Novel Cooperative Relaying Network Scheme with Exchange Communication and Distributed Transmit Beamforming

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***Abstract*—In this paper, we propose a novel scheme of cooperative relaying network based on data exchange between relays before forwarding it to destination. This inter-relay data exchange step is done during an additional middle-slot in order to enhance the transmit signals from relays to the destination. To reduce the propagation errors between relays as well as the required sum total transmit power for relays during this data exchange, only the relay possessing the highest SNR is engaged into exchanging data by forwarding its received signal to the other relays. As for the remaining non-selected relays, i.e., with low SNR, the transmitted signal is estimated by using both signals received separately at different time slots (i.e., 1st and 2nd slot) from source and the 'best' relay, respectively, emulating 2-element virtual antenna array where appropriate weights for the antenna array are developed. In addition, we investigate distributed transmit beamforming and MRC at the relays and the destination, respectively, to combine coherently the received signals. At the relay optimal location and at low SNR condition, the proposed method has significant better outage behaviour and average throughput than conventional methods using one or two time slots for transmission.**

Keywords-component; Cooperative relaying network, Adaptive antenna array, Transmit beamforming, MRC.

I. INTRODUCTION

Cooperative fixed-relaying cellular networks are new advantageous technologies for future generation of cellular systems, where relays have to transmit cooperatively the information from source to destination. The cooperative relaying technique effectively provides transmission diversity through distributed wireless relay networks over quasi-static fading channel without relying on actual multiple antennas. Prior work on cooperative relay network mainly focuses on exploiting spatial diversity for wireless relaying network [1], jointly optimising transmit beamforming weight and power allocation [2] and deriving the capacity of MIMO multiplexing relaying schemes [3].

In cooperative TDMA relaying networks, the data transmission takes usually place in two steps. In the first step, the source transmits to the relays and destination and in the second step; the relays process and forward their received signals to the destination (in either the same or a different time slot). However, to improve the quality of the transmit signals from relays to the destination, and especially for fixed-relaying networks; where the propagation channels between relays can be assumed static, an additional step can be inserted for exchanging information between relays. Some basic ideas to this exchange scheme were published in [4] for fixed relay-enabled user cooperation. In this work adaptive beamforming receiver was applied at the relay stations where each relay is dedicated to estimate one user signal, and then engaged into cooperation with the other relays using distributed space-time coding. During this exchange, each relay does not detect the data of other relays instead it simply forwards to the destination.

The purpose of this paper is to study a novel scheme of cooperative relaying network based on exchange between relays in order to enhance the transmit signals from relays to the destination by using three-time slots. In contrast to [4], instead of all relays exchange their received signals, only one relay, with the highest SNR in the source-relays link, engages into cooperation by forwarding its received signal to the other relays. By selecting the 'best' relay for this information exchange step, one can reduce the required sum total transmit power and also limit the propagation error between relays. Also during this step, we develop a virtual antenna array processing at the non-selected relays stations to estimate the transmitted signal by using both signals coming from source and the 'best' relay at different time slots (i.e., 1st and 2nd slot). In addition, we investigate distributed transmit beamforming and maximum ratio combiner (MRC) at the relays and destination, respectively, to combine coherently the received signals. Therefore, by maximizing the instantaneous SNR at the destination to the sum total transmitted power used in the whole cooperative network, we derive the transmit beamforming weight vector at the relay part and the MRC reception weight vector at the destination part.

The rest of the paper is organized as follows. Section II introduces the system model and describes the proposed cooperative network. Section III evaluates and analyzes the proposed method by computer simulation. Finally, section IV concludes the paper.

II. SYSTEM MODEL

Consider a wireless system where a source node transmits to a destination assisted by *m* relay nodes. For the sake of simplicity suppose that *m*=2. Fig.1 illustrates the proposed cooperative TDMA relaying scheme where each transmission block is divided into three non-overlapping steps in time.

