Enhancing Relay-based Resource Allocation With Adaptive Amplify-and-Forward Relaying

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Abstract:- This study considers the resource allocation problem in relay networks for downlink transmission where base station (BS) communicates with multiple mobile stations (MSs) via relay stations (RSs) operating in either half-duplex (HD) or full-duplex (FD) mode. Relay gain factors for Amplify and Forward (AF) protocol are studied and a new one called adaptive AF (AAF) relaying is proposed. The AAF scheme attempts to equalize the signal-to-noise ratio (SNR) across subcarriers, thus providing increased throughputs and proportional fairness in resource distribution. Simulation results of comparative analysis of the AAF relaying scheme and the two basic relaying protocols namely AF and Decode and Forward (DF) are presented in terms of average system throughput, fairness and percentage of call outage under maximum-sum rate (MSR) resource allocation technique. The results show that the AAF scheme achieves superior performances compared to the other ones.

Keywords:- amplify-and-forward relays, decode-and-forward relays, full-duplex relaying, loop interference, resource allocation

1 Introduction

As the radio spectrum increasingly becomes competitive new technologies must be developed to increase the spectral efficiency of wireless networks. Different strategies are required to enjoy the benefit of multiple-input-multiple-output (MIMO) transmission in a scenario where multiple antennas are not deployable at the terminal. One of such fast and economic strategies is the deployment of advanced wireless relays. Relaying strategies such as decode-and-forward (DF), amplify-and-forward (AF), coded-cooperation (CC), and compress-and-forward (CF) have been investigated for cooperative communications [1],[2],[3]. Comparison between DF and AF relaying schemes with long-term evolution (LTE) parameters is performed in [4]. Results show that spectral efficiency for DF outperforms AF when many relays are active at the same time. The authors in [5] proposed a distributed resource allocation algorithm, which enables the exploitation of the benefits of different relaying protocols and duplexing schemes to fulfill heterogeneous quality-of-service (QoS) requirements. However, the algorithm only enables dynamic selection between AF and DF relaying. In [6] and references therein, coherent gain allocation schemes that achieve a distributed spatial multiplexing gain are discussed. The authors concluded that one approach to allow multiple users to access the channel simultaneously is to compute the relay gain factors such that the source/destination streams are completely orthogonalized in space (multiuser zero-forcing (MUZF) relaying). The relay station parameters play a major role in the resource allocation to the active users in the orthogonal frequency division multiplexing (OFDM) relaying system [7]. The relay gain factor in the AF relay is an important relay station parameter. Different AF relay gain factors have been proposed in [1], [8], [11], [12]. In these AF schemes, the amplification of the signal is indirectly proportional to the channel gains. In other words, the lower the channel gains the higher the amplified signal. However, the optimal signal-to-noise ratio (SNR) can be achieved if some kind of feedback can be dynamically applied to further amplify signals that are still extremely low in strength while not affecting those that are already sufficiently strong. Therefore, in this paper we aim at improving the performances of the existing AF scheme through a novel and adaptive method that ensures that signals from low-gain channels are more optimally amplified than the signals from high-gain channels. This will be achieved by attempting to increase the scaling coefficient to its optimal value. The enhanced scaling coefficient thus proves efficient and optimal as it preserves the original power distribution among subcarriers (does not consume additional power). The performance improvement of the proposed adaptive AF (AAF) scheme is compared with existing AF and DF systems operating in both half-duplex and full-duplex modes in terms of throughput, fairness and call outage. The simulation results show that the AAF outperforms the AF and DF schemes in both half-and full-duplex modes. The rest of the paper is organized as follows. In Section 2, we establish a system model and relay transmission. In Section 3, we derive the scaling coefficient and adaptive relay gain factor. Section 4 formulates the optimization problem for resource allocation. In Section 5, we present the system performances. In Section 6, we summarize our work.

2 System Model and Relay Transmission

2.1. System Model

The traditional relaying system model is a network consisting of base station (BS), a relay station (RS) and a mobile station (MS) which is the primary building block of any larger relaying system and is illustrated in Fig. 1. The $\mathbf{P}_{BM}$, $\mathbf{P}_{BR}$ and $\mathbf{P}_{RM}$ are the allocated powers, $\mathbf{H}_{BM}$, $\mathbf{H}_{BR}$ and $\mathbf{H}_{RM}$ are the single-input-single-output (SISO) channel gain vectors and $\mathbf{Z}_{BM}$, $\mathbf{Z}_{BR}$ and $\mathbf{Z}_{RM}$ are the additive white Gaussians noise (AWGN) vectors on the B-M, B-R and R-M channels respectively. The channel gain vectors capture the effect of multipath fading, path loss and shadowing. $\mathbf{H}_{LI}$ is the loop interference channel vector when relay operates in full-duplexing mode. In half-duplexing there is no self-interference between the relay input and output antennas. We assume non-line-of-sight (NLOS) channel model for BS-MS and RS-MS links, and line-of-sight (LOS) model for the BS-RS link, since both BS and RS have fixed location. Furthermore, BS-RS and RS-MS links use the same frequency band, and BS-RS and RS-MS transmissions follow time-division-multiple-access (TDMA) protocol. We further assume that there is no interference in the signal paths from BS-MS and RS-MS. All the MS's are assumed to have fixed locations in the cell and so are assumed to be experiencing different channel statistics. All the RS's are also assumed to be experiencing different channel statistics as well.

