A Cooperative Diversity Scheme Based on Quadrature Signaling

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Abstract— **A bandwidth and energy efficient cooperative diversity scheme based on quadrature signaling is proposed. The quadrature signaling is achieved by transmitting in the in-phase and quadrature components of QPSK modulation. The diversity gain and the bit error rate of the proposed cooperative diversity scheme improve with the inter-user channel quality. It is shown that the proposed scheme can achieve a diversity order of two for high inter-user signal-to-noise ratios, if the cooperating users are located within a region that permits successful cooperation. The cooperative region corresponding to a specified bit error rate is defined and derived.**

Index Terms— **Cooperative diversity, MIMO, maximum ratio combining, user collaboration, cooperative region.**

I. Introduction

TRANSMIT diversity is a powerful technique for combating multipath fading in wireless communications. It has been used in 3^{rd} generation mobile communication systems to increase the downlink data rate. However, employing multiple antennas in a mobile terminal to achieve the transmit diversity in the uplink is not feasible due to the limited size of the mobile unit. In order to overcome this problem, a new mode of transmit diversity, called cooperative diversity (CD), based on user cooperation has been proposed in [1]-[6]. By user cooperation, it is meant that when the sender transmits to the destination, it also transmits copies to other users, called partners, for relaying to the destination. The antennas of the sender and the partners together form a multiple transmit antenna situation. CD schemes are immune not only against small scale channel fading but also against large scale channel fading.

An adaptive *regenerate and forward* scheme for CD networks is proposed in [3] and [4]. The partner forwards the information if it is decoded correctly[1]. The influence of the data rate, path loss and network geometry on the cooperative scheme is studied for an error free inter-user channel. In this scheme, the channel is divided into two sub-channels in the time domain, which requires a bandwidth twice as large compared to a non-cooperative diversity (NCD) scheme.

In this paper, a bandwidth and energy efficient CD scheme based on quadrature signaling is proposed for a two-user system. Instead of expanding the bandwidth or reducing the effective data rate of the cooperative system, we expand the signal constellations of the modulation scheme to accommodate the partner. Quadrature signaling is achieved by transmitting in the in-phase and quadrature components of a phase shift keying modulation scheme. Specifically, this paper is concerned with *fixed regenerate and forward* employing symbol by symbol detection and no cyclic redundancy check (CRC) in the partner's device, which provides implementation simplicity to the scheme. On the other hand, an *adaptive regenerate and forward* scheme provides more diversity gain at the expense of device complexity, which is not presented here due to space limitations.

The power and bandwidth of the proposed cooperative scheme are equal to those of a NCD scheme. Both processing delay at the partner mobile and propagation delay difference between the direct and the partner transmissions are taken into account at the base station (BS) receiver. Furthermore, the proposed scheme is simpler to implement than the CD schemes reported in the literature, since it only needs the additional hardware to receive the uplink signal of the partner. It also can be easily switched between CD and NCD modes based on the inter-user signal-to-noise ratio (iSNR). Bit error probability (BEP) and diversity gain achieved by the proposed CD scheme is studied, and a cooperative region for a user to find its partner with specified bit error performance is defined and analyzed.

The rest of the paper is organized as follows. In section II, the system architecture is described and a CD scheme is proposed. The BEP of the system is derived and analyzed in Section III. Section IV studies the diversity gain and coding gain of the proposed scheme. The region in which the partner can have cooperation, called the cooperative region, is derived in Section V. Conclusions are given in section VI.

II. System Architecture

Consider a cooperative wireless communication system in which each mobile user cooperates with another mobile user (the partner) to transmit information in the uplink. The transmission frame format and the signal constellation of the QPSK modulation scheme are shown in Fig. 1. Fig. 1(a) shows a frame of information symbols transmitted by *user 1* in *channel 1* and *user 2* in *channel 2*, respectively. In this case, the multiple access channels may be frequency division multiple access (FDMA) or time division multiple access (TDMA). Since the individual users use their own multiple access channels, the relaying user can transmit and receive simultaneously. In the first symbol interval, each user transmits its own information only. In successive symbol

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[1]The correctness can be verified using cyclic redundancy check (CRC)

