Static Hybrid Multihop Relaying

[1]Sami Touati, [2]Hatem Boujemaa
[1]King Saud University, Kingdom of Saudi Arabia
[2]University of Carthage, Sup'Com, COSIM Laboratory, Tunisia
stouati@ksu.edu.sa, boujemaa.hatem@supcom.rnu.tn

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Abstract—**In this work, we propose a new static hybrid multihop relaying protocol where some relays amplify the received signal whereas the remaining ones use Decode and Forward (DF) relaying. The relaying mode in each relay is set using the distance between the different nodes or the average SNR. The exact and asymptotic bit error probabilities are derived. Simulation results are provided in different contexts to compare the performance of hybrid relaying to conventional AF and DF relaying.**

Keywords : Cooperative diversity, Decode and Forward relaying, Amplify and Forward Relaying, Rayleigh fading channels.

I. Introduction

Multihop relaying can be used in wireless networks in order to increase the coverage and reduce the outage probability. By increasing the number of hops, the average Signal to Noise Ratio (SNR) at the destination increases for the same power spent by the source and all relays. Amplify and Forward (AF) and Decode and Forward (DF) relaying are the most widely used protocols. In AF relaying, each relay amplifies the received signal using an adaptive gain. DF relays demodulate the signal and regenerate it. To avoid error propagation, they transmit only if they correctly decoded. Therefore, AF protocol is less complex than DF but it may offer worse performance than DF since the noise is amplified with the useful signal.

The Bit Error Probabilities (BEP) of dual-hop and multihop relaying using AF have been derived in [1]-[3]. Multihop multibranch relaying using DF has been studied in [4]. Some adaptive AF and DF relaying protocols were proposed in the literature for dual-hop relaying [5]-[9]. In [5]-[7], the relay first tries to decode the received signal. If the decoding succeeds, it transmits the decoded signal as in DF protocol. If the decoding fails, the relay simply amplifies the received signal. In [8], the relay estimates the BEP using log-likelihood ratios. If the estimated BEP is above a given threshold, DF relaying is used. Otherwise, the relay amplifies the received signal since it contains no or only few errors. In [9], a Decode-Amplify Forward protocol is proposed where a relay amplifies the soft output of the channel decoder output. In [10], an adaptive relaying protocol has been proposed called Threshold based adaptive Decode-Amplify and Forward relaying. In this protocol, AF is used only when the instantaneous SNR is larger than the average one. Otherwise, DF is used. Static hybrid dual hop relaying has been proposed in [11]-[12] where some relays use AF and faraway relays decode the received signal. In this static dual hop hybrid relaying protocol, the relaying mode is fixed as long as the relay node position remains unchanged. The relaying mode of each relay is based on relays position or the average SNR. To the best of the authors' knowledge, static multihop hybrid relaying, where some relays use AF and other relays use DF relaying, hasn't been previously proposed or studied. The paper scope is to set the relaying mode (AF or DF) for each relay to have a good compromise between complexity and performance. For example, for 3 hops network, we will compare the performance of AF-DF, DF-AF, DF-DF and AF-AF. AF-DF means that the first relays amplifies the received signal whereas the next one use decode and forward relaying. [1]

The paper is organized as follows. The next section deals with hybrid three hops relaying whereas section III is dedicated to four hops relaying. Section IV generalizes the previous results to multihop relaying. Section V provides some simulation results. Section VI draws some conclusions and perspectives.

II. Hybrid three hops Relaying

A. Performance analysis of DF-DF relaying

We consider a cooperative network composed of a source S, two relays R_1 and R_2, and a destination D. Each symbol x is transmitted from S to R_1, then R_1 detects it and forwards it to R_2. Finally, R_2 detects the symbol and forwards it to D. Both relays transmit only they have correctly detected. Otherwise, $R_1$and/or R_2 are idle and the symbol will not be received at D.We assume that each relay perfectly judges if it has correctly decoded.