A. Relay Transmission Protocol

In step I, the source node transmits the unit power signal $s(t)$ to the destination and relays. The received signals at the relay node i and the destination are, respectively, given by

$$r_{s,i} = \sqrt{P_s} \cdot h_{s,i} \cdot s + \eta_{s,i}, \qquad i = 1, 2 \tag{1}$$

$$r_{d,1} = \sqrt{P_s} \cdot h_{s,d} \cdot s + \eta_{s,d}, \tag{2}$$

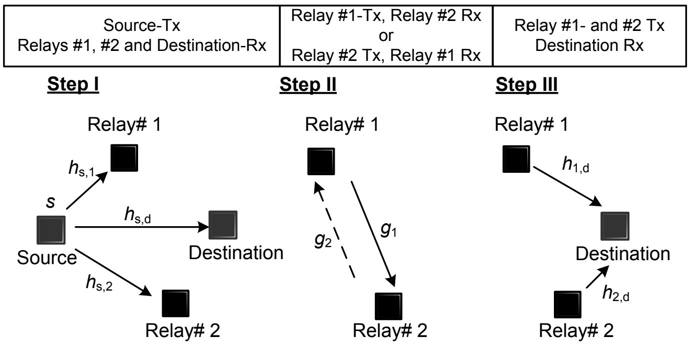

Figure 1. Illustration of the novel cooperative relaying network

where P_s is the transmit power used by the source node, $h_{s,i}$ and $h_{s,d}$ are complex path gains, including path-loss and Rayleigh fading, of the source-relay and source-destination channels, respectively, where the square of path-loss inversely proportional to the power of the distance is assumed, and $\eta_{s,i}$ and $\eta_{s,d}$ are the AWGN's in the corresponding channels with unit variance.

By using the amplify-and-forward (AF) relay scheme in step II, the 'best' relay, having the highest *SNR* for source-relay channel, normalizes and retransmits its received signal to the other relay. Without loss of generality, we assume that the relay #1 is selected, as shown in Fig.2, and consequently its transmitted signal to the 2nd relay is given by

$$s_i = \sqrt{P_1} \cdot \frac{r_{s,i}}{\sqrt{P_s \cdot \left\| h_{s,i} \right\|^2 + 1}}, \text{ for } i=1 \tag{3}$$

where P_1 is the transmit power used by relay 1 during step II.

The received signal at the 2nd relay is expressed as

$$r_2 = g_1 \cdot s_1 + \eta_{r,2}, \tag{4}$$

where g_1 and $\eta_{r,2}$ are complex path gains of the relay1-relay2 channel, and the AWGN with unit variance, respectively. Subsequently, the 2nd relay enhances its received signal by combining the signals received separately through steps I and II; emulating the usage of 2-element virtual antenna array, as shown in Fig.2, where each virtual antenna element output may undergo independent fading. By doing so, an adaptive antennas array (AAA) algorithm may be applied in this stage to combine coherently the received signals. The virtual AAA output can be expressed as follows

$$y_{c2} = w_{c_{21}} \cdot s_2 + w_{c_{22}} \cdot r_{c2}, \tag{5}$$

where s_2 is given by (3) for i=2, $[w_{c_{21}}, w_{c_{22}}]$ represents the AAA weight vector, and

$$r_{c2} = r_2 \cdot \frac{g_1^*}{\left\| g_1 \right\|^2} = \left(g_1 \cdot s_1 + \eta_{r,2} \right) \cdot \frac{g_1^*}{\left\| g_1 \right\|^2}. \tag{6}$$

By substituting (1-4) and (6) into (5), we obtain

$$y_{c2} = \sqrt{P_s} \cdot s \cdot \mathbf{h}_1 \cdot \mathbf{w}_{c2}^H + \boldsymbol{\eta}_1 \cdot \mathbf{w}_{c2}^H, \tag{7}$$

where $\mathbf{h}_1 = \left[\sqrt{P_1} \rho_2 h_{s,2}, \quad \sqrt{P_1} \rho_1 h_{s,1} \right]$, $\mathbf{w}_{c2} = [w_{c21}^*, w_{c22}^*]$,

