\beta_i = \sqrt{E_R}/\sqrt{N_o^R(1+\gamma_{SR,i})}$ represent the amplification used at the RS at subcarrier i determined such that $\mathcal{E}\{|s_{R,i}^{AF}|^2\} = E_R$ [22]. At the end of the two phases at a given subcarrier i, the MS creates the following received signal vector for each transmitted symbol:

$$\begin{aligned}\mathbf{y} &= \begin{bmatrix} y_{D,i}[n+2] \\ y_{D,i}^*[n+3] \end{bmatrix} \\ &= \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \\ &= \mathbf{H_{eff}} \mathbf{x} + \mathbf{n} \end{aligned} \tag{1}$$

where $\mathbf{x} = [x_{1,i} \quad x_{2,i}]^T$ and $\mathbf{n} = [n_1 \quad n_2^*]^T$. At the end of the two phases, the 1×2 cooperative–MISO channel achieved with AF based relaying is given by

$$\begin{aligned}\mathbf{h}^{AF} &= \begin{bmatrix} h_1 & h_2 \end{bmatrix} \\ &= \begin{bmatrix} \frac{\sqrt{E_R E_S}}{\beta_i} h_{SR,i} h_{RD,i} & \sqrt{E_S} h_{SD,i} \end{bmatrix}. \end{aligned} \tag{2}$$

The noise components n_j where $j \in \{1, 2\}$ are given by $n_j = n_{D,i}[n+j+1] + h_{RD,i} \frac{\sqrt{E_R}}{\beta_i} n_{R,i}[n+j-1]$. The MS performs maximum ratio combining on $\mathbf{y}$ according to

$$\mathbf{z} = \mathbf{H_{eff}}^H \mathbf{y} = ||\mathbf{h}^{AF}||_F^2 \mathbf{x} + \tilde{\mathbf{n}} \tag{3}$$

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[3] Note that, this study can be extended to the case where in the second phase the BS repeats the packets that are erroneously received by the RS.

Table 1. Transmission sequence of the BS and RS to achieve cooperative transmit diversity with Alamouti space–time coding.

First phase	First phase	Second phase	Second phase	...
nth symbol	$n+1$st symbol	$n+2$nd symbol	$n+3$rd symbol	...
$S \rightarrow R\,(x_{1,i})$	$S \rightarrow R\,(-x^*_{2,i})$	$S \rightarrow D\,(x_{2,i})$, $R \rightarrow D\,(x_{1,i})$	$S \rightarrow D\,(x^*_{1,i})$, $R \rightarrow D\,(-x^*_{2,i})$	...

where $\tilde{\mathbf{n}} = \mathbf{H}_{\mathbf{eff}}{}^H \mathbf{n} = [\tilde{n}_1 \quad \tilde{n}_2]^T$. At a given sub-carrier i, the post processing instantaneous SINR achieved after maximum ratio combining at the MS can be derived from (2), (3) as

$$\gamma_{s,i}^{AF} = \frac{\left(\|\mathbf{h}^{\mathbf{AF}}\|_{\mathbf{F}}^{\mathbf{2}}\right)^2}{\mathcal{E}\{|\tilde{n_1}|^2\}} = \frac{\gamma_{SD,i} + \frac{\gamma_{SR,i}\gamma_{RD,i}}{(1+\gamma_{SR,i})}}{1 + \frac{\gamma_{RD,i}}{(1+\gamma_{SR,i})}}. \tag{4}$$

After combining at a given sub-carrier, the MS observes an effective point-to-point link with a post processing SINR as given by 4. In a point-to-point flat fading link with instantaneous SINR γ, let $thr(\gamma) = R(\gamma)(1 - PER(\gamma))$ represent the end-to-end throughput when AMC is used and the AMC mode which provides the highest throughput is selected. The term $R(\gamma)$ in b/s/Hz represents the nominal rate of the selected AMC mode. The term $PER(\gamma)$ represents the packet error rate with the selected AMC mode based on γ. With AF based relaying at a given subcarrier i, the end-to-end throughput achieved with Alamouti scheme based cooperative transmit diversity is finally given by

$$\rho_{tx-div.}^{AF} = 0.5thr(\gamma_{s,i}^{AF}) \tag{5}$$

where the AMC mode per transmission phase is decided based on $\gamma_{s,i}^{AF}$. The factor of 0.5 accounts for the fact that, two time phases with equal duration is needed with AF based relaying.