The Bit Error Probability (BEP) at D is given by

$$P_{e,D}^{DFDF} = 1-(1-P_{e,SR_1})(1-P_{e,R_1R_2})(1-P_{e,R_2D}), \quad (1)$$

where $P_{e,XY}$ is the BEP between nodes X and Y, $(X,Y) \in \{(S,R_1);(R_1,R_2);(R_2,D)\}$. For $M-QAM$ modulation and Rayleigh fading channels, it is given by

$$P_{e,XY} = \frac{A}{2}\left(1-\sqrt{\frac{\overline{\Gamma}_{XY}}{\overline{\Gamma}_{XY}+\frac{2}{B}}}\right), \quad (2)$$

A and B depend on the considered modulation (for example, $A=1$, $B=2$ for $BPSK$), $\overline{\Gamma}_{XY}$ is the average SNR of X-Y link

$$\overline{\Gamma}_{XY} = E(\Gamma_{XY}) = \frac{E_X}{N_0}E(|h_{XY}|^2), \quad (3)$$

$E(.)$ is the expectation operator, E_X is the transmitted energy per symbol by X and $E(|h_{XY}|^2)$ is the power of the Rayleigh fading channel h_{XY}.

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The asymptotic BEP at D can be written as

$$\begin{aligned}\widetilde{P}_{e,D}^{DFDF} &= \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}}+\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2D}}\right] \\ &-\left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}}\left(\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2D}}\right)+\frac{1}{\overline{\Gamma}_{R_1R_2}}\frac{1}{\overline{\Gamma}_{R_2D}}\right]\end{aligned} \quad (4)$$

B. Performance analysis of AF-AF relaying

For AF relaying, the SNR at the destination can be written as [2]

$$\Gamma_D = \frac{\Gamma_{SR_1R_2}\Gamma_{R_2D}}{1+\Gamma_{SR_1R_2}+\Gamma_{R_2D}} < \Gamma_D^{up} = \min(\Gamma_{SR_1},\Gamma_{R_1R_2},\Gamma_{R_2D}), \quad (5)$$

where $\Gamma_{SR_1R_2}$ is the SNR of SR_1R_2 AF link.
For Rayleigh fading channels, Γ_D^{up} follows an exponential distribution with mean

$$\overline{\Gamma_D^{up}} = \frac{1}{\frac{1}{\overline{\Gamma}_{SR_1}}+\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2D}}}. \quad (6)$$

We deduce a lower bound of the BEP at the destination for M-QAM modulations :

$$P_{e,D}^{AFAF} > \int AQ(\sqrt{B\gamma})p_{\Gamma_D^{up}}(\gamma)d\gamma = \frac{A}{2}\left(1-\sqrt{\frac{\overline{\Gamma_D^{up}}}{\overline{\Gamma_D^{up}}+\frac{2}{B}}}\right). \quad (7)$$

Using (7), the asymptotic BEP of AFAF relaying is given by

$$\widetilde{P}_{e,D}^{AFAF} = \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}}+\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2D}}\right] \quad (8)$$

C. Performance analysis of the proposed DF-AF relaying

In DF-AF relaying, the first relay detects the transmitted symbol whereas R_2 amplifies the received signal. The BEP at the destination is given by

$$P_{e,D}^{DFAF} = 1-(1-P_{e,SR_1})(1-P_{e,R_1R_2D}), \quad (9)$$

We can derive the exact expression of the BEP of R_1R_2D link [3]. However, we prefer to use min upper bound to obtain closed form expressions

$$\Gamma_{R_1R_2D} < \Gamma_{R_1R_2D}^{up} = \min(\Gamma_{R_1R_2},\Gamma_{R_2D}) \quad (10)$$

This upper bound gives

$$P_{e,R_1R_2D} > \frac{A}{2}\left[1-\sqrt{\frac{\overline{\Gamma}_{R_1R_2D}^{up}}{\overline{\Gamma}_{R_1R_2D}^{up}+\frac{2}{B}}}\right] \quad (11)$$

where

$$\overline{\Gamma}_{R_1R_2D}^{up} = \frac{\overline{\Gamma}_{R_1R_2}\overline{\Gamma}_{R_2D}}{\overline{\Gamma}_{R_1R_2}+\overline{\Gamma}_{R_2D}} \quad (12)$$

Combining (9) and (11), we obtain a lower bound on the BEP at the destination for hybrid DF-AF relaying.
The asymptotic BEP of hybrid DFAF relaying is given by

$$\begin{aligned}\widetilde{P}_{e,D}^{DFAF} &= \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}}+\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2D}}\right] \\ &-\left(\frac{A}{2B}\right)^2\frac{1}{\overline{\Gamma}_{SR_1}}\left[\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2D}}\right]\end{aligned} \quad (13)$$