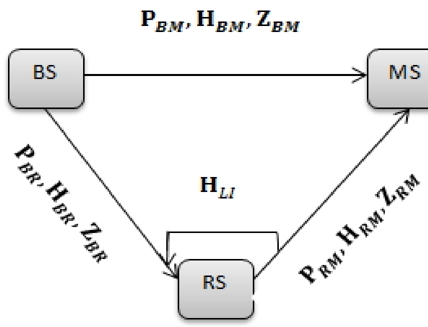

Fig. 1. The relaying system model.

The instantaneous SNR at any node for user m can be expressed as

$$\mathrm{SNR}_m(k,t) = \frac{\mathcal{P}_m(k,t)\ \mathbb{H}_\mathrm{m}(\mathrm{k,t})}{N_0} \quad (1)$$

where $\mathbb{H}_\mathrm{m}(\mathrm{k,t}) = \mathbf{h}_\mathrm{m}(\mathrm{k,t}) * PL_{\boldsymbol{m}} * \mathcal{X}_\sigma$ and $\mathbb{H}_\mathrm{m}(\mathrm{k,t}) = \mathbf{h}_\mathrm{m}(\mathrm{k,t}) * PL_{\boldsymbol{m}}$ represents NLOS and LOS propagation path, respectively. The $\mathcal{P}_m$ is the allocated power and N_0 is the noise power. The multipath fading channel, distance-dependent path-loss and shadowing is denoted by $\mathbf{h}_\mathrm{m}$, $PL_{\boldsymbol{m}}$ and $\mathcal{X}_\sigma$, respectively. To facilitate transmission, a time-division subcarrier allocation with two time slots is considered. As described in Table 1, the BS broadcasts its signal to the RS and MS in the first timeslot. If subcarrier k is using full-duplex (FD) relaying, the corresponding RS receives a copy of the signal, decodes/amplifies and forwards it to the MS in the second timeslot, while the BS transmits the next signal. If half-duplex (HD) relaying is used on subcarrier, the relays perform the same signal processing on subcarrier k as for FD transmission;

however, the BS remains silent during the second time slot.

Table 1: TDMA transmission protocol for the HD and FD relaying system.

	BS	RS	MS
Timeslot 1	Transmits	Listens	Listens
Timeslot 2	-	Transmits	Listens

2.2 Amplify-and-Forward Relaying

In AF protocol, the relay node simply amplifies the received signal and then forwards it to the destination. In HD mode, the AF relay takes two time slots to transmit a packet from BS to MS. In the first timeslot, the BS broadcasts its unit-energy signal vector and the signal vector received by MS m in subcarrier k is

$$\boldsymbol{y}_{BM_{m,k}}^{[k,t]} = \sqrt{\boldsymbol{P}_{BM_{m,k}}^{[k,t]}}\,\mathbf{H}_{BM_{m,k}}^{[k,t]}\,\mathbf{x}_{BM_{m,k}}^{[k,t]} + \boldsymbol{Z}_{BM_{m,k}}^{[k,t]} \quad (2)$$

The signal vector by RS r on the same subcarrier k is

$$\boldsymbol{y}_{BR_{m,r}}^{[k,t]} = \sqrt{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}}\,\mathbf{H}_{BR_{m,r}}^{[k,t]}\,\mathbf{x}_{BR_{m,r}}^{[k,t]} + \boldsymbol{Z}_{BR_{m,r}}^{[k,t]} \quad (3)$$

In the second timeslot, the RS r multiplies the received signal vector on subcarrier k by a relay gain vector $\boldsymbol{D}_{m,r}^{[k,t]^2}$ and then forwards the amplified signal vector to MS m on subcarrier k. Then the signal vector at MS m on subcarrier k from RS r can be expressed by

$$\boldsymbol{y}_{RM_{m,r}}^{[k,t]} = \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\,\mathbf{H}_{RM_{m,r}}^{[k,t]}\sqrt{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}}\,\mathbf{H}_{BR_{m,r}}^{[k,t]}\mathbf{x}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2} + \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\,\mathbf{H}_{RM_{m,r}}^{[k,t]}\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2} + \boldsymbol{Z}_{RM_{m,r}}^{[k,t]} \quad (4)$$