1.B) Input Output Relations with Simple–AdDF Based Relaying: In the first phase, the RS using simple–AdDF based relaying demodulates the OFDM symbols received from the BS. After the FFT operation the RS decodes the signal at each sub-channel and performs cyclic redundancy check to determine the packets that are correctly received. The RS re-encodes and buffers only the packets that are correctly received over a given sub-channel. At the end of the first phase, it informs the BS and the MS about the decoding status of each packet. In the second phase, the RS and the BS make cooperative transmission only for the packets which are correctly received at the RS. The cooperative–MISO channel achieved with simple–AdDF based relaying is given by $\mathbf{h}^{\mathbf{DF}} = \begin{bmatrix} h_1 & h_2 \end{bmatrix} = \begin{bmatrix} \sqrt{E_R}h_{RD,i} & \sqrt{E_S}h_{SD,i} \end{bmatrix}$. Since the RS relays only when it can decode the packets correctly, the post processing instantaneous SINR achieved at the MS after Alamouti scheme based space–time decoding can be derived as [2], [3]:

$$\gamma_{s,i}^{DF} = \frac{\|\mathbf{h}^{\mathbf{DF}}\|_{\mathbf{F}}^{\mathbf{2}}}{N_o^D} = \gamma_{SD,i} + \gamma_{RD,i}. \tag{6}$$

With simple–AdDF based relaying at a given subcarrier i, the end-to-end throughput is finally given by

$$\rho_{tx-div.}^{AdDF} = \frac{thr(\gamma_{SR,i})thr(\gamma_{s,i}^{DF})}{R(\gamma_{SR,i}) + R(\gamma_{s,i}^{DF})} \tag{7}$$

where the AMC mode in the first phase is decided based on $\gamma_{SR,i}$ and the AMC mode in the second phase is decided based on $\gamma_{s,i}^{DF}$ in order to optimize the end-to-end throughput.

B.2 Cooperative Receive Diversity

This scheme was analyzed in detail in a previous study in [22] and it is referred to as cooperative–SIMO scheme in [7]. To achieve cooperative receive diversity via maximum ratio combining, we need two time phases with equal duration since both the BS and the RS need to make transmission with the same modulation to constitute a cooperative–SIMO channel [7]. In the first phase, the BS transmits information which is intended for a given MS. Both the RS and MS receive and buffer this information. In the second phase, the RS forwards this information to the MS and the BS remains silent. For AF based relaying, we assume the same kind of amplification as in the case of AF based cooperative transmit diversity scheme. For each one of the AF or simple–AdDF based relaying, the MS combines the signals received from the BS and the RS via maximum ratio combining. Over the sub-carrier where the cooperative receive diversity with AF based relaying is used, the post processing instantaneous SINR obtained at the MS after maximum ratio combining was derived in [22] as[4]

$$\gamma_{s,i}^{AF} = \frac{(\gamma_{SD,i} + \frac{\gamma_{SR,i}\gamma_{RD,i}}{1+\gamma_{SR,i}})^2}{\gamma_{SD,i} + \frac{\gamma_{SR,i}\gamma_{RD,i}}{1+\gamma_{SR,i}} + \frac{\gamma_{RD,i}^2\gamma_{SR,i}}{(1+\gamma_{SR,i})^2}}. \tag{8}$$

On the other hand, the simple–AdDF based relaying achieves the post processing instantaneous SINR as given in (6) [22]. With AF based relaying at a given subcarrier i, the end-to-end throughput achieved by the cooperative receive diversity is given by

$$\rho_{rx-div.}^{AF} = 0.5thr(\gamma_{s,i}^{AF}) \tag{9}$$

where the AMC mode per transmission phase is decided based on $\gamma_{s,i}^{AF}$. The factor of 0.5 accounts the fact that two time phases with equal duration is used. For simple–AdDF based relaying, we propose to choose the AMC mode to be used by the BS and the RS based on

$$\rho = \min\{thr(\gamma_{s,i}^{DF}), thr(\gamma_{SR,i})\}. \tag{10}$$

This is analogous to $\min(\gamma_{s,i}^{DF}, \gamma_{SR,i})$. If $\rho = thr(\gamma_{SR,i})$ then the AMC mode is decided based on $\gamma_{SR,i}$, otherwise, the AMC mode is decided based on $\gamma_{s,i}^{DF}$. This way, we can keep negligible error rates at the RS if $\gamma_{SR,i} > \gamma_{s,i}^{DF}$ and at the MS if $\gamma_{s,i}^{DF} > \gamma_{SR,i}$. Furthermore, we can keep acceptable error rates at the RS if $\gamma_{SR,i} < \gamma_{s,i}^{DF}$. With this AMC mode decision, the end-to-end throughput achieved with simple–AdDF scheme, i.e., $\rho_{rx-div.}^{AdDF}$, will be given by

$$\rho_{rx-div.}^{AdDF} = \begin{cases} 0.5thr(\gamma_{s,i}^{DF})P_c(\gamma_{SR,i}), & \rho = thr(\gamma_{s,i}^{DF}) \\ 0.5thr(\gamma_{SR,i})P_c(\gamma_{s,i}^{DF}), & \rho = thr(\gamma_{SR,i}). \end{cases} \tag{11}$$

$P_c(\gamma)$ represents the probability of correct reception of a packet with the selected AMC mode (based on ρ) over an AWGN channel with SINR γ.

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[4] Note that for this derivation, the same system considerations were done in [22].