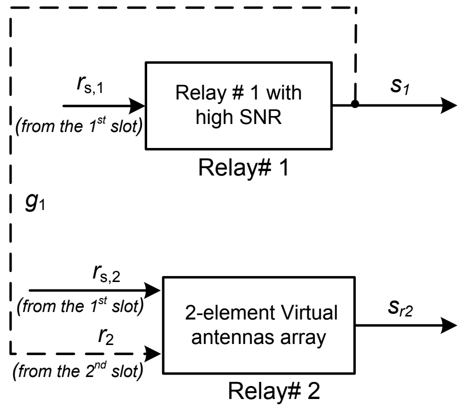

Figure 2. Data exchange between relays during step II.

$$\boldsymbol{\eta}_1 = \left[\sqrt{P_1} \rho_2 \eta_{s,2}, \quad \sqrt{P_1} \rho_1 \eta_{s,1} + \frac{g_1^*}{\left\| g_1 \right\|^2} \right] \quad , \quad E\left[\left| \eta_{s,i}(k) \right|^2 \right] = 1, \quad \text{for}$$

i=1,2, and $\rho_i = \left(\sqrt{P_s \cdot \left\| h_{s,i} \right\|^2 + 1} \right)^{-1}$ for i=1,2.

Therefore, the relays 1 and 2 normalize their received signal and retransmit at the 3rd time-slot the signals s_{r1} and s_{r2}, respectively to the destination; with the i-th complex transmit beamforming weight $w_{TB_{2i}}$ as follows

$$s_{r1} = w_{TB_{21}} \cdot y_{cn1}, \tag{8}$$

$$s_{r2} = w_{TB_{22}} \cdot y_{cn2}, \tag{9}$$

where

$y_{cn1} = \rho_1 \cdot r_{s,1}$, $y_{cn2} = \rho_{c2} \cdot y_{c2}$, and $\rho_{c2} = \left(\sqrt{E\left[y_{c2}^* \cdot y_{c2} \right]} \right)^{-1}$.

Then, the received signal at the destination at step III is expressed as

$$r_{d,2} = \sum_{i=1}^{2} \sqrt{P_2} \cdot w_{TB_{2i}} \cdot h_{i,d} \cdot s_{ri} + \eta_{r,d}, \tag{10}$$

where P_2 represents the transmitted power used by the relay nodes during the step III, $h_{i,d}$ is a complex path gain of the relay$_i$-destination channel and η_d is an AWGN with unit variance. By substituting (8-9) into (10), we obtain

$$r_{d2} = \sqrt{P_s} \cdot s \cdot \mathbf{a}_2 \cdot \mathbf{w}_{TB2}^H + \boldsymbol{\eta}_2 \cdot \mathbf{A}_2 \cdot \mathbf{w}_{TB2}^H + \eta_{r,d}, \tag{11}$$

where

$\mathbf{a}_2 = \left[\rho_1 \cdot h_{s,1} \cdot h_{1,d}, \quad \rho_{c2} \cdot \mathbf{h}_1 \cdot \mathbf{w}_{c2}^H \cdot h_{2,d} \right]$, $\mathbf{w}_{TB2} = [w_{TB_{21}}^*, w_{TB_{22}}^*]$

$\boldsymbol{\eta}_2 = \left[\eta_{s,1}, \quad \boldsymbol{\eta}_1 \cdot \mathbf{w}_{c2}^H \right]$, and $\mathbf{A}_2 = diag\left[\rho_1 \cdot h_{1,d}, \quad \rho_{c2} \cdot h_{2,d} \right]_{2\times 2}$.