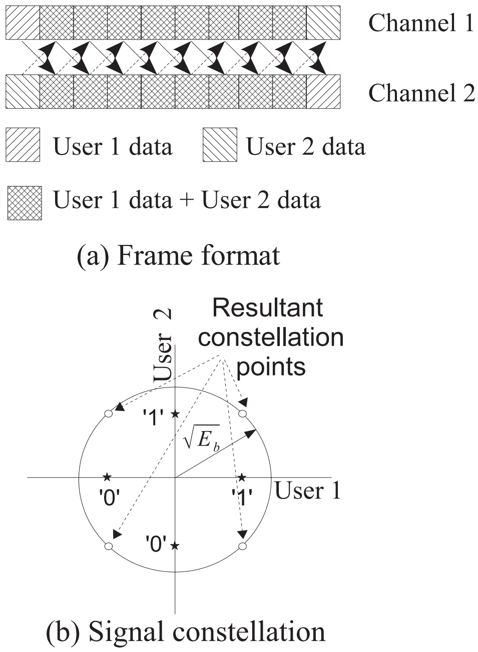

Fig. 1. Transmission frame format and the signal constellation of QPSK modulation.

intervals, each user transmits not only its own information but also the partner's information received in the previous symbol interval. In the last symbol interval of the frame, each user only transmits the partner's information. In our proposed scheme, *user 1* and *user 2* use the in-phase and the quadrature components of a QPSK modulated signal, respectively. This means that each user equivalently employs BPSK modulation. The signal constellation is illustrated in Fig. 1(b). In the uplink receiver of *user 2*, the in-phase and quadrature components are demodulated separately and forward the detected *user 1*'s data bits to the base station. In this paper, we assume that the channel state information is available at the respective receivers and proper synchronization is established.

The signals are received from both users' channels and combined using a maximum ratio combiner (MRC). To decode the information of *user 1*, the received signal from channel 1 is delayed by one symbol interval and combined with the received signal from channel 2 in the MRC. Similarly, to decode the information of *user 2*, the received signal from channel 2 is delayed by one symbol interval and combined with the received signal from channel 1. The output of the MRC is sent to a decision device which converts it to a binary data. Even though the symbol is delayed by one symbol interval, this is different from the delay diversity proposed in [7] when symbols from different antennas are transmitted in the same multiple access channel.

The baseband equivalent received signals from *user i* at the BS is denoted as $r_{i,b}(t)$. Similarly, *user i*'s uplink signal received by *user j* is denoted as $r_{i,j}(t)$. From the system model, $r_{i,b}(t)$ and $r_{i,j}(t)$ can be written as:

$$\begin{aligned} r_{i,b}(t) &= h_{i,b}(t)s_i(t) + \eta_{i,b}(t) \\ r_{i,j}(t) &= h_{i,j}(t)s_i(t) + \eta_{i,j}(t) \end{aligned} \tag{1}$$

where the channel fading coefficient between user i and the BS is denoted by $h_{i,b}(t)$ and the channel fading coefficient from user i to user j is denoted by $h_{i,j}(t)$. When the inter-user channel is symmetric, $h_{i,j}(t) = h_{j,i}(t)$. In this paper, we consider Rayleigh flat fading channels. $\eta_{i,b}(t)$ and $\eta_{i,j}(t)$ are additive noise at the respective receivers and modelled as zero mean circularly symmetric, complex Gaussian distributed process with variance $N_0/2$. $s_i(t)$ is the transmitted signal from *user i* and chosen from the QPSK signal constellation shown in Fig. 1(b). Therefore, $s_1(t)$ and $s_2(t)$ can be written as $s_1(t) = \sqrt{E_b/2}(b_1(t) + j\bar{b}_2(t - T_s))$ and $s_2(t) = \sqrt{E_b/2}(\bar{b}_1(t - T_s) + jb_2(t))$, respectively, where $b_i(t)$ is the BPSK information symbol of *user i* and $\bar{b}_i(.)$ is the corresponding reproduced symbol at the partners. T_s denotes the symbol duration and E_b is the bit energy of NCD transmission.

At the BS, the signals received from both user channels are combined using MRC and decoded by the ML rule [8]. The results are

$$\begin{aligned} \tilde{b}_1 &= \Re\{h^*_{1,b}(t - T_s)r_{1,b}(t - T_s) + h^*_{2,b}(t)r_{2,b}(t)\} \\ \tilde{b}_2 &= \Im\{h^*_{2,b}(t - T_s)r_{2,b}(t - T_s) + h^*_{1,b}(t)r_{1,b}(t)\}. \end{aligned} \tag{2}$$

In the above, the symbols $\Re\{Z\}$ and $\Im\{Z\}$ denote the real and the imaginary parts of the complex number Z, respectively, and the decision rule reduces to $\hat{b}_i = sign\{\tilde{b}_i\}$.

