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Receiver Design in Relaying Systems based on the Level of CSI at Relay

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Abstract: Receiver structure either coherent or non-coherent in a relay channel with amplify and forward (AF) and decode and forward (DF) relaying schemes is studied and a new receiver is proposed for both relaying schemes. In the network with multiple relays the performance of the receiver at the destination node is categorized based on the available source-relay (S-R) channel state information (CSI) including no, partial, and full CSI. Next, an adaptive receiver is proposed where full CSI of the S-R channel is exploited in the receiver of the destination node. It is shown that the proposed receiver outperforms other designed receivers in the sense of bit error rate (BER) criterion.

Index Terms: Receiver Structure, Relay Systems, Wireless Communications.

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I. INTRODUCTION

Cooperative relaying has been studied in the last decade to provide spatial diversity in wireless communications. This technique allows a collection of radios to effectively create a virtual antenna array for combating multipath fading and path-loss phenomena in wireless channels. Initial studies in cooperative relaying focus on an information theoretic perspective [1], [2]. However, majority of work address the performance improvement and implementation of cooperative relaying in wireless networks such as cellular or sensor networks [2]-[4]. In [4] DF with re-encoding ability in the relay is proposed to improve the system spectral efficiency. The optimum receiver has been designed to improve BER in [3]-[5]. In [7] an approach has been presented to approximate symbol error rate (SER) and outage probability in high SNR regimes. These studies about relaying system and transceiver design have been extending during last decade which can be categorized in different perspectives as follows. 1) relaying schemes such as AF, DF, coded DF, coded cooperation, etc., ([3], [7]); 2) relaying protocols such as half duplex (HD) [5], [6], full duplex (FD) [8]-[11], automatic repeat request (ARQ) based relaying [12], [13] and two way relaying [14], [15]: while in HD the relay receives and transmits in separated time intervals, in FD relay receives and transmits simultaneously [11]; 3) multi antenna relays and multi input multi output (MIMO) relay channels [11] where massive MIMO [16], mm wave transceivers [17], reconfigurable intelligent surfaces (RIS) [18], [19], [20], [21] are considered as hot topics in this area; 4) relaying with energy harvesting (EH) nodes [8], [9], [22]-[24]; 5) relaying with multiple nodes [25] either as single or multi-hop [13], [17] systems; and 6) special applications such as sensor networks [26], under water communications [27], non-terrestrial applications such as unmanned aerial vehicle (UAV) and high altitude platforms (HAPs) [28], [25], [29].

Transceiver design in the aforementioned works is the main challenge. In particular, using different equalizers with zero forcing (ZF) or minimum mean square error (MMSE) criteria and different receiver e.g., maximum likelihood (ML) and successive interference canceller (SIC) receivers in a rich fading environment are considered in [14], [29]. Also, classical challenges in MIMO and MIMO-orthogonal-frequency-multiplexing (OFDM) transceivers such as outdated CSI [30], peak to average power ratio (PAPR) reduction [31], etc., are addressed in relay transceiver design too.

Combinations of the approaches in the aforementioned work to improve the system spectral efficiency and/or energy efficiency are used in the recent studies. For instance, as a new trend of research, the relay is equipped by multiple passive antenna arrays as a reconfigurable intelligent surface (RIS) [18]; each antenna in the RIS shifts the incident signal phase to make co-phase signals those strengthen the received signal power at the final receiver [32]. A receiver design and a symbol error rate (SER) analysis of the RIS system is made in [19]. The RIS system is extended to exploit active antenna arrays in e.g., [20] and [21]. The active RISs can be implemented in UAVs to cover a terrestrial area [28]. RIS with EH capability [8], [9], [22], [23], Nakagami-*m* fading channel modeling [10], [22], FD active relaying [8]-[10], and multiple antennas in relays [9] are as the recent work in this trend.

These growing researches show the importance of relaying in wireless communication systems. In majority of the aforementioned studies, 1) the focus is on the transceiver for only one of the relaying schemes, i.e., AF or DF, 2) rich fading environment is considered, 3) coherent receivers are designed, and 4) global perfect CSI is assumed to be available in all system transceivers. In particular, these two latter design assumptions, i.e., 2 and 3, are to design coherent receiver and different beamforming strategies. However, the CSI acquisition may be cumbersome e.g., in fast fading channels. Also, the perfect CSI estimation induces redundant processing and consumes system resources. These considerations are challenging in particular for applications with cheap energy efficient single antenna nodes in e.g., sensor networks. In the seminal work [33] bases of an optimum receiver for a multi-relay system with M-ary signal is presented which is a non-linear and complicated structure. This structure is reduced to a simpler form based on a piecewise-linear approximation of the optimum receiver which performs rather close to the optimum receiver. However, the performances of coherent and non-coherent receivers are not compared. Besides, the S-R link CSI is not exploited in the destination node to improve the SER performance.