In order to combine constructively the signals $r_{d,1}$ and $r_{d,2}$ from the source and relay channels, respectively, the MRC combining cooperative diversity is considered. Thus the final detection is given by

$$y = w_{MRC_{21}} \cdot r_{d,1} + w_{MRC_{22}} \cdot r_{d,2}. \tag{12}$$

By substituting (2) and (11) into (12), we obtain

$$y = \sqrt{P_s} \cdot s \cdot \mathbf{H}_2 \cdot \mathbf{w}_{MRC2}^H + \mathbf{N}_2 \cdot \mathbf{w}_{MRC2}^H, \tag{13}$$

where

$\mathbf{H}_2 = \left[h_{s,d},\ \mathbf{a}_2 \cdot \mathbf{w}_{TB2}^H\right], \mathbf{w}_{MRC2} = \left[w_{MRC_{21}}^*,\ w_{MRC_{22}}^*\right]$, and

$\mathbf{N}_2 = \left[\eta_{s,d},\quad \boldsymbol{\eta}_2 \cdot \mathbf{A}_2 \cdot \mathbf{w}_{TB2}^H + \eta_{d,2}\right]$.

B. Derivation of the weight vector

Many various weight adaptation algorithms are developed in literature to determine the optimal complex weight for the AAA. They all combine the received signals from multiple antenna elements to satisfy specific optimization criteria. These criteria may include methods for minimizing the mean square error (MMSE), maximizing the SNR, and minimizing the variance of interference. Among them, we employ here the maximizing SNR criterion based on generalized Eigen-value problem [5,7]. From (7) and for a given weight vector $\boldsymbol{w}_{c2}$, the instantaneous SNR at the virtual AAA output for 2nd Relay is expressed as

$$\gamma_{c2} = P_s \cdot \frac{\mathbf{w}_{c2} \cdot \mathbf{h}_1^H \cdot \mathbf{h}_1 \cdot \mathbf{w}_{c2}^H}{\mathbf{w}_{c2} \cdot \boldsymbol{\Omega}_{c2} \cdot \mathbf{w}_{c2}^H}, \tag{14}$$

where

$$\boldsymbol{\Omega}_{c2} = diag\left(P_1\rho_2^2,\ P_1\rho_1^2 + \frac{1}{\|g_1\|^2}\right)_{2\times 2}.$$

The weight optimization can be estimated by maximizing (14), in the form of Rayleigh quotient, by solving the generalized Eigen-value problem [5, 7]. Hence, for any weight vector $\boldsymbol{w}_{c2}$, we have

$$\gamma_{c2} \le P_s \lambda_{max}, \tag{15}$$

where λ_{max} is the largest Eigen-value of $\left(\boldsymbol{\Omega}_{c2}^{H/2}\right)^{-1}\mathbf{h}_1^H\mathbf{h}_1\left(\boldsymbol{\Omega}_{c2}^{1/2}\right)^{-1}$. The equality holds if $\mathbf{w}_{c2} = c.\mathbf{h}_1\left(\boldsymbol{\Omega}_{c2}^{1/2}\right)^{-1}$ where c can be any non-zero constant [5]. Then the optimum weight vector $\boldsymbol{w}_{c2}$ derived by maximizing the *SNR* γ_{c2} based on generalized Eigen-value problem is given by

$$\mathbf{w}_{c2} = \left[\frac{h_{s,2}}{\sqrt{P_1}\cdot\rho_2},\quad \frac{h_{s,1}}{\sqrt{P_1}\cdot\rho_1 + \frac{\sigma_2^2}{\|g_1\|^2 \cdot \sqrt{P_1}\cdot\rho_1}}\right]. \tag{16}$$