III. Analysis of Bit Error Probability

Without loss of generality, consider the data transmission of *user 1*. Assume quasi static flat Rayleigh fading, i.e., $h_{i,b}(t) = h_{i,b}(t - T_s) = h_{i,b}$ and $h_{i,j}(t) = h_{i,j}$. The decision rule at the MRC receiver can be written as $\hat{b}_1 = sign\{\Re(\mathbf{H}^*\mathbf{r})\} = sign\{\Re((|h_{1,b}|^2 + \Omega\,|h_{2,b}|^2)b_1 + \eta)\}$, where Ω is an indicator of decoding error of b_1 at *user 2*, i.e., $\Omega = -1$ with probability $P_{1,2}$ and $\Omega = 1$ with probability $1 - P_{1,2}$, where $P_{1,2}$, is the inter-user average bit error probability (BEP). η is the additive noise with zero mean and variance $(|h_{1,b}|^2 + |h_{2,b}|^2)N_0/2$. The instantaneous error probability for equiprobable bits is given by

$$\begin{aligned} P_e^c &= P\left(\hat{b} = 1 | b_1 = -1\right) \\ &= P\left(\eta > (|h_{1,b}|^2 + \Omega\,|h_{2,b}|^2)\sqrt{E_b/2}\right) \\ &= (1 - P_{1,2})P\left(\eta > (|h_{1,b}|^2 + |h_{2,b}|^2)\sqrt{E_b/2}\right) \\ &\quad + P_{1,2}P\left(\eta > (|h_{1,b}|^2 - |h_{2,b}|^2)\sqrt{E_b/2}\right). \end{aligned} \tag{3}$$

By averaging the instantaneous error probability over the corresponding pdfs, the lower bound of the average BEP is given by:

$$P_e^L = (1 - P_{1,2})P_{MRC} + P_{1,2}P_{dMRC}^L \tag{4}$$

where, for dissimilar channel towards the BS, $P_{1,2}$, P_{MRC} and P_{dMRC}^L are given by (5). Similarly, $P_{MRC} = \left(2 + \sqrt{\frac{\bar{\gamma}_1}{2+\bar{\gamma}_1}}\right)\left[\frac{1}{2}\left(1 - \sqrt{\frac{\bar{\gamma}_1}{2+\bar{\gamma}_1}}\right)\right]^2$ and $P_{dMRC}^L = 0.5$ for similar channel towards the BS. Let $\gamma_i = \frac{E_b}{N_0}|h_{i,b}|^2$ be the received bit energy-to-noise spectral density ratio, $\bar{\gamma}_i$ be the average bit energy-to-noise spectral density ratio from the i^{th} channel and $\bar{\gamma}_{1,2} = \frac{E_b}{N_0}E\{|h_{1,2}|^2\} = \sigma^2_{1,2}\frac{E_b}{N_0}$. Although, γ is the bit-energy-to-noise spectral density ratio, for notational convenience, in what follows we refer to γ as SNR.

$$
\begin{aligned}
P_{1,2} &= \frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma}_{1,2}}{2+\bar{\gamma}_{1,2}}}\right)\\
P_{MRC} &= \frac{1}{2}\left[\frac{\bar{\gamma}_1}{\bar{\gamma}_1-\bar{\gamma}_2}\left(1-\sqrt{\frac{\bar{\gamma}_1}{2+\bar{\gamma}_1}}\right)+\frac{\bar{\gamma}_2}{\bar{\gamma}_2-\bar{\gamma}_1}\left(1-\sqrt{\frac{\bar{\gamma}_2}{2+\bar{\gamma}_2}}\right)\right]\\
P^L_{dMRC} &= \left(\frac{\bar{\gamma}_2}{\bar{\gamma}_1+\bar{\gamma}_2}\right)+\left(\frac{\bar{\gamma}_1-\bar{\gamma}_2}{\bar{\gamma}_1+\bar{\gamma}_2}\right)\frac{1}{2}\left[\frac{\bar{\gamma}_1}{\bar{\gamma}_1+\bar{\gamma}_2}\left(1-\sqrt{\frac{\bar{\gamma}_1}{2+\bar{\gamma}_1}}\right)+\frac{\bar{\gamma}_2}{\bar{\gamma}_1+\bar{\gamma}_2}\left(1-\sqrt{\frac{\bar{\gamma}_2}{2+\bar{\gamma}_2}}\right)\right]
\end{aligned}
\tag{5}
$$