The mentioned shortcomings of the abovementioned studies motivate the author to compare both relaying schemes, i.e., AF and DF and to consider the non-coherent receiver structure in a relaying system along with the coherent receiver structure. It is worth mentioning that even with the CSI availability at the receivers, using non-coherent receiver structure is still justified for the sake of complexity and low-power hardware implementation affairs.

In this paper, a relay system with multiple relays in both coherent and non-coherent receiver structures and both AF and DF relaying schemes is studied. We use the piecewise approximation in [33] in the receiver design and categorize and compare the BER performance in the destination node based on the available level of the CSI from S-R channel. We categorize this level of the S-R CSI to no, partial, and full information. Also, an adaptive receiver based on full CSI of the S-R channel in the destination node is proposed. It is shown that proposed receiver offers better performance than those previously designed receivers so far in the literature. Contributions of this paper are as follows:

- ◇ Both coherent and non-coherent receivers and both AF and DF relaying schemes are considered and compared in the considered system

◇ The level of S-R CSI availability in the receiver of the destination node is categorized to no, partial and full CSI; then, a receiver based on the full S-R CSI availability in the destination node is proposed

◇ The clipping level defined in [33] for the partial CSI of the S-R channel is defined for the full CSI of the S-R channel; then, a simple approximation of this clipping level is proposed which is useful for the BER analysis

The remainder of this paper is organized as follows: Section II introduces the system and channel model. Section III presents the receiver structure in AF and DF relaying schemes on coherent and non-coherent structures. In Section IV impact of S-R link on the system performance is analyzed and the proposed receiver is presented. Finally, simulation results and conclusion are provided in Sections V and VI, respectively.

II. SYSTEM MODEL

As illustrated in Fig. 1, in a cooperative relaying system the source node, denoted by S, broadcasts the signal x_0 to the relay nodes, denoted by R_r, $r=1,...,M-1$, and the destination node in the first time interval. The signals received by the r th relay node and the destination node are denoted by y_r and y_0, respectively. The relay nodes retransmit the signals to the destination node in their assigned separated time intervals, i.e. $M-1$ orthogonal sub channels. We note that channel coding and/or space-time coding can be used in relay nodes to improve spectral efficiency [34]. However, to ensure a power constraint at relay nodes with potential coding application in mind, for the sake of simplification and concentration on the receiver structure, the un-coded protocol is considered in this paper. The fading coefficient between source and r th, $r=1,...,M-1$ relay is denoted by $\partial_{0,r}$. Also, $\partial_{0,M}$ and $\partial_{r,M}$ denote the fading coefficient in source-destination and R_r -destination links, respectively.

All relays can either amplify and forward (AF) or decode and forward (DF) the received signal to the destination node. In the AF relaying scheme the received signal at r th, $r=1,...,M-1$ relay is amplified by the factor of

$$\alpha_r \leq \sqrt{\frac{E_r}{\sigma^2_{\partial_{0,r}} E_0 + N_r}} \tag{1}$$

where E_0 is the average sample energy of the source node, E_r is the average sample energy of r th relay, N_r is noise variance and $\sigma^2_{\partial_{0,r}}$ is variance of the link fading coefficient between the source node and the r th relay.

In DF relaying scheme, relays decode and retransmit the received signal. The destination node receives the signals y'_r ($y'_0 := y_0, r = 0,1,...,M-1$), from M orthogonal relay channels and delivers these signals to appropriate matched filters. A base-band-equivalent discrete-time model, as the same as the one considered in [35] is assumed here too. Throughout the paper only binary frequency shift keying (BFSK) is considered due to simplicity of exposition [33].

As shown in Fig. 2, for BFSK signaling the outputs from the matched filters in the direct link, i.e., $r = 0$, are as follows

$$\begin{aligned} y'_{01} &= \frac{x_0+1}{2}\sqrt{E_0}\partial_{0,M} + n_{01} \\ y'_{02} &= \frac{1-x_0}{2}\sqrt{E_0}\partial_{0,M} + n_{02} \end{aligned} \tag{2}$$