From (12), the instantaneous *SNR* at the destination is expressed as

$$\gamma_{d2} = P_s \cdot \frac{\mathbf{w}_{MRC2} \cdot \mathbf{H}_2^H \cdot \mathbf{H}_2 \cdot \mathbf{w}_{MRC2}^H}{\mathbf{w}_{MRC2} \cdot \boldsymbol{\Omega}_{d2} \cdot \mathbf{w}_{MRC2}^H}, \tag{17}$$

where $\boldsymbol{\Omega}_{d2} = diag\left[1, \mathbf{w}_{TB2} \cdot \mathbf{A}_2^H \cdot \boldsymbol{\Gamma}_2 \cdot \mathbf{A}_2 \cdot \mathbf{w}_{TB2}^H + 1\right]_{2\times 2}$ and

$$\boldsymbol{\Gamma}_2 = \left[1,\ \sqrt{P_1}\rho_1 w_{c_{22}};\ \sqrt{P_1}\rho_1 w_{c_{22}}^*,\ P_1\left|w_{c_{21}}\right|^2\rho_2^2 + \left|w_{c_{22}}\right|^2\left(P_1\rho_1^2 + \frac{1}{\|g_1\|^2}\right)\right].$$

The weight vector optimization is derived as

$$\left(\mathbf{w}_{TB2}, \mathbf{w}_{MRC2}\right) = \underset{(\mathbf{w}_{TB2},\mathbf{w}_{MRC2})}{arg\ max}\ (\gamma_{d2}),\ \text{s.b.t}\ P_s + P_1 + P_2 = P_t, \tag{18}$$

where P_t represents the sum total transmit power used in the whole cooperative relay network and $P_2 = \mathbf{w}_{TB2} \cdot \mathbf{w}_{TB2}^H$ is the total transmit power at the relay stations at the step III..

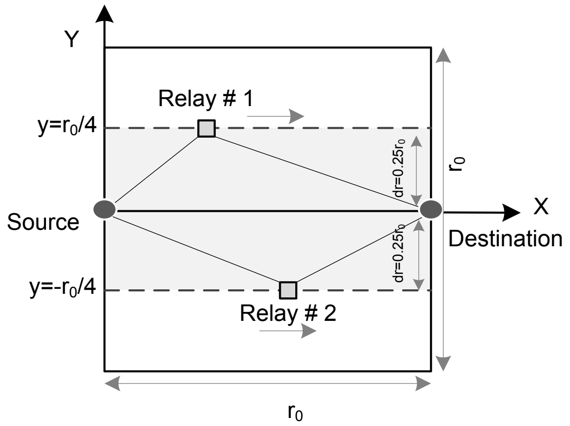

Figure 3. Square cell

Solving the optimization problem (18) in closed form appears to be complicated. But we relaxed the optimization problem by finding a sub-optimally closed form. Therefore, the optimum MRC weight vector $\boldsymbol{w}_{MRC2}$ is derived first by maximizing the instantaneous *SNR* given in (17) and then by substituting its expression in (17) we derive consecutively the transmit beamforming weight vector $\boldsymbol{w}_{TB2}$. Using the same presented principle to derive the weight vector by means of maximizing (17) based on the generalized Eigen-value problem, we obtain for any weight vector $\boldsymbol{w}_{MRC2}$

$$\gamma_{d2} \le P_s \lambda_{dmax}, \tag{19}$$

where λ_{dmax} is the largest Eigen-value of $\left(\boldsymbol{\Omega}_{d2}^{H/2}\right)^{-1}\mathbf{H}_2^H\mathbf{H}_2\left(\boldsymbol{\Omega}_{d2}^{1/2}\right)^{-1}$. The equality holds if $\mathbf{w}_{MRC2} = c \cdot \mathbf{H}_2 \cdot \left(\boldsymbol{\Omega}_{d2}^{1/2}\right)^{-1}$, where c can be any non-zero constant. Following the same analysis described above, we can prove that the MRC and the transmit beamforming weight vectors are given by [7]

$$\mathbf{w}_{MRC2} = \left[h_{s,d},\quad \frac{\mathbf{a}_2 \cdot \mathbf{w}_{TB2}^H}{\mathbf{w}_{TB2} \cdot \mathbf{A}_2^H \cdot \boldsymbol{\Gamma}_2 \cdot \mathbf{A}_2 \cdot \mathbf{w}_{TB2}^H + 1}\right], \tag{20}$$

$$\mathbf{w}_{TB2} = c\mathbf{a}_2\left(\boldsymbol{\Omega}_2\right)^{-1}, \tag{21}$$

where $\boldsymbol{\Omega}_2 = \mathbf{A}_2^H \cdot \boldsymbol{\Gamma}_2 \cdot \mathbf{A}_2 + I_{2\times 2}/P_2$ and $c = \sqrt{P_2} / .\sqrt{\left|\mathbf{a}_2(\boldsymbol{\Omega}_2)^{-1}\right|^2}$.