B.3 Cooperative–MIMO Scheme

In this section, the cooperative diversity is achieved with cooperative–MIMO transmissions [7]. The transmission sequence and hence the space-time coding given in Table 1 is considered. The difference is that the MS receives during both phases. For AF and simple-AdDF based relaying, the cooperative–MIMO channel observed at the MS at the end of the two phases is given by

$$\mathbf{H}^{\mathbf{AF}} = \begin{bmatrix} \sqrt{E_S} h_{SD,i} & 0 \\ \frac{\sqrt{E_R E_S}}{\beta_i} h_{SR,i} h_{RD,i} & \sqrt{E_S} h_{SD,i} \end{bmatrix} \quad (12)$$

and

$$\mathbf{H}^{\mathbf{DF}} = \begin{bmatrix} \sqrt{E_S} h_{SD,i} & 0 \\ \sqrt{E_R} h_{RD,i} & \sqrt{E_S} h_{SD,i} \end{bmatrix}, \quad (13)$$

respectively. Note that, this channel can be achieved if the RS and BS use the same modulation [7]. Hence, to observe a cooperative-MIMO channel, two phases with equal duration are needed. In this study, cooperative diversity with cooperative-MIMO scheme is achieved as follows. At the end of the two phases, the MS performs space-time decoding of the signals received from the BS and the RS terminals during the second phase. Thus, it can exploit transmit diversity. The MS achieves further SINR gain by combining the space time decoded symbols with the corresponding symbols received in the first phase. Finally, with AF based relaying, the post processing SINR achieved at the MS is given by

$$\gamma_{s,i}^{AF} = \frac{\left(2\gamma_{SD,i} + \frac{\gamma_{SR,i}\gamma_{RD,i}}{(1+\gamma_{SR,i})}\right)^2}{\gamma_{SD,i} + \left(1 + \frac{\gamma_{RD,i}}{(1+\gamma_{SR,i})}\right)\left(\frac{\gamma_{SR,i}\gamma_{RD,i}}{(1+\gamma_{SR,i})} + \gamma_{SD,i}\right)}. \quad (14)$$

With AF based relaying, the MS can achieve an end-to-end throughput given by $0.5thr(\gamma_{s,i}^{AF})$. With simple-AdDF based relaying, the post processing SINR achieved at the MS is given by $\gamma_{s,i}^{DF} = 2\gamma_{SD,i} + \gamma_{RD,i}$. Hence, the MS can achieve an end-to-end throughput given by (11) where the AMC mode is selected based on $\rho = \min\{thr(\gamma_{s,i}^{DF}), thr(\gamma_{SR,i})\}$ as in the case of cooperative receive diversity.

B.4 Conventional Relaying

With conventional relaying, the MS relies solely on the signals transmitted by the RS. Hence, the end-to-end throughput corresponds to the end-to-end throughput of cooperative–MISO scheme for $\gamma_{SD,i} = 0$.

Note that, with simple–AdDF based relaying, the MSs do not need to know any channel state information regarding $S \rightarrow R$ link condition. However, with the AF based relaying, the channel state information regarding the $S \rightarrow R$ link is necessary at the MSs which in turn increases complexity.

III. END-TO-END THROUGHPUT PERFORMANCE COMPARISON OF AF, SIMPLE–ADDF AND W/O RELAY SCHEMES

In this section, the end-to-end throughput performance of the simple–AdDF, AF, and w/o relay schemes are compared to each other. The results are presented for each of the relaying schemes described in the previous section while using the proposed AMC decision rules. The AMC decision is made based on a lookup table. For each SINR value γ, the lookup table stores

1. the needed AMC mode
2. $thr(\gamma)$
3. $P_c(\gamma)$ for each and every AMC mode available.

Such a lookup table is needed for the proposed link adaptation and selection method which will be described in detail in the next section. The lookup table is created for discrete values of γ with resolution 0.1 dB. Perfect channel state information and synchronization is assumed. Throughout this study, a packet contains 96 coded bits. In the following, the results are plotted versus $\gamma_{SR,i}$ for given $\gamma_{SD,i}$ and $\gamma_{RD,i}$.

1) *Cooperative–MISO scheme*: Fig. 1 presents simulation results with $\gamma_{SD,i} = 20$ dB and $\gamma_{RD,i} = 6$ dB. The results in this figure show that, even if the $S \rightarrow R$ link has a very good SINR level, relaying may not improve the end-to-end throughput. Hence, the relaying should be selected only if it can improve the end-to-end throughput. Furthermore, in the figure, the simple–AdDF scheme is throughput limited as compared to the AF scheme. However, over this region, relaying does not improve the end-to-end performance. The main conclusions for the relative performance of AF and simple–AdDF based relaying should be done over the region where relaying improves the performance. Fig. 2 presents the simulation results with $\gamma_{SD,i} = 9$ dB and $\gamma_{RD,i} = 23.5$ dB. The results show that relaying can improve the end-to-end throughput for higher $\gamma_{SR,i}$ and the simple–AdDF based relaying can provide significant throughput gain as compared to AF based relaying. For the cooperative–MISO scheme, over the region where relaying improves the end-to-end throughput, our simulation results indicate that the AF based relaying cannot outperform the simple–AdDF based relaying for all the instantaneous SINR conditions in the $S \rightarrow R$, $S \rightarrow D$, and $R \rightarrow D$ links. This is due to the fact that, with simple–AdDF based relaying, we can adjust the transmission rates in each phase and hence use the radio resources more efficiently than AF scheme. Note that the end-to-end throughput with simple–AdDF based relaying is not monotonically increasing as the nominal transmission rates take discrete values (7).
2) *Cooperative–SIMO scheme*: Fig. 3 presents the simulation results with $\gamma_{SD,i} = -6$ dB and $\gamma_{RD,i} = 23.5$ dB. The results in this figure show that simple–AdDF based relaying has a throughput gain of as much as 0.72 b/s/Hz compared to AF based relaying. Over the instantaneous SINR region where relaying improves the end-to-end throughput, our simulation results indicate that the AF based relaying can outperform both the end-to-end throughput achieved with simple–AdDF based relaying and w/o relay scheme as much as 0.02 b/s/Hz. Hence, AF scheme cannot outperform simple–AdDF based relaying significantly over this SINR region.
3) *Cooperative–MIMO scheme*: Over the instantaneous SINR region where relaying improves the end-to-end throughput, our simulation results with cooperative-