Also, the outputs from the matched filters at r th, $r = 1,...,M-1$ relay can be modeled as follows; for the AF relaying scheme:

$$\begin{aligned} y'_{r1} &= \left(\frac{x_0+1}{2}\sqrt{E_0}\partial_{0,r} + n0_{r1}\right)\partial_{r,M}\alpha_r + n_{r1} \\ y'_{r2} &= \left(\frac{1-x_0}{2}\sqrt{E_0}\partial_{0,r} + n0_{r2}\right)\partial_{r,M}\alpha_r + n_{r2} \end{aligned} \tag{3}$$

and for the DF relaying scheme:

$$\begin{aligned} y'_{r1} &= \frac{x_r+1}{2}\sqrt{E_r}\partial_{r,M} + n_{r1} \\ y'_{r2} &= \frac{1-x_r}{2}\sqrt{E_r}\partial_{r,M} + n_{r2} \end{aligned} \tag{4}$$

In Eq.s (2), (3) and (4): x_0 is the symbol from the source; x_r is the symbol from r th relay that takes values ± 1, E_r, $r = 0,1,...,M-1$ is the average sample energy in source and relays; α_r is the amplification factor in the AF relaying scheme; $n0_{r1}$, $n0_{r2}$ are zero mean additive white complex Gaussian noise (AWCGN) with the variance N_r at r th relay for AF relaying scheme, and n_{r1}, n_{r2} are zero mean AWCGN in the destination node with the variance N_0. In the considered system, the fading coefficient between two nodes i and j, i.e., $\partial_{i,j}$, is modeled as zero mean, circularly symmetric, complex Gaussian random variable with the variance $\sigma^2_{\partial_{i,j}}$. For the sake of simplicity it is assumed that $N_r = N_0$, $r = 1,...,M$ where N_M is defined as the noise variance in the destination node. The average SNR between ith and jth nodes is defined as follows

$$\bar{\gamma}_{ij} = \sigma^2_{\partial_{i,j}} E_i / N_0, \tag{5}$$

where E_i is the average sample energy in Node i.

III. RECEIVER STRUCTURE

As a conventional criterion for the optimum receiver design, maximum likelihood (ML) criterion is used and coherent and non-coherent receivers are introduced. To maximize the received SNR,

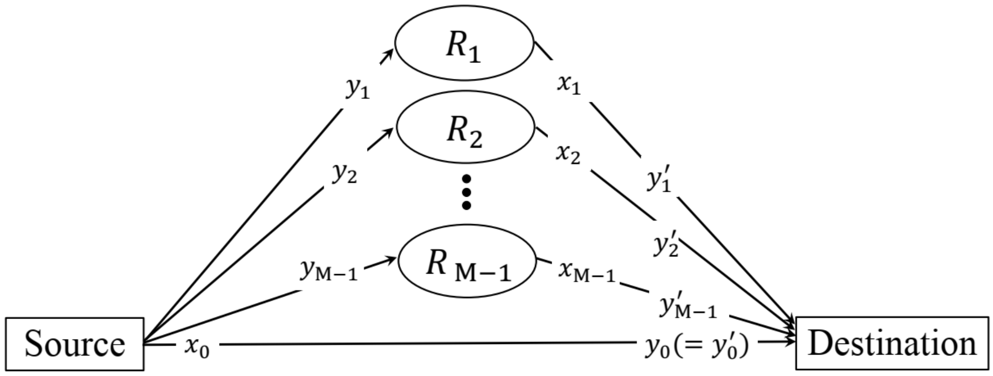

Fig. 1. Cooperative relaying system with *M*-1 relays. Relays retransmit the received signal to the destination node

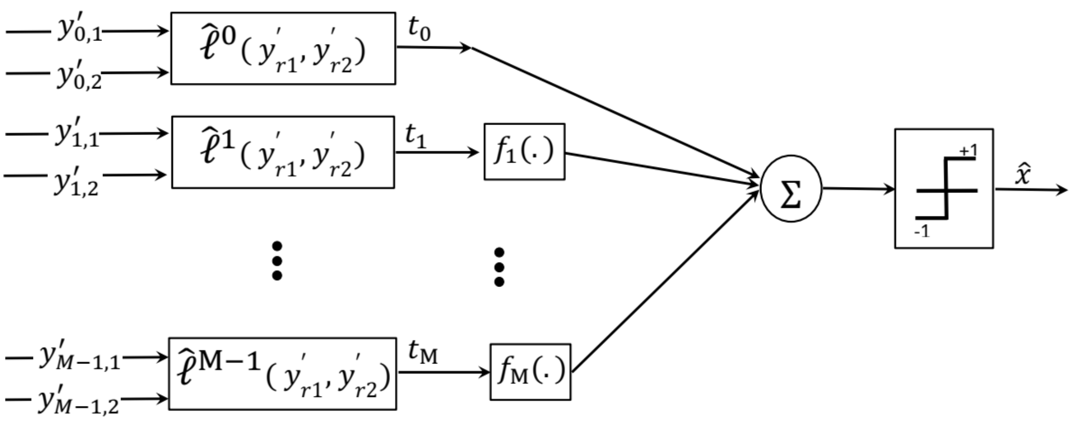

Fig. 2. Demodulator structure in the destination node. The provided statistics at the destination node are used to make a decision for the received bit

a maximum ratio combining (MRC) is used in the destination node.