The SNR at the destination on BS-RS-MS link in terms of the relay gain, D, for the half-duplex AF (HD-AF) can expressed as

$$SNR_{AF-HD_{m,r}}^{[k,t]} = P_{BR_{m,r}}^{[k,t]}\Upsilon_{BR_{m,r}}^{[k,t]}\frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]} + \frac{1}{\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{HD_{m,r}}^{[k,t]^2}}} \quad (5)$$

where $\Upsilon_{BR_{m,r}}^{[k,t]} = \frac{\mathbf{H}_{BR_{m,r}}^{[k,t]}}{\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}$, $\Upsilon_{RM_{m,r}}^{[k,t]} = \frac{\mathbf{H}_{RM_{m,r}}^{[k,t]}}{\boldsymbol{Z}_{RM_{m,r}}^{[k,t]}}$, $\Upsilon_{BM_{m,r}}^{[k,t]} = \frac{\mathbf{H}_{BM_{m,r}}^{[k,t]}}{\boldsymbol{Z}_{BM_{m,r}}^{[k,t]}}$, $\Upsilon_{BM_{m}}^{[k,t]} = \frac{\mathbf{H}_{BM_{m}}^{[k,t]}}{\boldsymbol{Z}_{BM_{m}}^{[k,t]}}$. and the relay gain factor is given in [8] as

$$\boldsymbol{D}_{HD_{m,r}}^{[k,t]} = \sqrt{\frac{1}{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\mathbf{H}_{RM_{m,r}}^{[k,t]} + \boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}} \quad (6)$$

The generalized SNR for full-duplex AF (FD-AF) relaying can also be derived in terms of the relay gain factor, D. However, the relay gain factor for the FD-AF will include the residual loop interference SNR as shown later in the section. In the first time slot, the received signal vector by RS r from BS for MS m on subcarrier k is

$$\boldsymbol{y}_{BR_{m,r}}^{[k,t]} = \sqrt{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}}\,\mathbf{H}_{BR_{m,r}}^{[k,t]}\,\mathbf{x}_{BR_{m,r}}^{[k,t]} + \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\mathbf{H}_{LI_{m,r}}^{[k,t]}\boldsymbol{q}_{m,r}^{[k,t]} + \boldsymbol{Z}_{BR_{m,r}}^{[k,t]} \quad (7)$$

Following the same procedure as described in [5], the RS r subtracts the loop interference cancellation vector

$\boldsymbol{C}_{BR_m}^{[k,t]} = \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\,\widehat{\mathbf{H}}_{LI_{m,r}}^{[k,t]}\boldsymbol{q}_{m,r}^{[k,t]}$ from $\boldsymbol{y}_{BR_{m,r}}^{[k,t]}$ for loop interference cancellation to yield

$$\breve{\boldsymbol{y}}_{BR_{m,r}}^{[k,t]} = \boldsymbol{y}_{BR_{m,r}}^{[k,t]} - \boldsymbol{C}_{BR_{m,r}}^{[k,t]} = \sqrt{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}}\,\mathbf{H}_{BR_{m,r}}^{[k,t]}\,\mathbf{x}_{BR_{m,r}}^{[k,t]} + \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\boldsymbol{\Delta H}_{LI_{m,r}}^{[k,t]}\boldsymbol{q}_{m,r}^{[k,t]} + \boldsymbol{Z}_{BR_{m,r}}^{[k,t]} \quad (8)$$

where $\widehat{\mathbf{H}}_{LI_{m,r}}^{[k,t]}$ the estimated loop interference channel and $\boldsymbol{\Delta H}_{LI_{m,r}}^{[k,t]} \sim \mathcal{CN}\left(0, \Xi_m^{[t]}\right)$ the residual loop interference channel due to imperfect channel estimation. $\Xi_m^{[t]}$ is a diagonal covariance matrix with each main diagonal element equal to σ_e^2. $\boldsymbol{q}_{m,r}^{[k,t]}$ is the $N \times 1$ accumulated loop interference signal vector at RS r on subcarrier k caused by AF-FD relaying. In the second timeslot, RS r multiplies the signal vector received from BS by $\boldsymbol{D}_{m,r}^{[k,t]^2}$ and forwards it to the MS m. Then the received signal vector at MS m on subcarrier k from RS r is given as

$$\boldsymbol{y}_{RM_{m,r}}^{[k,t]} = \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\,\mathbf{H}_{RM_{m,r}}^{[k,t]}\sqrt{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}}\,\mathbf{H}_{BR_{m,r}}^{[k,t]}\mathbf{x}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2} + \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\,\mathbf{H}_{RM_{m,r}}^{[k,t]}\sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\,\boldsymbol{\Delta H}_{LI_{m,r}}^{[k,t]}\boldsymbol{q}_{m,r}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2} + \sqrt{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}}\,\mathbf{H}_{RM_{m,r}}^{[k,t]}\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2} + \boldsymbol{Z}_{RM_{m,r}}^{[k,t]} \quad (9)$$