D. Performance analysis of the proposed AF-DF relaying

For AF-DF relaying, the BEP at D is given by

$$P_{e,D} = 1-(1-P_{e,SR_1R_2})(1-P_{e,R_2D}), \quad (14)$$

$$P_{e,SR_1R_2} > \frac{A}{2}\left[1-\sqrt{\frac{\overline{\Gamma}_{SR_1R_2}^{up}}{\overline{\Gamma}_{SR_1R_2}^{up}+\frac{2}{B}}}\right], \quad (15)$$

and

$$\overline{\Gamma}_{SR_1R_2}^{up} = \frac{\overline{\Gamma}_{SR_1}\overline{\Gamma}_{R_1R_2}}{\overline{\Gamma}_{SR_1}+\overline{\Gamma}_{R_1R_2}}. \quad (16)$$

The asymptotic BEP of hybrid AFDF relaying is given by

$$\begin{aligned}\widetilde{P}_{e,D}^{AFDF} &= \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}}+\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2D}}\right] \\ &-\left(\frac{A}{2B}\right)^2\frac{1}{\overline{\Gamma}_{R_2D}}\left[\frac{1}{\overline{\Gamma}_{SR_1}}+\frac{1}{\overline{\Gamma}_{R_1R_2}}\right]\end{aligned} \quad (17)$$

E. Performance comparison of the different protocols

By comparing the asymptotic BEP, we first notice that AFAF relaying offers worse performance than the other protocols. Also, DFDF offers always better performance than DFAF and AFDF. The difference between the asymptotic performance of DFAF and AFDF is given by

$$\widetilde{P}_{e,D}^{DFAF}-\widetilde{P}_{e,D}^{AFDF} = \left(\frac{A}{2B}\right)^2\frac{1}{\overline{\Gamma}_{R_1R_2}}\left[\frac{1}{\overline{\Gamma}_{R_2D}}-\frac{1}{\overline{\Gamma}_{SR_1}}\right], \quad (18)$$

which clearly shows that DFAF outperforms AFDF only when $\overline{\Gamma}_{R_2D} > \overline{\Gamma}_{SR_1}$. Furthermore, equations (4) and (13) show that the proposed hybrid DFAF protocol offer the same performance as DFDF relaying for large values of $\overline{\Gamma}_{R_1R_2}$ or $\overline{\Gamma}_{R_2D}$ (i.e R_2 is close to R_1 or the destination). Also, equations (4) and (17) show that the proposed hybrid AFDF protocol offer the same performance as DFDF relaying for large values of $\overline{\Gamma}_{SR_1}$ or $\overline{\Gamma}_{R_1R_2}$ (i.e R_1 is close to S or R_2). The proposed hybrid relaying protocols are less complex than DFDF since decoding is not performed at one relay which reduces power consumption and transmission delays.

III. Hybrid four hops relaying

A. DFDFDF relaying

For DFDFDF relaying, the BEP at the destination is given by

$$\begin{aligned}P_{e,D}^{DFDFDF} &= 1-(1-P_{e,SR_1})(1-P_{e,R_1R_2}) \\ &\times(1-P_{e,R_2R_3})(1-P_{e,R_3D})\end{aligned} \quad (19)$$

Therefore, the asymptotic BEP is given by

$$\begin{aligned}\widetilde{P}_{e,D}^{DFDFDF} &= \frac{A}{2B}\left(\frac{1}{\overline{\Gamma}_{SR_1}}+\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2R_3}}+\frac{1}{\overline{\Gamma}_{R_3D}}\right) \quad (20)\\ &-\left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}}\left(\frac{1}{\overline{\Gamma}_{R_1R_2}}+\frac{1}{\overline{\Gamma}_{R_2R_3}}+\frac{1}{\overline{\Gamma}_{R_3D}}\right)\right. \\ &\left.+\frac{1}{\overline{\Gamma}_{R_1R_2}}\left(\frac{1}{\overline{\Gamma}_{R_2R_3}}+\frac{1}{\overline{\Gamma}_{R_3D}}\right)+\frac{1}{\overline{\Gamma}_{R_2R_3}\overline{\Gamma}_{R_3D}}\right]\end{aligned}$$