A. AF relaying scheme

Considering the model presented in Section II, the log likelihood ratio (LLR) in the coherent structure is as follows:

$$\hat{\ell}^r(y'_{r1}, y'_{r2}) = \frac{2\sqrt{E_r}\,\mathrm{Re}\{(y'_{r1} - y'_{r2})g^*_{r,M}\}}{N_{r,M}}, \tag{6}$$

where $g_{r,M} = \partial_{r,M}\alpha_r\partial_{0,r}$ and $N_{r,M} = |\partial_{r,M}|^2\alpha_r^2 N_r + N_M$ and $r = 1,\dots,M-1$. In the non-coherent case it is impossible to obtain the ML detector without resorting to numeric integration [35]; however by definition of effective parameters as: $Ne_{r,M} = E(N_{r,M})$, and $\sigma^2_{e\partial_{r,M}} = E(g^2_{r,M})$, we can write simple form for the non-coherent structure as follows

$$\hat{\ell}^r(y'_{r1}, y'_{r2}) = \frac{E_r\sigma^2_{e\partial_{r,M}}(|y'_{r1}|^2 - |y'_{r2}|^2)}{(E_r\sigma^2_{e\partial_{r,M}} + Ne_{r,M})Ne_{r,M}}, \tag{7}$$

B. DF relaying scheme

If ε_r denotes the decision error at r th relay, the final LLR for the DF relaying scheme is given by [35]:

$$\hat{\ell}^r(y'_{r1}, y'_{r2}) = \ln\left(\frac{\varepsilon_r + (1-\varepsilon_r)\exp(\hat{\ell}^r(y'_{r1}, y'_{r2}))}{(1-\varepsilon_r) + \varepsilon_r \exp(\hat{\ell}^r(y'_{r1}, y'_{r2}))}\right), \tag{8}$$

where $\hat{\ell}^r(y'_{r1}, y'_{r2})$ is identical to Eq.s (6) and (7) for coherent and non-coherent cases, respectively; however, $g_{r,M} = \partial_{r,M}$ and $N_{r,M} = N_0$, $r = 1,\ldots,M-1$. For both AF and DF relaying schemes, In the direct link Eq.s (6) and (7) can be still used for coherent and non-coherent cases, respectively, if we consider $r = 0$, and define $\alpha_0 = 0$ and $\partial_{0,0} = 1$. Finally using (6)-(8), the $f_r(t_r)$ function in the ML receiver, shown in Fig. 2, for AF and DF relaying schemes is obtained as:

$$f_r(t_r) = \begin{cases} t_r, & \text{For AF} \\ \ln\left(\dfrac{\varepsilon_r + (1-\varepsilon_r)\exp(t_r))}{(1-\varepsilon_r) + \varepsilon_r \exp(t_r)}\right), & \text{For DF} \end{cases} \tag{9}$$

To reduce the receiver complexity in the DF relaying scheme, (9) can be approximated in a piecewise linear (PL) manner as follows [33]:

$$f_r(t_r) \approx f_P\ (t_r) = \begin{cases} C_{\varepsilon r}, & t_r \geq C_{\varepsilon r} \\ t_r, & |t_r| < C_{\varepsilon r} \\ -C_{\varepsilon r}, & t_r \leq C_{\varepsilon r} \end{cases}, \tag{10}$$

where $C_{\varepsilon r}$ is a clipping level defined by

$$C_{\varepsilon r} = \mathrm{h}\left(\frac{1-\varepsilon_r}{\varepsilon_r}\right) \tag{11}$$

The approximation in (10), which is used frequently in this paper, can facilitate the BER analysis. Also, Eq. (10) says that the diversity combiner resulting from this PL approximation includes the impact of the decision uncertainty at the relay by the clipping level defined in (11). Low decision error in each relay leads to increase the clipping level and vice versa. In other words, the clipping level limits the received information from relay based on uncertainty in the decision at the relay.

IV. IMPACT OF S-R LINK CSI ON THE SYSTEM PERFORMANCE

The level of the S-R link CSI availability in the destination node affects the BER performance significantly. By the S-R link CSI we mean the CSI between the source and relay(s). According to Eq.s (6) and (7), in AF relaying scheme it is straightforward to see that we have full information of the S-R link CSI in the coherent structure and partial information of the S-R link CSI, as a statistical average of the S-R channel gain, in the receiver of the destination node. However, in the DF relaying scheme a nonlinear function, defined in (9), appears in the receiver structure which is precisely approximated in (11). The clipping level value in (11) depends on the available information from the S-R link CSI and type of either coherent or non-coherent receiver structures in the relay which is considered in the following.