The SNR at MS m on subcarrier k can expressed as

$$SNR_{AF-FD_{m,r}}^{[k,t]} = \frac{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\Upsilon_{BR_{m,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{LI_{m,r}}^{[k,t]}+1} * \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]} + \frac{1}{\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{FD_{m,r}}^{[k,t]^2}\left(\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{LI_{m,r}}^{[k,t]}+1\right)}} \quad (10)$$

where $\Upsilon_{LI_{m,r}}^{[k,t]} = \frac{\Delta H_{LI_{m,r}}^{[k,t]}}{\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}$ denotes the residual loop interference SNR. Similar to relay gain factor for HD-AF relaying in (6), the relay gain factor for FD-AF relaying can be derived in terms of residual loop interference SNR, $\Upsilon_{LI_{m,r}}^{[k,t]}$ as follow:

$$\boldsymbol{D}_{FD_{m,r}}^{[k,t]} = \sqrt{\frac{1}{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\mathbf{H}_{RM_{m,r}}^{[k,t]}+\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}+\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{LI_{m,r}}^{[k,t]}\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}} \quad (11)$$

3 Scaling Coefficient and Adaptive Relay Gain

The SNR for AF-HD and AF-FD in (5) and (10) can be re-written as

$$SNR_{AF-HD_{m,r}}^{[k,t]} = \boldsymbol{P}_{BR_{m,r}}^{[k,t]}\Upsilon_{BR_{m,r}}^{[k,t]} \,.\, \boldsymbol{\alpha}_{HD-AF_{m,r}}^{[k,r]} \quad (12)$$

$$SNR_{AF-FD_{m,r}}^{[k,t]} = \frac{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\Upsilon_{BR_{m,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{LI_{m,r}}^{[k,t]}+1} \,.\, \boldsymbol{\alpha}_{FD-AF_{m,r}}^{[k,t]} \quad (13)$$

where $\boldsymbol{\alpha}_{HD-AF_{m,r}}^{[k,r]} = \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]} + \frac{1}{\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2}}}$

and

$$\boldsymbol{\alpha}_{FD-AF_{m,r}}^{[k,t]} = \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{RM_{m,r}}^{[k,t]} + \frac{1}{\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2}\left(\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{LI_{m,r}}^{[k,t]}+1\right)}}$$

The authors in [7][9], first introduced the parameter, $\boldsymbol{\alpha}$, which they called the cooperation coefficient and which lies between 0 and 1 for HD-AF relay protocol as follow:

$$\boldsymbol{\alpha}_{HD-AF_{m,r}}^{[k,r]} = \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}+\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BR_{m,r}}^{[k,t]}+1} \quad (14)$$

In [7], the authors defined the cooperation coefficient as the cooperation level (level of contribution) in the capacity from the indirect (relay) path to the total capacity (in terms of SNR) at the destination. We, however, wish to simply refer to this parameter as the scaling coefficient which it suggests in (12) and (13). The scaling coefficients can be re-written in a generalized form, for any type of relay gain factor, as

$$\boldsymbol{\alpha}_{HD-AF_{m,r}}^{[k,r]} = \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{HD_{m,r}}^{[k,t]^2}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{HD_{m,r}}^{[k,t]^2}+1} \quad (15)$$

$$\boldsymbol{\alpha}_{FD-AF_{m,r}}^{[k,t]} = \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{FD_{m,r}}^{[k,t]^2}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{FD_{m,r}}^{[k,t]^2}+1} \quad (16)$$

where $\boldsymbol{\beta}_{HD-AF_{m,r}}^{[k,r]} = \boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{HD_{m,r}}^{[k,t]^2}$

and $\boldsymbol{\beta}_{FD-AF_{m,r}}^{[k,r]} = \boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{FD_{m,r}}^{[k,t]^2}$

represent the open-loop gains, and $\boldsymbol{\alpha}_{HD-AF_{m,r}}^{[k,r]}$ and $\boldsymbol{\alpha}_{FD-AF_{m,r}}^{[k,r]}$ are the closed-loop gains of the AF amplifier with unity feedback in half-duplex and full-duplex modes, respectively. From (15) and (16), it is obvious that if α can be increased towards its maximum value of 1, then both the SNR_{AF-HD} and SNR_{AF-FD} will also increase. To achieve this, the relay gain factor must be made to increase in response to a decreasing scaling coefficient. Therefore, the relay gain factor D which increases as α decreases can be expressed by the gain ratio

$$\overline{\boldsymbol{D}}_{m,r}^{[k,t]} = \frac{\boldsymbol{D}_{m,r}^{[k,t]}}{\boldsymbol{\alpha}_{m,r}^{[k,t]}} \quad (17)$$

$$= \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2}+1}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]}}$$

where $\boldsymbol{D}_{m,r}^{[k,t]}$ is still the relay gains defined in the previous section for HD and FD. When