B. AFAFAF relaying

Similarly to section II.B, a lower bound of the BEP at the destination for AFAFAF relaying is given by

$$P_{e,D}^{AFAFAF} > \frac{A}{2}\left(1-\sqrt{\frac{\overline{\Gamma}_D^{up}}{\frac{2}{B}+\overline{\Gamma}_D^{up}}}\right), \tag{21}$$

where

$$\frac{1}{\overline{\Gamma}_D^{up}} = \frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}. \tag{22}$$

The asymptotic BEP is expressed as follows

$$\widetilde{P}_{e,D}^{AFAFAF} = \frac{A}{2B}\left(\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right). \tag{23}$$

C. AFDFDF relaying

For 4-hops AFDFDF relaying, the BEP at D is given by

$$P_{e,D}^{AFDFDF} = 1-(1-P_{e,SR_1R_2})(1-P_{e,R_2R_3})(1-P_{e,R_3D}). \tag{24}$$

The asymptotic BEP is given by

$$\widetilde{P}_{e,D}^{AFDFDF} = \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right] \tag{25}$$
$$-\left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}}\left(\frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right) + \frac{1}{\overline{\Gamma}_{R_2R_3}\overline{\Gamma}_{R_3D}} + \frac{1}{\overline{\Gamma}_{R_1R_2}}\left(\frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right)\right].$$

Therefore, the difference between the asymptotic BEP of AFDFDF and DFDFDF relaying is

$$\widetilde{P}_{e,D}^{AFDFDF} - \widetilde{P}_{e,D}^{DFDFDF} = \left(\frac{A}{2B}\right)^2 \frac{1}{\overline{\Gamma}_{SR_1}\overline{\Gamma}_{R_1R_2}} \tag{26}$$

AFDFDF relaying offers close performance to DFDFDF relaying if R_1 is close to S or R_2. We also notice that the difference between the asymptotic BEP of AFDFDF and DFDFDF is proportional to the product of the inverse SNRs of the AF relaying link (i.e. $\frac{1}{\overline{\Gamma}_{SR_1}\overline{\Gamma}_{R_1R_2}}$).

D. DFAFDF relaying

For DFAFDF relaying, the BEP at D is given by

$$P_{e,D}^{DFAFDF} = 1-(1-P_{e,SR_1})(1-P_{e,R_1R_2R_3})(1-P_{e,R_3D}). \tag{27}$$

The asymptotic BEP is given by

$$\widetilde{P}_{e,D}^{DFAFDF} = \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right] \tag{28}$$
$$-\left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}}\left(\frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right) + \frac{1}{\overline{\Gamma}_{R_3D}}\left(\frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}}\right)\right].$$

Therefore, the difference between the asymptotic BEP of DFAFDF and DFDFDF relaying is given by

$$\widetilde{P}_{e,D}^{DFAFDF} - \widetilde{P}_{e,D}^{DFDFDF} = \left(\frac{A}{2B}\right)^2 \frac{1}{\overline{\Gamma}_{R_1R_2}\overline{\Gamma}_{R_2R_3}} \tag{29}$$

DFAFDF relaying offers close performance to DFDFDF relaying if R_2 is close to R_1 or R_3. We also notice that (29) is proportional to the product of the inverse SNRs of the AF relaying link (i.e. $\frac{1}{\overline{\Gamma}_{R_1R_2}\overline{\Gamma}_{R_2R_3}}$).

E. DFDFAF relaying

For DFDFAF relaying, the BEP at D is given by

$$P_{e,D}^{DFDFAF} = 1-(1-P_{e,SR_1})(1-P_{e,R_1R_2})(1-P_{e,R_2R_3D}). \tag{30}$$

The asymptotic BEP is given by

$$\widetilde{P}_{e,D}^{DFDFAF} = \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right] \tag{31}$$
$$-\left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}}\left(\frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right) + \frac{1}{\overline{\Gamma}_{R_1R_2}}\left(\frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right)\right].$$

Therefore, the difference between the asymptotic BEP of DFDFAF and DFDFDF relaying is given by

$$\widetilde{P}_{e,D}^{DFDFAF} - \widetilde{P}_{e,D}^{DFDFDF} = \left(\frac{A}{2B}\right)^2 \frac{1}{\overline{\Gamma}_{R_2R_3}\overline{\Gamma}_{R_3D}} \tag{32}$$

DFDFAF relaying offers close performance to DFDFDF relaying if R_3 is close to R_2 or D. We also notice that (32) is proportional to the product of the inverse SNRs of the AF relaying link (i.e. $\frac{1}{\overline{\Gamma}_{R_2R_3}\overline{\Gamma}_{R_3D}}$).