A. No CSI from S-R link

In this case, the receiver of the destination node acts as a simple combiner and assumes S-R channel to be perfect. Consequently, the nonlinear function reduces to a simple linear function $f_r(t_r) \approx f_{PL}(t_r) = t_r$ and the clipping level is $C_{\varepsilon r} = \infty$.

B. Partial CSI from S-R link

In this case, the average S-R channel gain(s) is available in the destination node, meaning this node becomes aware of the average decision error in relay(s). Knowing the average decision error in relays is equivalent to knowing the geographical distances between the source and the relays. For the coherent receiver this decision error is given as [36]

$$\varepsilon_r = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\gamma}_{0,r}}{2+\bar{\gamma}_{0,r}}}\right) \tag{12}$$

Substituting (12) into (11) yields

$$C_{\varepsilon r} = \ln\left(1 + \bar{\gamma}_{0,r} + \sqrt{(1+\bar{\gamma}_{0,r})^2 - 1}\right) \tag{13}$$

For the non-coherent receiver the decision error is given as [36]

$$\varepsilon_r = \frac{1}{2+\bar{\gamma}_{0,r}}, \tag{14}$$

and similar to (13) the clipping level is obtained as

$$C_{\varepsilon r} = \ln(1+\bar{\gamma}_{0,r}) \tag{15}$$

C. Full CSI from S-R link (proposed receiver)

In this case, the instantaneous S-R channel gain(s) is available in the destination node. This leads the clipping level to be adapted to the instantaneous received SNR in each relay i.e., $\gamma_{0,r}$. Since the clipping level is a function of instantaneous decision error probability in each relay, it is a complicated function of $\gamma_{0,r}$. Here we propose approximations for the clipping level as follows.

Proposition:

For the case of available full CSI from S-R channels in the destination node, the clipping level is approximated for the coherent receiver as follows

$$C_{\varepsilon r} \approx \begin{cases} \sqrt{\lambda_0 \gamma_{0,r}}, & \gamma_{0,r} \le \gamma_{th} \\ \lambda_1 + \lambda_2 \gamma_{0,r} & \gamma_{0,r} > \gamma_{th} \end{cases}, \tag{16}$$

where $\lambda_0 = 8/\pi$, $\lambda_1 = 1.4265$, $\lambda_2 = 0.5616$, $\lambda_{th} = \frac{\lambda_0}{4\lambda_2^2}$, and for the non-coherent receiver as follows

$$C_{\varepsilon r} \approx \begin{cases} \gamma_{0,r}, & \gamma_{0,r} \le \gamma_{th} \\ \ln(2) + \frac{1}{2}\gamma_{0,r}, & \gamma_{0,r} > \gamma_{th} \end{cases} \tag{17}$$

where $\lambda_{th} = 2\ln(2)$.

Proof:

For the sake of simplicity, let $\lambda := \gamma_{0,r}$. In the coherent receiver structure the decision error probability in a relay for BFSK signaling is given as $\varepsilon_r = Q(\sqrt{\lambda})$, where $Q(x) := \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp(-\frac{t^2}{2})dt$, consequently, using (11) the clipping level is given as

$$C_{\varepsilon r}(\gamma) = \ln\left(\frac{1 - Q(\sqrt{\gamma})}{Q(\sqrt{\gamma})}\right) \tag{18}$$

Using the Taylor series of $C_{\varepsilon r}(x^2)$ around $x = 0$ yields

$$C_{\varepsilon r}(x^2) = \sqrt{\frac{8}{\pi}}x + O(x^n), \qquad n \ge 2, \tag{19}$$

where $O(x^n)$ denotes the polynomials of order n and higher than n. Thus, the approximation $C_{\varepsilon r}(\gamma) = \sqrt{\frac{8}{\pi}\gamma}$ holds for some γ_{th}, $0 < \gamma < \gamma_{\text{th}}$. Using the following approximation for the Q-function [37] as

$$Q(x) \approx 0.24015\exp(-0.5616x^2), \tag{20}$$

into (18) and considering $\gamma > \gamma_{\text{th}}$ yields

$$C_{\varepsilon r}(\gamma) \approx 1.4265 + 0.5616\gamma \tag{21}$$

Finally, minimizing the non-continuity at $\gamma = \gamma_{\text{th}}$ obtains γ_{th}.