$\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]^2} \gg 1$ the adaptive relay gain $\overline{\boldsymbol{D}}_{m,r}^{[k,t]} = \boldsymbol{D}_{m,r}^{[k,t]}$ and the signals with $\boldsymbol{\alpha}_{m,r}^{[k,t]}$ already close to 1 are not affected. When $\boldsymbol{\alpha}_{m,r}^{[k,t]}$ is far away from 1, the signal is amplified by $\overline{\boldsymbol{D}}_{m,r}^{[k,t]} = \boldsymbol{D}_{m,r}^{[k,t]} + 1/\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\boldsymbol{D}_{m,r}^{[k,t]}$ so as to equalize and increase the linear gain $\boldsymbol{\alpha}_{m,r}^{[k,t]}$ over all the subcarriers, and hence increase the SNR received at the MS through the relay. Therefore, the proposed relay gain factors for HD and FD protocols can be expressed, respectively, by

$$\overline{\boldsymbol{D}}_{HD_{m,r}}^{[k,t]} = \frac{\left(\frac{1}{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\mathbf{H}_{BM_{m,r}}^{[k,t]}+\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}+L\right)}{\left(\frac{1}{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\mathbf{H}_{BM_{m,r}}^{[k,t]}+\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}\right)^{1/2}} \tag{18}$$

$$\overline{\boldsymbol{D}}_{FD_{m,r}}^{[k,t]} = \frac{\left(\frac{1}{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\mathbf{H}_{BM_{m,r}}^{[k,t]}+\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}+\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{LI_{m,r}}^{[k,t]}\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}+L\right)}{\left(\frac{1}{\boldsymbol{P}_{BR_{m,r}}^{[k,t]}\mathbf{H}_{BM_{m,r}}^{[k,t]}+\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}+\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\Upsilon_{LI_{m,r}}^{[k,t]}\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}}\right)^{1/2}} \tag{19}$$

where $L = \frac{1}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\mathbf{H}_{RM_{m,r}}^{[k,t]}}$

The proposed relay gain is adaptive because it dynamically increases the scaling coefficients towards their optimal values and thus attempts to equalize the SNRs over all the subcarriers. The resulting scaling coefficients (enhanced scaling coefficient) for HD and FD systems can be written as

$$\overline{\boldsymbol{\alpha}}_{HD-AF_{m,r}}^{[k,r]} = \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\overline{\boldsymbol{D}}_{HD_{m,r}}^{[k,t]^2}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\mathbf{Z}_{BR_{m,r}}^{[k,t]}\overline{\boldsymbol{D}}_{HD_{m,r}}^{[k,t]^2}+1} \tag{20}$$

$$\overline{\boldsymbol{\alpha}}_{FD-AF_{m,r}}^{[k,r]} = \frac{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\overline{\boldsymbol{D}}_{FD_{m,r}}^{[k,t]^2}}{\boldsymbol{P}_{RM_{m,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m,r}}^{[k,t]}\boldsymbol{Z}_{BR_{m,r}}^{[k,t]}\overline{\boldsymbol{D}}_{FD_{m,r}}^{[k,t]^2}+1} \tag{21}$$

It should be noted that $\overline{\boldsymbol{\alpha}}_{AF_{m,r}}^{[k,r]}$ in (20) and (21) must remain bounded between 0 and 1, in order to preserve the original power distribution among the subcarriers at the relay node. Therefore, the adaptive relay gain does not lead to increase in power consumption.

4 Optimization Problems

The total SNR at the MS for both FD and HD in two-way AF relaying using maximum ratio combiner (MRC) combiner is

$$\mathrm{SNR}_{HD-AF_{m2,r}}^{[k,t]} = \boldsymbol{P}_{BM_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BM_{m2,r}}^{[k,t]} + \boldsymbol{\alpha}_{HD-AF_{m2,r}}^{[k,t]}\boldsymbol{P}_{BR_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BR_{m2,r}}^{[k,t]} \tag{22}$$

$$\mathrm{SNR}_{FD-AF_{m2,r}}^{[k,t]} = \boldsymbol{P}_{BM_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BM_{m2,r}}^{[k,t]} + \boldsymbol{\alpha}_{FD-AF_{m2,r}}^{[k,t]}\frac{\boldsymbol{P}_{BR_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BR_{m2,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{LI_{m2,r}}^{[k,t]}+1} \tag{23}$$