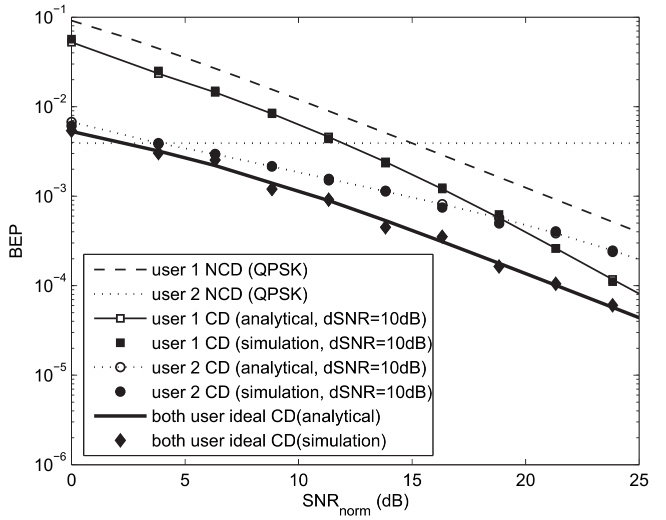

Fig. 2. Bit error performance of both users when SNR of user 2 is fixed at 15dB for differential SNR gain of 10 dB.

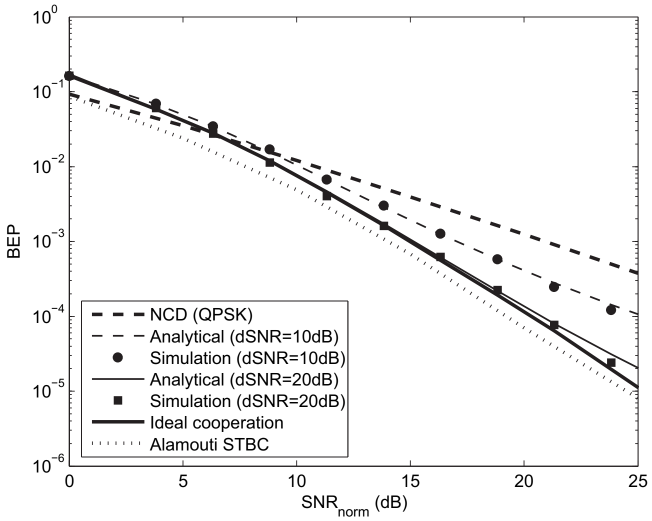

Fig. 3. Bit error performance of user 1 compared with Alamouti STBC scheme for similar channels towards the BS for various inter-user channel conditions.

Because of the proximity, it is expected that the inter-user channel between *user i* and *user j* to be of better quality than the i^{th} channel (between *user i* and BS), and define the differential signal-to-noise ratio (dSNR) as $dSNR_i[dB] = \bar{\gamma}_{i,j}[dB] - \bar{\gamma}_i[dB]$.

Numerical Results: The BEP of the proposed scheme is studied analytically as well as by simulation. In our simulation, a frame, consisting of 128 information symbols (effectively it needs 129 symbol durations to transmit), is transmitted through a Rayleigh flat fading channel. The additive noise is assumed as a zero mean complex Gaussian process with variance $N_0/2$. The channel is also considered as slow fading that remains constant over the interval of a frame. We assume that the channel state information (CSI) is available at the respective receivers for decoding the received signal.