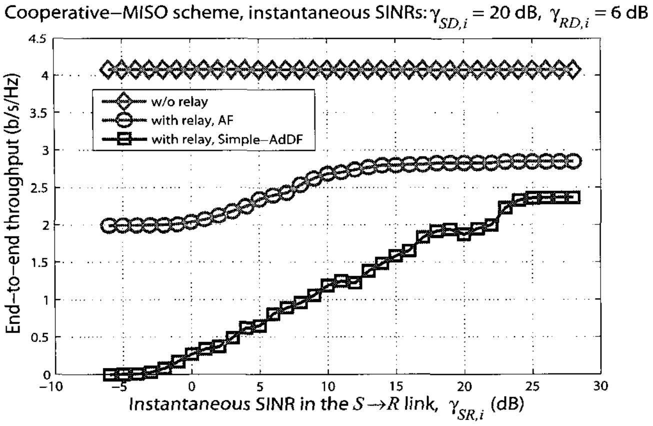

Fig. 1. Cooperative–MISO scheme: The instantaneous end-to-end throughput achieved with AF, simple–AdDF and w/o relay schemes versus $\gamma_{SR,i}$ with $\gamma_{SD,i} = 20$ dB and $\gamma_{RD,i} = 6$ dB.

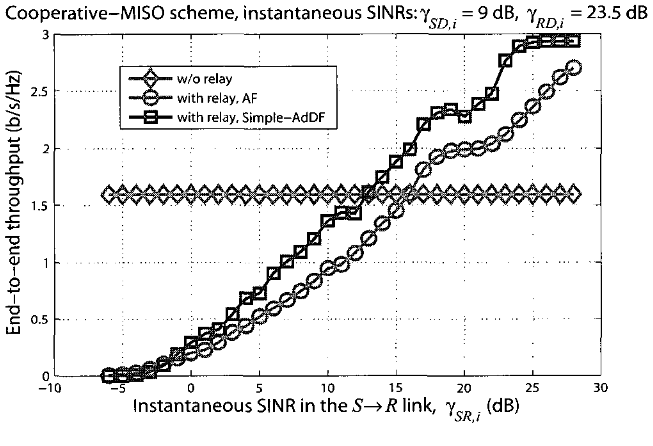

Fig. 2. Cooperative–MISO scheme: The instantaneous end-to-end throughput achieved with AF, simple–AdDF and w/o relay schemes versus $\gamma_{SR,i}$ with $\gamma_{SD,i} = 9$ dB and $\gamma_{RD,i} = 23.5$ dB.

MIMO scheme indicate that the AF based relaying cannot provide significant throughput enhancement over simple-AdDF based relaying. Fig. 4 presents the simulation results with $\gamma_{SD,i} = 1.5$ dB and $\gamma_{RD,i} = 23.5$ dB. The results show that, simple-AdDF based relaying can provide significant throughput enhancement to both AF based relaying (as much as 0.73 b/s/Hz) and w/o relay (as much as 2.48 b/s/Hz) transmissions.

4) *Conventional Relaying*: For all the combinations of $\gamma_{SR,i}$ and $\gamma_{RD,i}$, our simulation results with conventional relaying indicate that, AF based relaying cannot outperform simple–AdDF based relaying. Simple–AdDF based relaying on the other hand can provide a throughput gain of as much as 0.71 b/s/Hz compared to AF based relaying.

Consequently, the results presented in this section motivate a link adaptation and selection method that dynamically selects the best scheme among simple–AdDF and w/o relay based on channel state information.

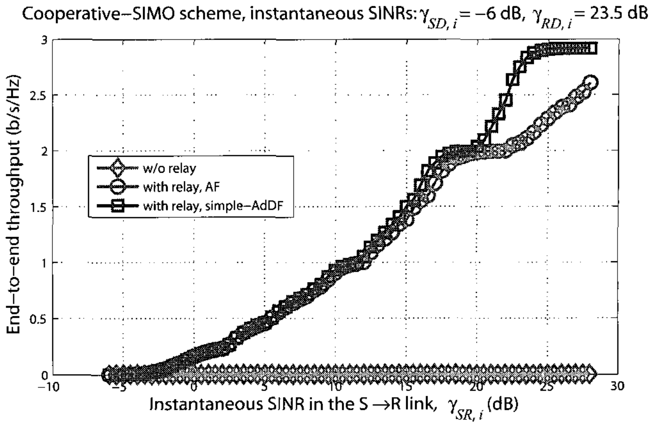

Fig. 3. Cooperative–SIMO scheme: The instantaneous end-to-end throughput achieved with AF, simple–AdDF and w/o relay schemes versus $\gamma_{SR,i}$ with $\gamma_{SD,i} = -6$ dB and $\gamma_{RD,i} = 23.5$ dB.