For the non-coherent receiver structure the decision error probability in a relay for BFSK signaling is given as [36] $\varepsilon_r = \frac{1}{2}\exp(-\frac{\gamma}{2})$. Thus, using (11) the clipping level is given as

$$C_{\varepsilon r}(\gamma) = \ln\left(\frac{1 - \frac{1}{2}e^{-\frac{\gamma}{2}}}{\frac{1}{2}e^{-\frac{\gamma}{2}}}\right) = \ln\left(2e^{\frac{\gamma}{2}} - 1\right) \tag{22}$$

By the similar argument made in (19)-(21) the following approximation is obtained.

$$C_{\varepsilon r} \approx \begin{cases} \gamma, & \gamma \le \gamma_{th} \\ \ln(2) + \frac{1}{2}\gamma, & \gamma > \gamma_{th} \end{cases}, \tag{23}$$

Meeting the continuity constraint obtains γ_{th}.

In Fig. 3 the exact form of the clipping levels for coherent and non-coherent receiver structures and their corresponding proposed approximations in (16) and (17) are plotted. The close behavior of the approximated clipping levels with the exact ones is evident in this figure.

V. SIMULATION RESULTS

In order to compare the coherent and non-coherent receivers for AF and DF relaying schemes, simulation results are provided in Figs. 4–6 showing the average BER of un-coded BFSK transmissions for the different relay locations as (0.5, 0), (0.9, 0) and (0.1, 0), respectively. The simulation assumptions are based on what considered in [33]. The coordinates of the network elements are normalized by the distance between source and destination transceivers ($d_{s,d}$). The fading variances $\sigma^2_{\partial_{r,M}}$ obey the general path-loss model in the form of $\sigma^2_{\partial_{i,j}} \propto d^{-4}_{i,j}$, where $d_{i,j}$ is the distance between Node i and Node j. The total network energy per transmitted bit is also normalized to be 1. For single-hop transmission i.e., $E_0 = 1$, equal energies are assigned to the transmitters i.e., $E_0 = E_1 = 1/2$. Without loss of generality, the source, destination and relay nodes are assumed to be located at (0, 0), (1, 0), and $(l,0)$, $0 < l < 1$, respectively. The three selected coordinates of the relay are as follows: close to the source ($l = 0.1$), middle of the S-R distance ($l = 0.5$) and far from the source ($l = 0.9$).

As illustrated in Fig.s 4-6, slops of curves in the case of the presence of the relay are larger than those of the absence of the relay due to diversity gain offered in cooperative relaying. It is seen that there is ~6dB difference in coherent and non-coherent cases. Fig.s 4 and 5 show that in DF relaying scheme the proposed receiver, i.e., receiver with full CSI from S-R link, offers better performance than two other cases i.e. no and partial CSI from S-R link. In Fig. 6 the performance for DF relaying scheme for all cases are rather the same due to the good S-R channel. Fig. 4 shows that the DF relaying scheme, especially for the proposed receiver, outperforms the AF relaying scheme. The same result is seen in Fig. 6 where relay is close to the source. When relay is far from the source, in Fig. 5, AF relaying scheme outperforms the DF relaying scheme. In this case the error propagation possibility in the DF relaying scheme has worse impact on the performance than the noise amplification effect in the AF relaying scheme. In the DF relaying scheme when the relay is getting close to the destination node, i.e., Fig. 5, the proposed receiver outperforms