The BEPs as a function of *user 1*'s SNR normalized by the transmission rate [2], $SNR_{norm} = \frac{\bar{\gamma}_1}{2^R-1}$, of the proposed CD scheme for dissimilar channels are plotted in Fig. 2 for $\bar{\gamma}_2 = 15dB$ and SNR_{norm} varying from 0 to 25 dB, where R is the spectral efficiency in bits per two dimensions (R=1/2 for the proposed CD scheme). Inspection of the curves in Fig. 2 shows that the analytical results for the lower bound coincides with the simulation results. This is because the difference between P_{dMRC} and P^L_{dMRC} is not significant in the calculation of the overall BEP. The simulation and analytical results of the proposed CD scheme are also compared with the BEP vs $SNR_{norm} = \frac{\bar{\gamma}_{nc}}{2^R-1}$ performance of the NCD scheme for both users at a differential SNR gain of 10dB, where $\bar{\gamma}_{nc}$ is the average SNR of the NCD scheme to achieve the same bit error probability as the CD scheme. For the NCD scheme, we consider direct transmission of standard QPSK modulated signals (R=1) with the same bit energy as the proposed CD scheme. In Fig. 3, the BEP vs SNR_{norm} performance characteristics for various values of dSNR are compared with those of the NCD scheme, Alamouti's space-time block coding (STBC) scheme employing QPSK modulation [9] and ideal cooperation (assuming that the partner's information is perfectly decoded) scheme, for $\bar{\gamma}_1 = \bar{\gamma}_2$. The proposed scheme achieves diversity order of two when ideal cooperation takes place, and similar performance can be achieved when dSNR is 20dB. In addition, the BEP improves with the inter-user channel quality, as shown in Fig. 3. Thus, the BEP performance of the proposed scheme improves with the increase of the dSNR gain. For ideal cooperation, the performance of the proposed scheme approaches the performance of the Alamouti scheme in the rate normalized SNR frame work of [1].

In summary, the results show that the BEP of both users is enhanced significantly by the proposed scheme. It means that cooperation enhances not only the performance of the user far away from the BS but also the user near to the BS. In addition, the diversity gain achieved by the proposed scheme increases with the inter-user channel quality, and the derived analytical lower bound of the BEP follows the simulated BEP ($P_e \approx P^L_e$).

[2]The authors wish to thank an anonymous reviewer for suggesting normalizing the SNR by the transmission rate to provide a fair comparison between the CD and NCD schemes.

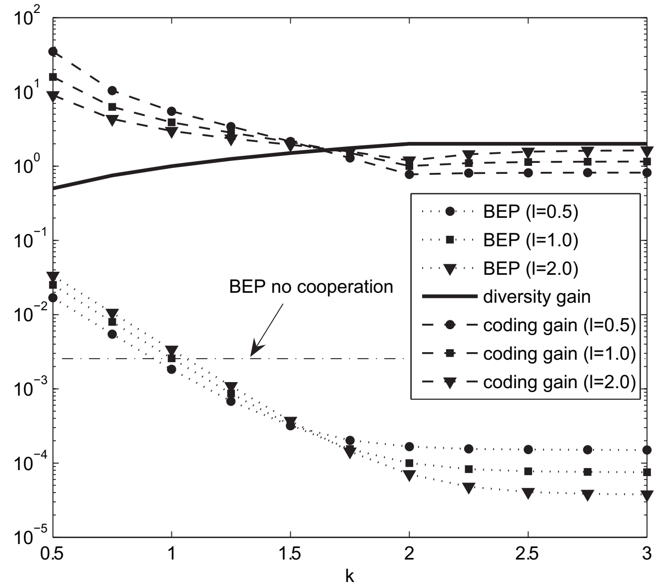

Fig. 4. BEP, coding gain and diversity gain provided by the scheme at high SNR for various inter-user and *user 2* to BS channel conditions.

IV. Diversity Gain and Coding Gain

In the previous section, the effects of the inter-user channel on the performance of the proposed scheme was studied, in which the diversity gain achieved by the system increases with the inter-user channel quality. An alternative way to characterize the performance is to plot the diversity gain and coding gain[3] for specified channel conditions. This should help to understand the interested range of inter-user channel quality for a better cooperation.