For HD and FD in two-way DF relaying the MRC combiner at destination receiver yields

$$\mathrm{SNR}_{HD-DF_{m2,r}}^{[k,t]} = \boldsymbol{P}_{BM_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BM_{m2,r}}^{[k,t]} + min\left(\boldsymbol{\varepsilon}_{m2,r}^{[k,t]}\boldsymbol{P}_{BR_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BR_{m2,r}}^{[k,t]}, \boldsymbol{P}_{RM_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m2,r}}^{[k,t]}\right) \tag{24}$$

$$\mathrm{SNR}_{FD-DF_{m2,r}}^{[k,t]} = \boldsymbol{P}_{BM_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{BM_{m2,r}}^{[k,t]} + min\left(\boldsymbol{\varepsilon}_{m2,r}^{[k,t]}\frac{\boldsymbol{P}_{BR_{m2,r}}^{[k,t]}\Upsilon_{BR_{m2,r}}^{[k,t]}}{\boldsymbol{P}_{RM_{m2,r}}^{[k,t]}\Upsilon_{LI_{m2,r}}^{[k,t]}+1}, \boldsymbol{P}_{RM_{m2,r}}^{[k,t]}\boldsymbol{\Upsilon}_{RM_{m2,r}}^{[k,t]}\right) \tag{25}$$

Where $\boldsymbol{\varepsilon}_{m,r}^{[k,t]} \in \{0,1\}$ represents the decoding factor. Some works in [10] have assumed that the DF relay is only capable of detecting the errors. In this case, the relay intelligently stops the transmission in case any error is detected at the relay. However, if the received signal y_{BR} is perfectly decoded then $\varepsilon_{m,r}^{[k,t]} = 1$, otherwise $0 \leq \varepsilon_{m,r}^{[k,t]} < 1$. Therefore, the optimization objective can be expressed by

$$\max_{p(t)\in\mathcal{P}} \; w_m[t]\left\{\frac{B}{JK}\sum_{m=1}^{N_m}\sum_{k=1}^{N_k}\log_2\left(1+\frac{\mathbf{SNR}_{HD/FD}^{[k,t]}}{\Gamma}\right)\right\} \tag{26}$$

where $w_m[t,k]$ is the scheduling weight for user m on subcarrier k. The total channel bandwidth is denoted by B and scaled by the duplexing factor J which either 1 or 2 depending on whether the network is operating in FD or HD mode. The received signal power SNR is also scaled by the SNR gap Γ for a given bit-error-rate (BER).

5 Simulation Results

In this section, we will evaluate and compare the performances of the AF, DF and the proposed adaptive AF (AAF) relaying scheme in terms of average system throughput, fairness and call outage both in HD and FD modes. The simulation settings are summarized in Table 2. For DF, the decoding factor $\varepsilon_{m,r}^{[k,t]} = 1$ is used. For resource allocation, we consider an opportunistic scheduling provided by the maximum-sum-rate (MSR) with the scheduling weight, $w_m[t] = 1$. The simulation is run for 10s.

5.1. Performance Evaluations

The following performance metrics will be used for comparison of different relaying schemes in the downlink of an orthogonal frequency division multiple access (OFDMA) system:

5.1.1. Average system throughput

Average system throughput is the total amount of transmitted packet rate for user m averaged over all time slots and averaged over all users.

5.1.2. Call Outage

Call outage is defined as the percentage of users who did not achieve their required QoS (such as minimum average throughput, packet loss ratio or maximum latency). In this case, a minimum average throughput of 9Kbps is set.

5.1.3. Fairness

Jain Fairness Index (JFI): a fairness index is used to calculate fairness among users that belong to the same class (i.e., intra-class fairness). Let ψ_m be the performance metric for user m, where ψ_m is set to the user's average throughput, then the JFI is calculated as follows [13]:

$$JFI_{\mathcal{C}} = \frac{(\sum_{m \in \mathcal{C}} \psi_m)^2}{|\mathcal{C}| \sum_{m \in \mathcal{C}} (\psi_m)^2} \quad , \psi_m \leq 0 \ \forall m \qquad (27)$$

where $\mathcal{C}$ is the set of users of the same QoS class and $|\mathcal{C}|$ denotes the number of users in each class. Note that if all users that request the same QoS get the same ψ_m, then $JFI_{\mathcal{C}} = 1$. Lower $JFI_{\mathcal{C}}$ values indicate that users have high variances in their achieved QoS, which reveals unfairness in distributing the wireless resources among them according to this scheme.