III. SIMULATION RESULTS

In this section we evaluate the performance of the proposed method with comparison of the two approaches presented in [2] and [6] with a benchmark comparison of the direct transmission when the source sends the information to the destination with the total transmit power P_t, without help from relays. The approach [2] uses 2-time slots with distributed transmit beamforming and MRC reception at the relays and destination, respectively. The approach [6] uses 3-time slots with an MRC at the destination and equal power allocation across the relay terminals, i.e. $P_i = P_r/2$, for $i=1,2$ where $P_r = P_s = P_t/2$.

We assume all channels have spatially uncorrelated Rayleigh fading which are constant within one slot, but varying between slots. The modulation scheme of the transmit

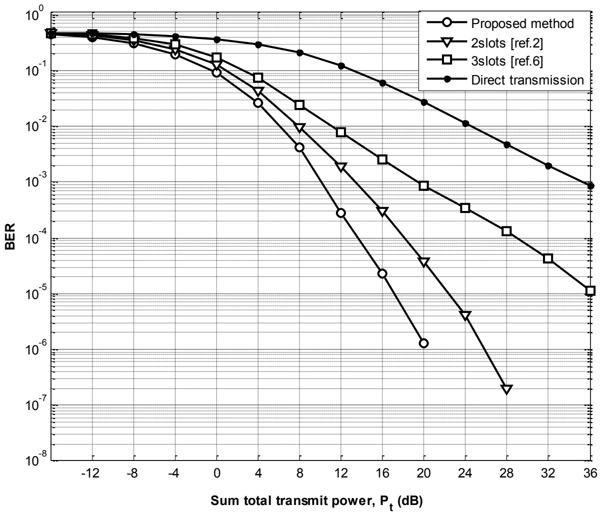

Figure 4. BER as a function of the sum total transmit power by using the four schemes

signal is QPSK. The source node is located at coordinates (0,0) and the destination node at (0,r_0) within a square of side length of r_0 , while the two relays are located between source and destination as shown in Fig.3. To obtain the maximum benefit of the inter-relay information exchange, the minimum distance between relays is set to be half of the source-destination distance. Thus the y-axis of the relay 1 and 2 are set to be equal to (r_0/4) and (-r_0/4), respectively, as shown in Fig.3. Finally, the path loss exponent is assumed to be 3.

To find the optimal location for the relays (x-axis) that gives the lowest BER, we conduct several channel realizations with a statistical averaging, where relay 1 and relay 2 move according to their corresponding lines with equation ("y"= r_0/4) and ("y"=- r_0/4), respectively. Without loss of generality we assume all distances are normalized to r_0. The optimal location (normalized to the source-destination distance r_0) for each method is obtained by averaging over 100 channel realizations and presented in Table 1.

TABLE I. RELAYS' OPTIMAL LOCATIONS NORMALIZED BY r_0

	Proposed method	[2]	[6]
Relay#1	x =0.3	x =0.4	x =0.5
	y=0.25	y =0.25	y =0.25
Relay#2	x =0.7	x =0.5	x =0.5
	y =-0.25	y =-0.25	y =-0.25

We notice from Table 1 that the optimal location using method [6] is obtained at the middle line between source and destination while the one for method [2] is almost near this line. In contrast, the optimal locations for the proposed method are positioned far from this line and thus it is due to the exchange data between relays.