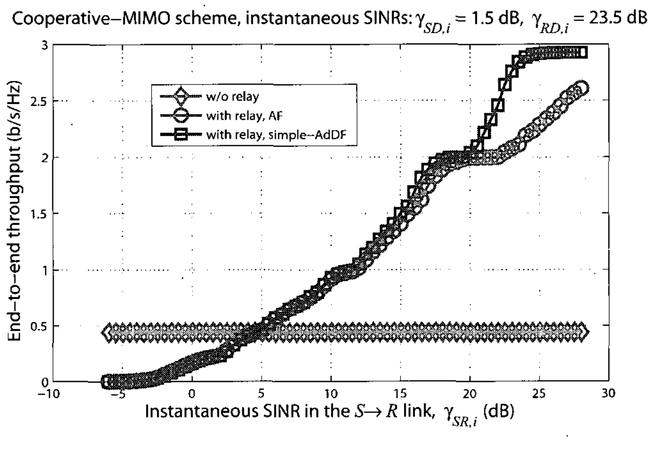

Fig. 4. Cooperative–MIMO scheme: The instantaneous end-to-end throughput achieved with AF, simple–AdDF and w/o relay schemes versus $\gamma_{SR,i}$ with $\gamma_{SD,i} = 1.5$ dB and $\gamma_{RD,i} = 23.5$ dB.

IV. THE PROPOSED END-TO-END LINK ADAPTATION & SELECTION METHOD AND ITS PERFORMANCE EVALUATION

A. The Proposed End-to-End Link Adaptation & Selection Method

With the observations presented in the previous section, we propose a link adaptation and selection method for OFDM/OFDMA-TDD based cellular wireless relay networks characterized by the following. The link adaptation and selection is done by the BS (in order to have centralized control). The channel state information regarding the SINRs in each sub-channel of $S \rightarrow R$, $S \rightarrow D$, and $R \rightarrow D$ links are obtained at the BS (i.e., fed–back by the users) at the end of each Uplink (UL) subframe via the channel quality indication channel (CQICH) [18]. Let this channel state information be referred to as $\gamma_{SR,j}$,$\gamma_{RD,j}$, and $\gamma_{SD,j}$ for each sub-channel j. The BS then calculates the post processing SINR for each sub-channel (i.e.,

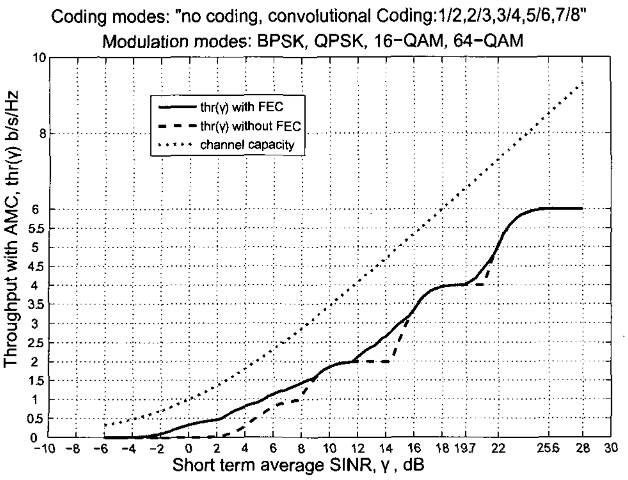

Fig. 5. The lookup table: The plot representing the stored $thr(\gamma)$ for each SINR value γ with resolution 0.1 dB.

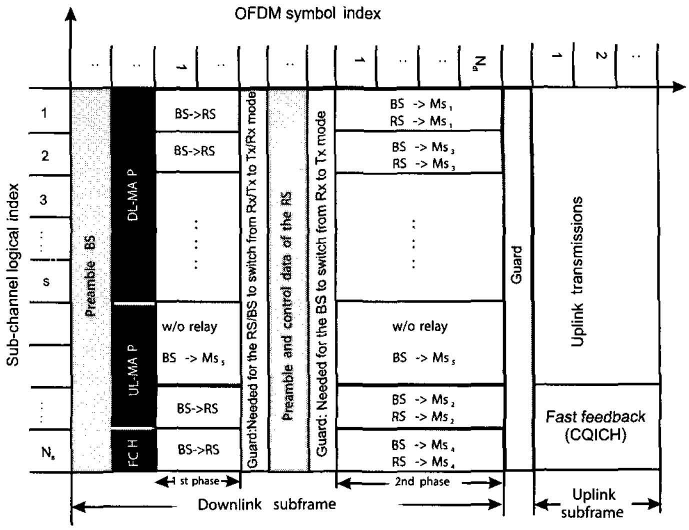

Fig. 6. The frame structure as a possible solution to enable the proposed link adaptation and selection in an OFDMA-TDD based cellular wireless relay network where the users are within the coverage of the BS and the RS.