F. AFDFAF relaying

For AFDFAF relaying, the BEP at D is given by

$$P_{e,D}^{AFDFAF} = 1-(1-P_{e,SR_1R_2})(1-P_{e,R_2R_3D}). \tag{33}$$

The asymptotic BEP is given by

$$\begin{aligned}\widetilde{P}_{e,D}^{AFDFAF} &= \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right] \\ &\quad -\left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}}\left(\frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right)\right. \\ &\quad \left. +\frac{1}{\overline{\Gamma}_{R_1R_2}}\left(\frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right)\right].\end{aligned} \tag{34}$$

Therefore, the difference between the asymptotic BEP of AFDFAF and DFDFDF relaying is given by

$$\widetilde{P}_{e,D}^{AFDFAF} - \widetilde{P}_{e,D}^{DFDFDF} = \left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}\overline{\Gamma}_{R_3D}}\right] \tag{35}$$

AFDFAF relaying offers close performance to DFDFDF relaying if R_1 is close to S or R_2 and R_3 is close to R_2 or D. We also notice that (35) is proportional to the sum of the product of the inverse SNRs of the two AF relaying link (SR_1R_2 and R_2R_3D i.e. $\frac{1}{\overline{\Gamma}_{SR_1}\overline{\Gamma}_{R_1R_2}}$ and $\frac{1}{\overline{\Gamma}_{R_2R_3}\overline{\Gamma}_{R_3D}}$). The last equation, (26) and (29) shows that AFDFAF relaying offers worse performance than AFDFDF and DFAFDF relaying.

G. AFAFDF relaying

For AFAFDF relaying, the BEP at D is given by

$$P_{e,D}^{AFAFDF} = 1 - (1 - P_{e,SR_1R_2R_3})(1 - P_{e,R_3D}). \quad (36)$$

The asymptotic BEP is given by

$$\widetilde{P}_{e,D}^{AFAFDF} = \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right] - \left(\frac{A}{2B}\right)^2 \frac{1}{\overline{\Gamma}_{R_3D}}\left[\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}}\right] \quad (37)$$

Therefore, the difference between the asymptotic BEP of AFAFDF and DFDFDF relaying is given by

$$\widetilde{P}_{e,D}^{AFAFDF} - \widetilde{P}_{e,D}^{DFDFDF} = \left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{SR_1}\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}}\left(\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}}\right)\right] \quad (38)$$

AFAFDF relaying offers close performance to DFDFDF if R_1 is close to S or R_2 and R_2 is close to R_3. The last equation, (26) and (29) shows that AFAFDF relaying offers worse performance than AFDFDF and DFAFDF relaying.

H. DFAFAF relaying

For DFAFAF relaying, the BEP at D is given by

$$P_{e,D}^{DFAFAF} = 1 - (1 - P_{e,SR_1})(1 - P_{e,R_1R_2R_3D}). \quad (39)$$

The asymptotic BEP is given by

$$\widetilde{P}_{e,D}^{DFAFAF} = \frac{A}{2B}\left[\frac{1}{\overline{\Gamma}_{SR_1}} + \frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right] - \left(\frac{A}{2B}\right)^2 \frac{1}{\overline{\Gamma}_{SR_1}}\left[\frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\right] \quad (40)$$

Therefore, the difference between the asymptotic BEP of DFAFAF and DFDFDF relaying is given by

$$\widetilde{P}_{e,D}^{DFAFAF} - \widetilde{P}_{e,D}^{DFDFDF} = \left(\frac{A}{2B}\right)^2\left[\frac{1}{\overline{\Gamma}_{R_1R_2}\overline{\Gamma}_{R_2R_3}} + \frac{1}{\overline{\Gamma}_{R_3D}}\left(\frac{1}{\overline{\Gamma}_{R_1R_2}} + \frac{1}{\overline{\Gamma}_{R_2R_3}}\right)\right] \quad (41)$$

DFAFAF relaying offers close performance to DFDFDF if R_2 is close to R_1 or R_3 and R_3 is close to D. The last equation, (29) and (32) shows that DFAFAF relaying offers worse performance than DFAFDF and DFDFAF relaying.