Table 2: Simulation Parameters

Parameter	Value
System bandwidth	3 MHz
Number of subcarriers	64
Relay distance	500 Km
Path-Loss Model Path-loss exponent, n Standard deviation for shadowing, χ_σ Cell radius, r Reference distance, d_0 Wavelength, λ	$.\ PL(d)[dB] = 20log\left(\frac{4\pi d_0}{\lambda}\right) + 10nlog\left(\frac{d}{d_0}\right) + \chi_\sigma$ 3 8dB 1000 Km 100 meters 120 mm
BS transmit power, P_t	$33.9897\ dBm$
Noise Power, σ_v^2	$-163\ dBm$
BER	10^{-6}
Slot duration, T_s	2.0571ms
Queue Size	500 Kbytes
Antenna configuration	SISO
Number of users	40

Table 3 illustrates how the adaptive AF relay amplifies the signal from low-gain channel more than the signal from high-gain channel. The conventional AF and adaptive AF scaling coefficients are denoted by α_{HD}, α_{FD} and $\bar{\alpha}_{HD}$, $\bar{\alpha}_{FD}$, respectively, for HD and FD. The $SNR_{B-R}^{HD/FD}$ represents the SNR in either HD or FD at RS before amplification. The SNR_{B-R-M}^{HD} and $\overline{SNR}_{B-R-M}^{HD}$ are the received SNR at the MS after amplification using conventional AF and adaptive AF amplifiers, respectively, in HD mode. The SNR_{B-R-M}^{FD} and $\overline{SNR}_{B-R-M}^{FD}$ are the amplified and received SNR when FD mode is used. The scaling coefficients are in linear units, and are used to scale the linear value of $SNR_{B-R}^{HD/FD}$. As it is shown in Table 3, the adaptive scaling coefficients $\bar{\alpha}_{HD}$ and $\bar{\alpha}_{FD}$ are substantially higher compared to their conventional counterparts α_{HD} and α_{FD}. This is because; the adaptive AF relay increases the scaling values when the relay is operated in either half- and full-duplex mode. This increase in the scaling factor is reflected as increase in the amplified SNR, i.e. $\overline{SNR}_{B-R-M}^{HD}$ and $\overline{SNR}_{B-R-M}^{FD}$ compared to SNR_{B-R-M}^{HD} and SNR_{B-R-M}^{FD} when conventional AF amplification factor is used. Also, noticeable is the fact that the adaptive scaling coefficient is still bounded within its maximum value of 1.

Fig. 2 shows the average system throughput performances of the different relaying schemes. The instantaneous loop interference power $\Upsilon_{LI} = 30\ dB$ is assumed for FD relaying. As it can be seen DF-HD and DF-FD relaying outperform the AF relaying protocols. This is due to the fact that the AF relays amplify the thermal noise power in the case of HD relaying and the loop interference in case of FD relaying. On the other hand, AF-FD and DF-FD relaying, at the 30dB of average loop interference power, outperform AF-HD and DF-HD relaying because DF-FD relaying has a better spectral efficiency by allowing the BS and the relays to transmit simultaneously in two phases, while the HD relays use two phases to transmit one message. However, the proposed adaptive AF (AAF) scheme outperforms both the AF and DF schemes operating in HD and FD modes. The noticeably superior performance of AAF in FD mode is that it is able to significantly overcome both the thermal noise and the loop interference impairments in order to produce the highest average system throughput.

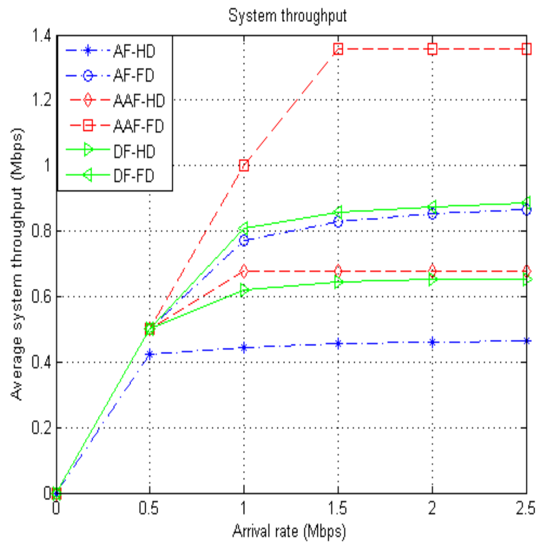

Fig. 2. Average system throughput for different relaying Schemes

Fig. 3 shows that the AAF scheme provides the best and almost equal throughput fairness performances in both HD and FD modes for a MSR scheduling which, by nature, exhibits very poor fairness performance at the expense of maximizing system throughput as shown for the conventional AF and DF schemes. This proportional fairness is achieved because the adaptive AF not only maximizes the signal-to-noise ratio across all subcarriers but ensures that SNR on bad channels are increased more than those on already good channels. Fig. 4 depicts the percentage of the ratio of the number of users whose calls are in outage to the total number of users in the network. Outage in this case represents the users' calls that are not allocated network resources. The AAF scheme operating in HD and FD achieves the lowest percentage of call outage which remains at 20% beyond the arrival rate of 1Mbps and 1.5Mbps, respectively, while the conventional AF and DF show increasing percentage of call outage as the arrival rate increases.