$\gamma_{s,j}^{DF}$, $\gamma_{s,j}^{AF}$) and for each scheme based on the derived equations in Section II-B. The scheme (among AF, simple–AdDF, and w/o relay) which provides the highest end-to-end throughput is then selected for each sub-channel based on $\gamma_{SR,j}$, $\gamma_{RD,j}$, and $\gamma_{SD,j}$. This selection is done with the proposed AMC decisions and it is based on a lookup table described in previous section. With this lookup table, the throughput for a given instantaneous SINR γ is determined by reading the corresponding throughput. Fig. 5 presents the stored $thr(\gamma)$ for each discrete value of γ with resolution 0.1 dB. Note that $thr(\gamma)$ depends on the packet length which is fixed to 96 coded bits in this study. We highlight that this study can be extended to accommodate packets with different lengths. For AF based relaying, γ is determined by the post processing SINRs derived in Section II-B. For simple-AdDF based relaying, $thr(\gamma_{s,j}^{DF})$, $thr(\gamma_{SR,j})$, $P_c(\gamma_{s,j}^{DF})$, and $P_c(\gamma_{RS,j})$ are read from the lookup table (11). Then, the end-to-end throughput for each scheme is calculated based on the derived equations in Section II-B. Finally the transmission scheme and the AMC modes providing the highest end-to-end throughput is determined for each sub-channel. In Fig. 6, a frame structure is presented as a possible solution to enable the proposed link adaptation and selection in an OFDM(A)–TDD based cellular wireless relay network where the users are within the coverage area of the BS and some of them are in the coverage area of both the BS and the RS. Before data transmissions start, the BS schedules the users per sub-channel with the selected scheme. Then, the BS broadcasts in down link (DL)-MAP which user is scheduled on which sub-channel and for each sub-channel which scheme (among AF, simple-AdDF, and w/o relay) and AMC mode is used. After the first phase and guard interval for transmit/receive turnaround time, the RS starts the transmission. The RS first transmits its preamble[5] and control information which informs the BS and the MSs of its decoding status for each of the received packets. The BS needs to receive this information as well and hence it has to switch from the receive mode to the transmit mode before data transmissions start. This necessitates a guard interval. Finally, transmissions with the selected schemes start in the second phase. In Fig. 6, cooperative–MISO based relaying is used. In the first and second phase, data transmission at each sub-channel take place which is designated for a given MS. For cooperative–MISO based relaying, the duration of the first phase can be adjusted based on the average SINR in the $S \rightarrow R$ link.

B. Performance Evaluation

In the following, we introduce our simulation setup for the performance evaluation of the proposed end-to-end link adaptation and selection method. We consider a total of 2048 subcarriers[6] with a system bandwidth of 22.4 MHz [18]. The system operates at a carrier frequency of 2.5 GHz. Frames have a 5 ms duration. 44 out of 48 OFDM symbols in a given frame are reserved for data transmission where 24 of them are reserved for downlink transmissions [18]. The frame structure depicted in Fig. 6 is considered. The downlink subframe is divided into two phases where each phase can have a duration of 12–OFDM symbols. We use a multi–path wireless channel model for $S \rightarrow D$ and $R \rightarrow D$ links with an rms delay spread of 0.231 μs [23]. A subcarrier spacing of 22.4 MHz/2048 $=$ 10.94 kHz is assumed. This corresponds to a 90% coherence bandwidth of 8 sub-carriers and a 50% coherence bandwidth of 80 sub-carriers in the $S \rightarrow D$ and $R \rightarrow D$ links [24]. For the $S \rightarrow R$ link, we use a wireless channel model that is developed for fixed wireless applications in [25], [26]. For this link, we consider an rms delay spread of 0.264 μs and a K factor of 1. This corresponds to a 50% coherence bandwidth of 70 sub-carriers for a subcarrier spacing of 10.94 kHz. The $S \rightarrow D$ and $R \rightarrow D$ links are assumed to be non line of sight, i.e., with a K factor of

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[5] Note that the BS and RS can also transmit their preambles simultaneously.

[6] In the simulations, only 360 point FFT is done in order to prevent very long simulation time.

zero. One sub-channel consists of 9 consecutive sub-carriers (8 for data, 1 for pilot) over m consecutive OFDM symbols where $m, m \in \{2,3,6,12\}$, depends on the selected modulation mode [18]. We assume a single user with a speed up to 7.7 km/h such that the 50% coherence time is equal to 10ms [24]. At a carrier frequency of 2.5 GHz, a speed of 7.7 km/h results in a maximum Doppler frequency shift of 17.8 Hz [24]. Since this maximum Doppler shift is much smaller than the sub-carrier spacing (i.e., 0.2 % of the sub-carrier spacing), the receiver at the MS does not see performance degradation due to inter-carrier-interference caused by Doppler frequency shift [27]. These system parameters enable us to assume a block fading channel which remains constant within a given sub-channel in a frame and to use SINR information for the end-to-end link adaptation. At the end of the first phase, the RS using simple–AdDF based relaying sends a feedback on its decoding status for each packet received from the BS. The overhead for this signaling will be smaller than or equal to $N_{sub-ch} \times 3$ bits per packet/(5ms),[7] which equals 24 kb/s or 11×10^{-4} b/s/Hz in a 22.4 MHz system bandwidth with a number of sub-channels, i.e., N_{sub-ch}, equal to 40.[8] Hence, this signaling will not cause significant overhead. This overhead can further be reduced if the RS sends information on only the packets that are not correctly received (efficient when $S \rightarrow R$ link is reliable) or that are correctly received (efficient if the $S \rightarrow R$ link is not reliable).