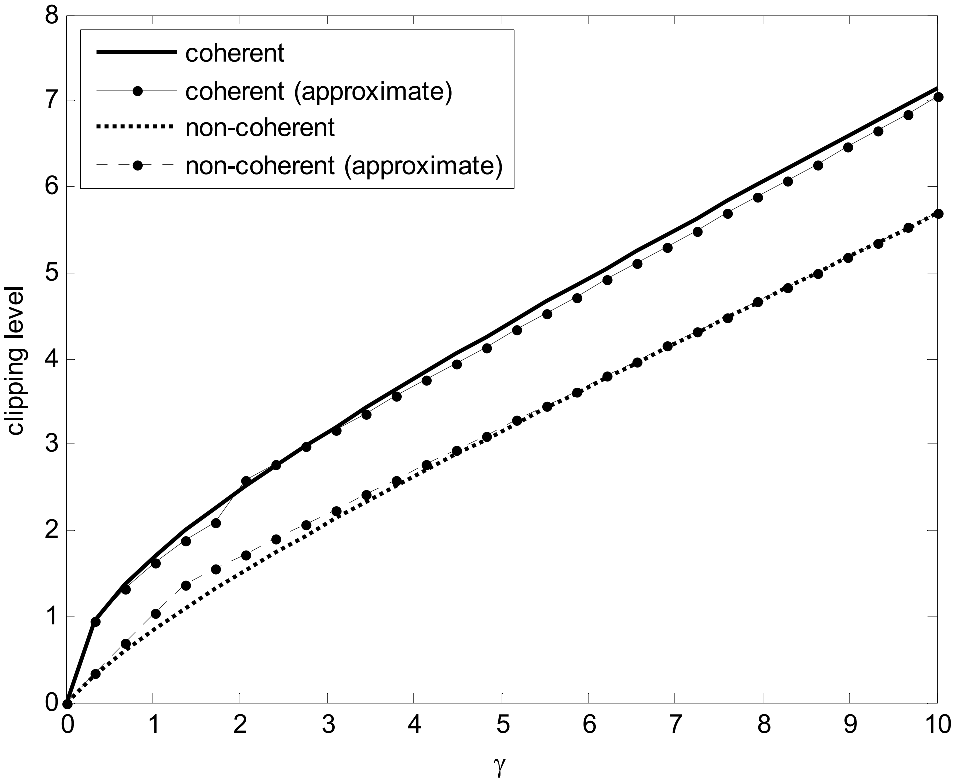

Fig. 3. Clipping level versus $\gamma := \gamma_{0,r}$ for coherent and non-coherent receiver structures and their corresponding approximations

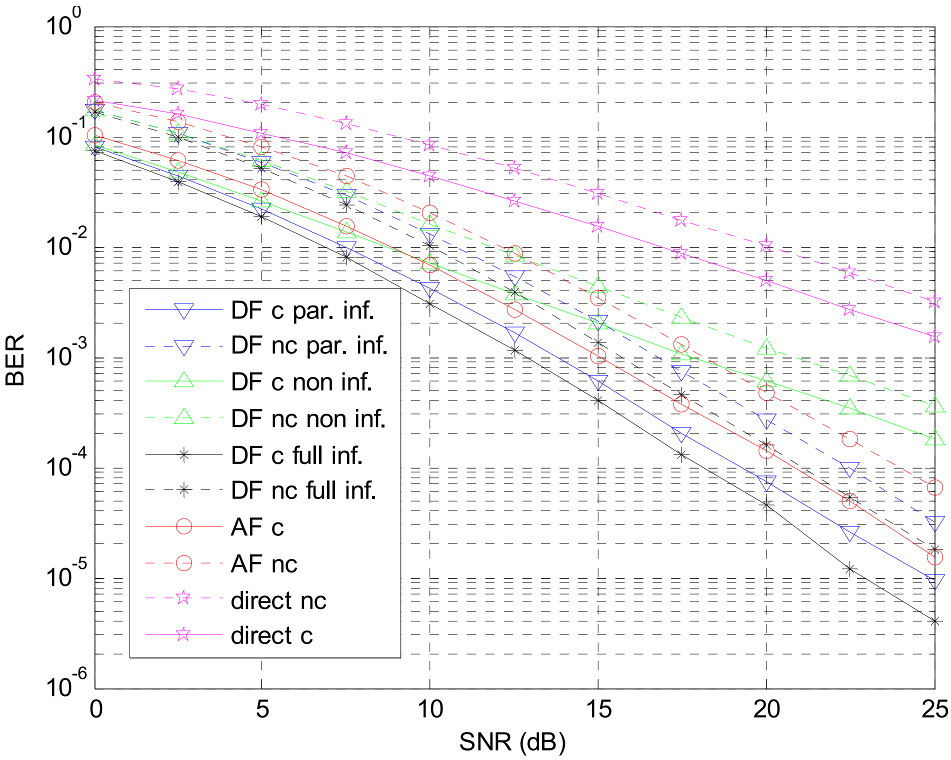

Fig. 4. BER performance for AF and DF relaying schemes in coherent and non-coherent receivers. The relay location is in the middle of the S-R distance (l=0.5)