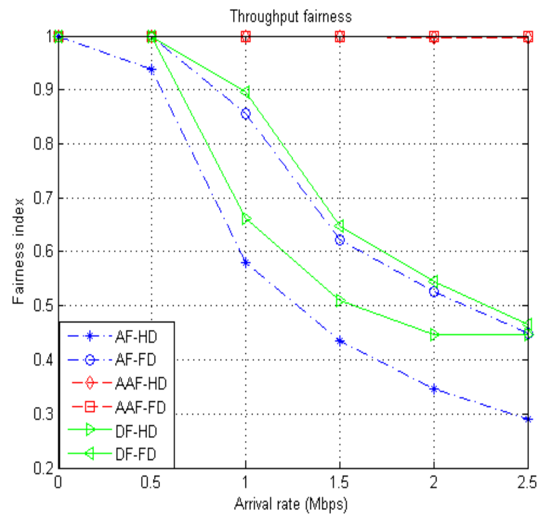

Fig. 3. Throughput fairness for different relaying schemes

Table 3: Scaling Coefficient and SNR

Subcarrier	1	2	3	4	5	6	7	8
$SNR_{B-R}^{HD/FD}$ (dB)	16.3100	19.4441	22.8685	24.7489	24.9918	26.0598	26.8439	31.3521
α_{HD}	0.5381	0.4262	0.7471	0.8549	0.6961	0.6343	0.5417	0.2441
$\bar{\alpha}_{HD}$	0.8009	0.8035	0.8411	0.8896	0.8254	0.8117	0.8011	0.8442
SNR_{B-R-M}^{HD} (dB)	13.6188	15.7401	21.6022	24.0681	23.4182	24.0826	24.1811	25.2279
$\overline{SNR}_{B-R-M}^{HD}$ (dB)	15.3460	18.4939	22.1168	24.2411	24.1583	25.1538	25.8809	30.6167
α_{FD}	0.1189	0.1351	0.5209	0.7358	0.5270	0.4872	0.4116	0.2060
$\bar{\alpha}_{FD}$	0.9052	0.8954	0.8003	0.8372	0.8005	0.8001	0.8050	0.8594
SNR_{B-R-M}^{FD} (dB)	7.0608	10.7507	20.0358	23.4164	22.2101	22.9365	22.9883	24.4912
$\overline{SNR}_{B-R-M}^{FD}$ (dB)	15.8774	18.9641	21.9009	23.9774	24.0252	25.0913	25.9021	30.6942

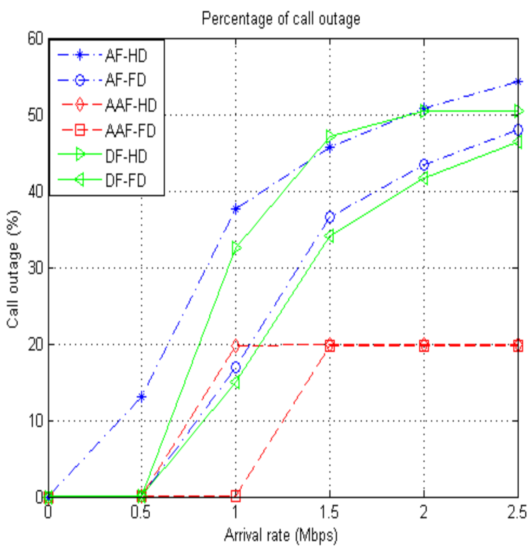

Fig. 4: Percentage of call outage for different relaying schemes

6 Conclusion

In this paper, we have analyzed the existing AF relaying schemes and have derived an adaptive AF (AAF) relay gain factor to combat the effect of thermal noise in AF in HD and FD, and loop interference in FD relaying. We have shown that the adaptive AF relay gain increases the scaling coefficient further and amplify signals on low-gain channel more than the signals from high-gain channels. The simulation results show that AAF outperforms the conventional AF and DF schemes operating in both half-and full-duplex modes in terms of throughput; its throughput performance in FD is very significant compared to AF and DF in similar mode. This is because both the thermal noise and loop interference renders the signals in FD mode extremely low; hence the signals are more highly amplified compared to that in the HD mode. Therefore, the proposed method performs better in low-SNR systems. The results also show that the proposed method achieves very high throughput fairness compared to the other schemes, when used with the MSR scheduling algorithm which is known to perform poorly in throughput fairness, because it attempts to equalize the SNR across subcarriers. It is also shown that the proposed scheme keep probability of call outage low and consistently flat, meaning that better service coverage can be guaranteed when it is employed.

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