In the following, the simulation results are provided for the performance evaluation of the proposed link adaptation and selection method. The following figures present

1. the average end-to-end throughput achieved with the proposed link adaptation and selection method
2. the average end-to-end throughput achieved with i) simple–AdDF ii) AF iii) w/o relay schemes which are used over all the sub-channels

To obtain the throughput results for each of the items mentioned above, the proposed AMC decision rules are used.

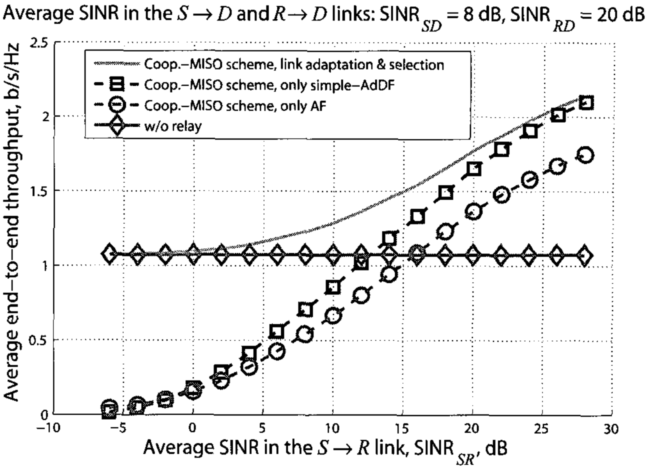

Fig. 7. Cooperative–MISO scheme: The average end-to-end throughput achieved with the proposed link adaptation method as compared to non-adaptive schemes where one type of transmission method is used. The average SINRs: $\text{SINR}_{SD} = 8$ dB and $\text{SINR}_{RD} = 20$ dB.

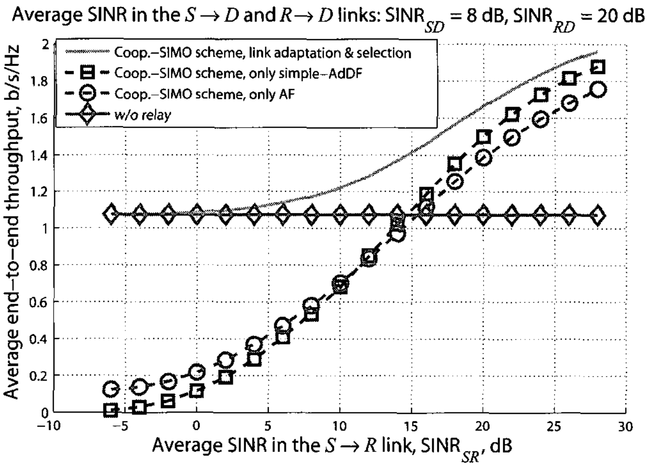

Fig. 8. Cooperative–SIMO scheme: The average end-to-end throughput achieved with the proposed link adaptation method as compared to non-adaptive schemes where one type of transmission method is used. The average SINRs: $\text{SINR}_{SD} = 8$ dB and $\text{SINR}_{RD} = 20$ dB.

For the Cooperative–MISO scheme, the results in Fig. 7 are obtained versus the average SINR condition in the $S \rightarrow R$ link where the average SINR conditions in the $S \rightarrow D$ and $R \rightarrow D$ links are fixed to 8 dB and 20 dB, respectively. The results presented in Fig. 7 show that, the average end-to-end throughput performance obtained via the proposed link adaptation and selection method is always better than or equal to that of i) w/o relay transmissions and ii) transmissions where the same forwarding scheme is used over all the sub-channels. For Cooperative–SIMO scheme, the results in Fig. 8 are obtained versus the average SINR condition in the $S \rightarrow R$ link where the average SINR conditions in the $S \rightarrow D$ and $R \rightarrow D$ links are fixed as 8 dB and 20 dB, respectively. The results show that the transmissions with the proposed link adaptation and selection method improves the performance and the AF based relaying cannot outperform simple-AdDF based relaying over the region where relaying improves the throughput. For Cooperative–MIMO scheme, the results in Fig. 9 are obtained versus the average SINR condition in the $S \rightarrow R$ link where the average SINR conditions in the $S \rightarrow D$ and $R \rightarrow D$ links are fixed as 8 dB and 20 dB, respectively. The same conclusion as in cooperative-SIMO scheme is drawn. For conventional relaying scheme, the results in Fig. 10 are obtained versus the average SINR condition in the $S \rightarrow R$ link where the average SINR condition in the $R \rightarrow D$ link is fixed as 8 dB. The results in this figure show that the AF scheme is throughput limited as compared to the simple–AdDF scheme and hence, the proposed link adaptation and selection method selects simple–AdDF based relaying.