By considering high SNR for both inter-user and user to BS transmissions ($\bar{\gamma}_1 \gg 1$, $\bar{\gamma}_2 \gg 1$,$\bar{\gamma}_{1,2} \gg 1$), (4) can be approximated by

$$P_e \approx \frac{1}{2\bar{\gamma}_{1,2}} \frac{\bar{\gamma}_2}{\bar{\gamma}_1 + \bar{\gamma}_2} + \frac{3}{4\bar{\gamma}_1\bar{\gamma}_2} + \frac{1}{2\bar{\gamma}_{1,2}} \frac{\bar{\gamma}_1 - \bar{\gamma}_2}{(\bar{\gamma}_1 + \bar{\gamma}_2)^2} - \frac{1}{2\bar{\gamma}_{1,2}} \frac{3}{4\bar{\gamma}_1\bar{\gamma}_2} \tag{6}$$

for dissimilar channel towards the BS and

$$P_e \approx \frac{1}{4\bar{\gamma}_{1,2}} + \frac{3}{4\bar{\gamma}_1^2} - \frac{3}{8\bar{\gamma}_{1,2}\bar{\gamma}_1^2}. \tag{7}$$

for similar channel towards the BS.

The asymptotic behavior of the BEP versus $\bar{\gamma}_1$ curve is dominated by the first term of (6) and (7) even though the remaining terms provide higher order diversity. The average bit error probability of the proposed scheme is of the form given in [10] and [11] and can be approximated by

$$P_e \approx (G_c\bar{\gamma}_1)^{-G_d}, \tag{8}$$

where G_d is the asymptotic diversity gain and G_c is the coding gain. A similar study is given in [12] for non-regenerative CD systems.

Numerical Results: The achieved diversity gain, coding gain, BEP are plotted in Fig. 4 as a function of $k = \log_{\bar{\gamma}_1} \bar{\gamma}_{1,2}$, with $l = \frac{\bar{\gamma}_2}{\bar{\gamma}_1}$ as a parameter. The diversity gain increases linearly with k until $k = 2$. After that, it remains constant. On the other hand, the coding gain decreases with k until $k = 2$. Afterward, it increases slightly and saturates to the coding gain of the MRC scheme. In addition, it is observed that the performance improvement is not significant when $k > 2$. This is more clearly shown when the BEP performance is plotted as a function of k for various values of l. The performance of the proposed CD scheme is worse than that of the direct transmission when $k < 1$. It is concluded that k should be in the range between 1 and 2 for a beneficial cooperation. Due to the inter-user channel errors, a system with $l > 1$ performs better at higher values of k (approximately greater than 1.6) and a system with $l < 1$ performs better at lower values of k. For cooperation to be worthwhile, the quality of the inter-user channel should be better than that of the user to BS channel.

[3]The term coding gain is used here to represent any system gain, e.g., modulation, not necessarily channel coding.

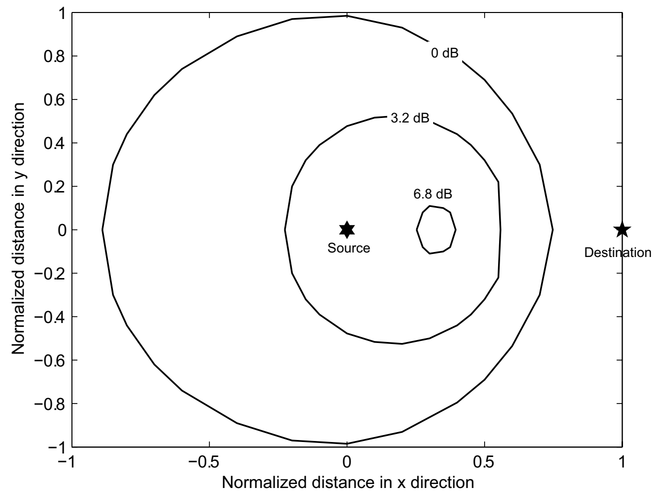

Fig. 5. Cooperative region of the proposed scheme for various SNR gain over direct transmission when $P_e = 10^{-2}$ and $\alpha = 3$ (urban area).

V. Cooperative Region

To achieve a specified diversity gain or BEP, it is necessary to know the geographical area within which the partner has to be located in order to have a successful cooperation. The area is called the cooperative region. The cooperative region should be known to all users as well as to the BS. In this section, we derive a cooperative region of the proposed CD scheme that yields specified normalized SNR gain over a NCD scheme.