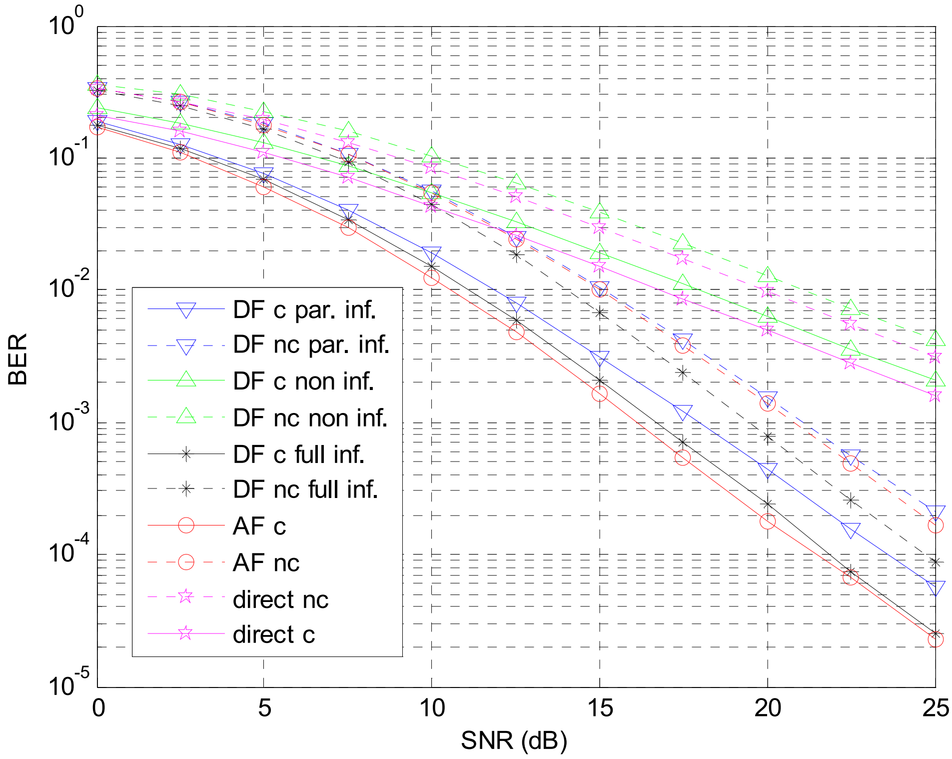

Fig. 5. BER performance for AF and DF relaying schemes in coherent and non-coherent receivers. The relay location is far from the source (*l*=0.9)

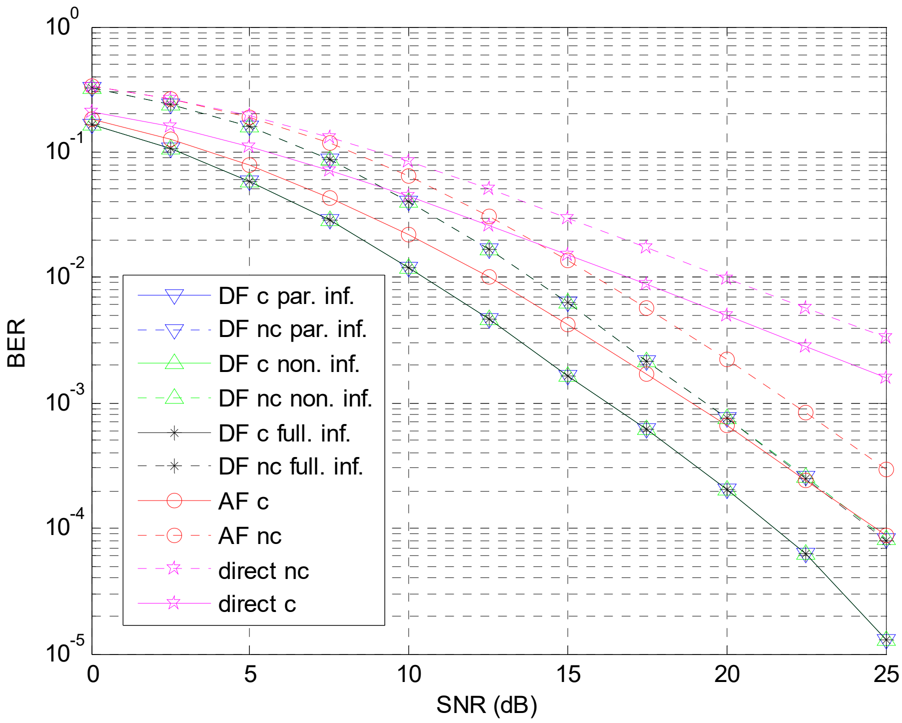

Fig. 6. BER performance for AF and DF relaying schemes in coherent and non-coherent receivers. The relay location is close to the source (*l*=0.1)

the two receivers with no and partial CSI from S-R link. Therefore, the error propagation is acceptably controlled in the proposed receiver in comparison with the two other counterparts.

VI. CONCLUSION

In this paper both coherent and non-coherent receivers in AF and DF relaying schemes were studied. Also, the performance of the receiver of the destination node was categorized and compared based on available S-R link CSI, i.e. no, partial and full CSI, from source relay link. In particular, an adaptive receiver based on full available CSI from S-R link was proposed which showed better performance than the two receivers with no and partial CSI from S-R link. Besides, it was shown that when relay is getting close to the source, the DF relaying scheme outperforms the AF relaying scheme for both coherent and non-coherent cases.

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