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[7] Since the AMC modes considered in this study can provide a maximum transmission rate of 6 b/s/Hz , we can send at most $12/(96/(8 \times 6)) = 6$ packets per 9 contiguous sub-carriers in the first phase which necessitates 3 bits per packet for identification of each packet.

[8] Note that the IEEE 802.16e system provides a maximum of 32 sub-channels in one frame [18].

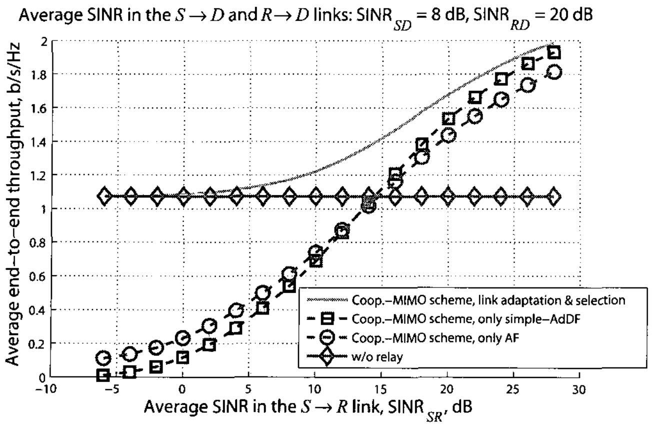

Fig. 9. Cooperative–MIMO scheme: The average end-to-end throughput achieved with the proposed link adaptation method as compared to non-adaptive schemes where one type of transmission method is used. The average SINRs: $\mathrm{SINR}_{SD} = 8$ dB and $\mathrm{SINR}_{RD} = 20$ dB.

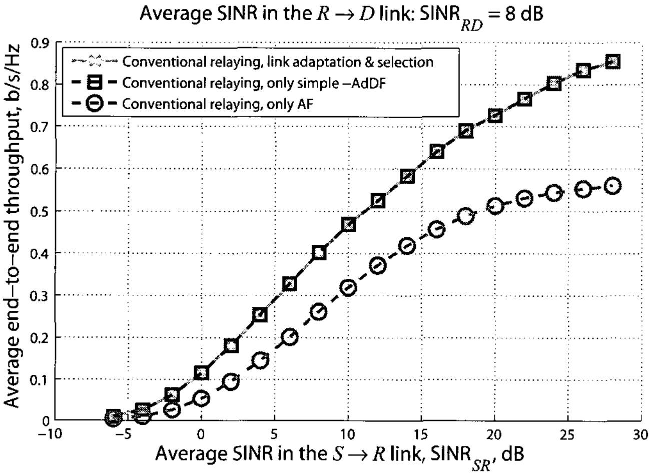

Fig. 10. Conventional relaying scheme: The average end-to-end throughput achieved with the proposed link adaptation method as compared to non-adaptive schemes where one type of transmission method is used. The average SINR: $\mathrm{SINR}_{RD} = 8$ dB.

V. CONCLUSIONS AND FUTURE WORKS

In this study, we have proposed an end-to-end link adaptation and selection method for wireless relay networks and provided a frame structure in order to enable the proposed link adaptation for OFDM(A)–TDD based cellular wireless relay networks. We have provided simple and efficient AMC decision rules for wireless relay networks. Such rules are able to take into account the fading conditions in all the wireless links constituting a relay network whereby the end-to-end throughput is optimized. Our investigations show that, the end-to-end throughput performance with the proposed link adaptation and selection method is always better than or equal to that of i) w/o relay transmissions and ii) relayed transmissions where relaying is always used. On the other hand, our investigations show that, in a practical system setting, the AF based relaying cannot outperform simple–AdDF based relaying over the region where relaying improves the end-to-end throughput as compared to w/o relay transmissions. Hence, transmissions with the DF scheme is promising as the error propagation can be avoided by error detection techniques which are already inherent in wireless transmissions. Future works out of this study include: 1. The effect of synchronization on OFDM(A) based relay networks using the proposed link adaptation and selection method. 2. The design of the proposed link adaptation and selection method with imperfect channel state information and investigations in a multiuser environment together with a practical scheduler. 3. The design of the proposed link adaptation and selection method for users with high speeds. For such users, the sub-channel allocation is done on frequency diverse sub-carriers to provide frequency diversity [18]. In this case, new lookup tables should be prepared with average SINR conditions as instantaneous SINR conditions cannot be taken into account due to high variations in the channel. 4. The evaluation of the reduction in power consumption at the MS by introducing the cooperative diversity only when necessary. 5. The investigations from channel capacity point of view where the performance with AF and simple-AdDF based relaying are compared over the region where relaying improves the end-to-end performance. 6. The design of a fully adaptive system which dynamically selects not only the best forwarding scheme but also the best relaying scheme.

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