The path losses are dependent on the distance between the transmitter and the receiver as well as on the propagation environment. There are many path loss models reported in the literature. We consider the log-distance path loss model in our analysis, $\sigma_{i,j}^2 \propto d_{i,j}^{-\alpha}$, where $d_{i,j}$ is the distance between i and j and α is the path loss exponent [13]. Since $\bar{\gamma}_i = \sigma_{i,b}^2(E_b/N_0)$, $\bar{\gamma}_i = \left(\frac{d_0}{d_{i,b}}\right)^{\alpha} \bar{\gamma}_0$, where $\bar{\gamma}_0 = (E_b/N_0)E\{|h_0|^2\}$ is the average SNR at the reference distance d_0 and h_0 is a fading coefficient with unity variance i.e., $\sigma_0^2 = 1$. Without loss of generality, considering *user 1* located at the reference point and fixing the distance between *user 1* and the BS at a unit distance apart ($d_{1,b} = 1$), the Cartesian coordinate of *user 1*, the BS and *user 2* are represented by (0,0), (1,0) and (x, y), respectively. Therefore, $\bar{\gamma}_2 = ((x-1)^2+y^2)^{-\alpha/2}\bar{\gamma}_1$ and $\bar{\gamma}_{1,2} =$

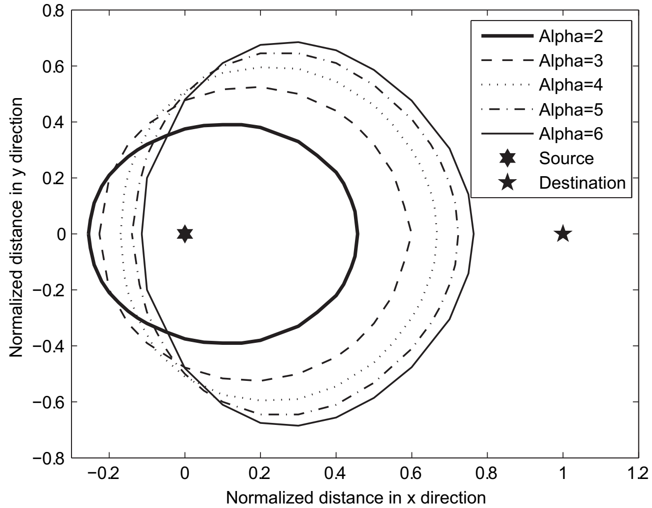

Fig. 6. Cooperative region of the proposed scheme for various path loss coefficient α when $P_e = 10^{-2}$ and $G_{cd_{norm}} = 3.2dB$.

$(x^2 + y^2)^{-\alpha/2}\bar{\gamma}_1$. For a given BEP, define the normalized cooperative SNR gain, G_{norm}, as $G_{norm} = \frac{\bar{\gamma}_{nc}/(2^1-1)}{\bar{\gamma}_1/(2^{0.5}-1)}$. Substituting $\bar{\gamma}_1$, $\bar{\gamma}_2$ and $\bar{\gamma}_{1,2}$ into (6) yields a function of contour in terms of x and y with P_e, $\bar{\gamma}_{nc}$,G_{norm} and α as parameters. The area inside the contour is defined as the cooperative region which provides at least specified G_{norm}.

Numerical Results: In Fig. 5, cooperative regions are drawn for various SNR gains over NCD transmission to achieve a $P_e = 10^{-2}$ when $\alpha = 3$. The cooperative region shrinks when the SNR gain increases, and locates near to user 1 (*sender*) rather than the BS (*destination*). This is due to the fact that the inter-user channel should be better than the channel between the user and the BS. In addition, similar cooperative regions for various path loss exponent, α, are compared in Fig. 6, where $P_e = 10^{-2}$ and $G_{norm} = 3.2dB$. The cooperative region expands in both the x and y directions and moves towards the destination when α increases. Since the cooperative region increases with α, the maximum achievable G_{norm} also increases.

VI. Conclusions

An energy and power efficient *fixed regenerate and forward* CD scheme has been proposed based on quadrature signaling. The proposed scheme is simple and can easily be switched between the cooperative and the NCD modes of operation. The diversity gain achieved and the bit error performance of the proposed scheme can be improved as the inter-user channel signal strength increases. In addition, the interested range of inter-user signal strength is also identified for a better cooperation. Finally, a cooperative region has been derived for a specified BEP and normalized SNR gain over the NCD scheme. Based on these studies, a power control scheme can be designed to optimize the system performance. Furthermore, knowledge of the cooperative region should be useful in designing an algorithm to choose a cooperative partner and to manage the cooperation handoff with the interaction of higher layer protocols.

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