IV. Hybrid multihop relaying

The previous results can be extended to hybrid multihop relaying. The difference between the asymptotic BEP of multihop hybrid relaying and DF is given by

$$\widetilde{P}_{e,D}^{hybrid} - \widetilde{P}_{e,D}^{DF} = \sum_{i=1}^{nAF}\sum_{j=1}^{n_i}\sum_{k=1,k\neq j}^{n_i}\frac{1}{\overline{\Gamma}_{ij}\overline{\Gamma}_{ik}}, \quad (42)$$

where nAF is the number of AF links, $\left\{\overline{\Gamma}_{ij}\right\}_{j=1}^{n_i}$ are the average SNRs characterizing the i-th AF link composed of n_i hops. For example, for AFDFAF relaying, we have : $nAF = 2$ AF links (SR_1R_2 and R_2R_3D), $\overline{\Gamma}_{11} = \overline{\Gamma}_{SR_1}$, $\overline{\Gamma}_{12} = \overline{\Gamma}_{R_1R_2}$, $\overline{\Gamma}_{21} = \overline{\Gamma}_{R_2R_3}$ and $\overline{\Gamma}_{22} = \overline{\Gamma}_{R_3D}$. Using (42), we verify that we obtain the result of the previous section (35). Equation (42) shows that hybrid relaying offers close performance to DF relaying if:

- In each AF link, all SNRs $\left\{\overline{\Gamma}_{ij}\right\}_{j=1}^{n_i}$ are high (ten times higher than the lowest SNR of the different links)

- Or, in each AF link, all $\left\{\overline{\Gamma}_{ij}\right\}_{j=1}^{n_i}$ are high except one value.

This will be our policy to set the relaying mode (i.e. AF or DF) for each relay node.

V. Simulation results

In this section, we provide some simulation results for BPSK modulation. The same power is allocated to the different nodes. The average power of the channel coefficient of the link between nodes X and Y is modeled as follows

$$E\left(|h_{XY}|^2\right) = \frac{\beta}{d_{XY}^{\alpha}} \quad (43)$$

where α is the path loss exponent, $d_{XY} = d_{XY}^{eff}/d_0$ is the normalized distance between X and Y, d_{XY}^{eff} is the effective distance in meters, d_0 is an arbitrary reference distance and β is the path loss at the reference distance. In the simulation results, the following parameters were used : $\alpha = 3$, and $\beta = 1$.

Fig. 1 shows the BEP at D for three hops relaying for $d_{SR_1} = 0.3$, $d_{R_1R_2} = 1$ and $d_{R_2D} = 1$. We notice that the AFDF offers better performance than DFAF which was expected since $\overline{\Gamma}_{SR_1} > \overline{\Gamma}_{R_2D}$ (see equation (18)). Since R_1 is close to S, the proposed protocol AFDF offers the same performance as DFDF (see equations (4) and (17)) and 1.1 dB gain with respect to AFAF for BER=0.05.

Fig. 2 shows the BER at D for three hops relaying when $d_{SR_1} = d_{R_1R_2} = 1$ and $d_{R_2D} = 0.4$. We notice that DFAF relaying outperforms AFDF which was expected since $\overline{\Gamma}_{SR_1} < \overline{\Gamma}_{R_2D}$. DFAF offers the same performance as DFDF relaying and 1.1 dB gain with respect to AFAF for BER=0.05.

Fig. 3 shows the BER at D for four hops relaying when $d_{SR_1} = 1$, $d_{R_1R_2} = d_{R_2R_3} = 2$ and $d_{R_3D} = 0.2$. Since R_3 is close to D, DFDFAF offers close performance to DFDFDF (see equation (32)). DFDFAF offers 1 dB gain with respect to AFAFAF and 3 dB gain with respect to noncooperative communications ($d_{SD} = d_{SR_1} + d_{R_1R_2} + d_{R_2R_3} + d_{R_3D}$). The order in performance of the different hybrid protocols is in accordance with the analysis provided in section III. Besides, AFDFDF offers the same performance as AFDFAF with is confirmed by the theoretical analysis (see (25) and (34)). DFAFDF offers the same performance as DFAFAF (see (28) and (40)). AFAFDF offers the same performance as AFAFAF (see (23) and (37)).

VI. Conclusions

In this paper, we have proposed and analyzed the performance of hybrid multihop relaying where some relays amplify the received signal and the remaining ones use DF relaying. We have shown that hybrid relaying offers better performance than AF relaying and close performance to DF relaying. The proposed protocol is less complex than DF and reduces power consumption and transmission delays since decoding is not performed at all nodes.

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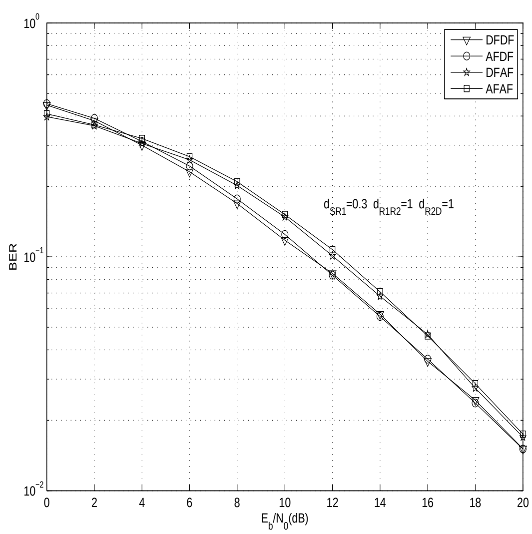

Fig. 1. BEP of 3-hops relaying with respect average SNR : $d_{SR_1} = 0.3$, $d_{R_1R_2} = 1$ and $d_{R_2D} = 1$.

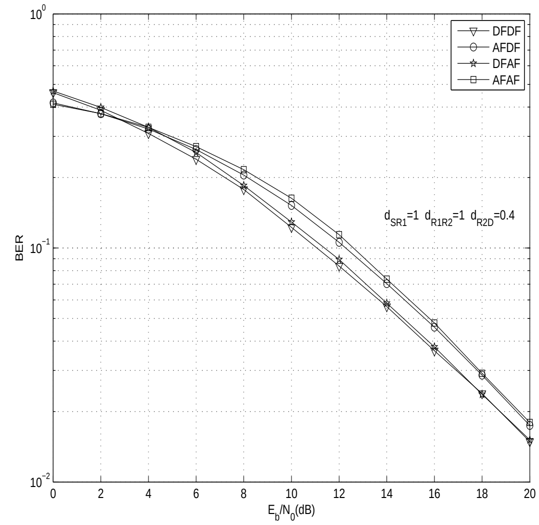

Fig. 2. BEP of hybrid 3-hops relaying with respect average SNR : $d_{SR_1} = 1$, $d_{R_1R_2} = 1$ and $d_{R_2D} = 0.4$.

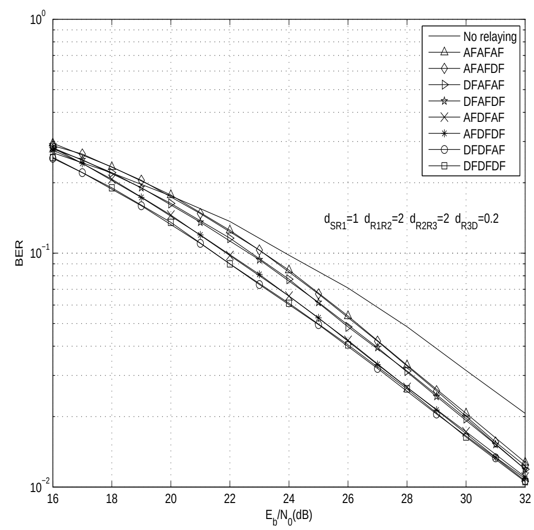

Fig. 3. BEP of hybrid 4-hops relaying with respect average SNR : $d_{SR_1} = 1$, $d_{R_1R_2} = 2$, $d_{R_2R_3} = 2$ and $d_{R_3D} = 0.2$.