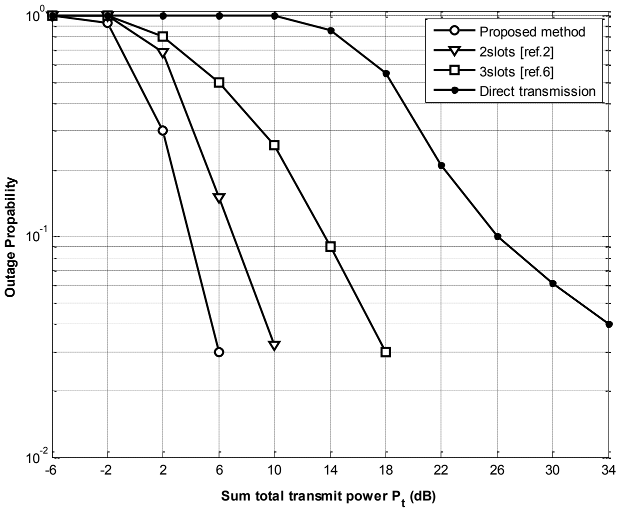

Figure 5. Outage Probability as a function of the sum total transmit power by using the four schemes

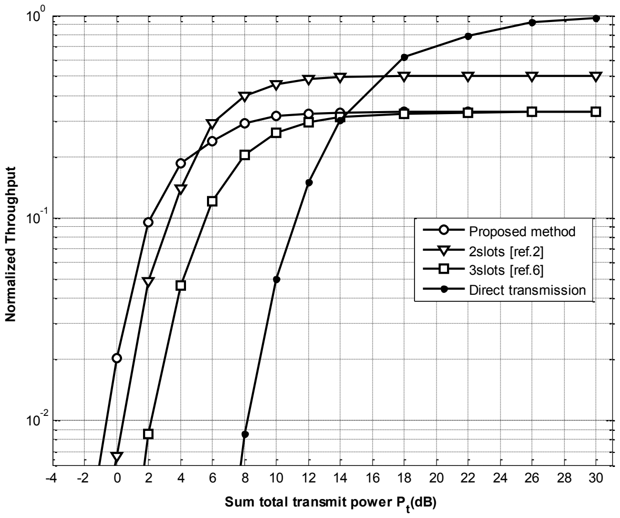

Figure 6. Average throughput of the four schemes as a function of the sum total transmit power

Figure 4 compares the average BER in terms of the total transmit power used in the complete cooperative network in the four schemes. The results are obtained by averaging over 2000 channel realizations and the relay locations for each method are positioned at their optimal value given in Table 1. From this figure it is shown that for a required BER equal to 0.001, the proposed method outperforms the ones presented in [2] and [6] by approximately 4dB and 10dB, respectively.

For the outage probability analysis, Monte-Carlo simulation was conducted in a unit square cell. The source is generated randomly 1000 times inside this cell while the results are obtained by averaging over 20 channel realizations for each source location. Also the relay locations for each method are positioned at their optimal value given in Table 1. The tolerable outage probability is assumed to be 0.1. Figure 5 illustrates that for tolerable outage probability the sum total transmit power should be equal to 4dB, 10dB, 22dB and 26dB by using the proposed method, [2], [6] and the direct transmission, respectively.

Figure 6 compares the average throughput in terms of the sum total transmit power used in the cooperative network in the four schemes. The normalized throughput is defined as the number of the correct received packets divided by the number of the transmitted ones during same period divided by the number of the slots used for this transmission, while the length of the packet is set to be 128 QPSK symbols. The results are obtained by averaging over 2000 channel realizations where the relay locations for each method are positioned at their optimal value given in Table 1. We notice from this figure that the proposed method outperforms the ones presented in [2] and [6] by 1dB and 3dB, respectively at low *SNR*[1]. Note that the approach [2] had greater throughput at high *SNR* (i.e., P_t>3dB) compared to the proposed method, but far poor outage probability. However lower transmit power is extremely desirable in highly dense new communication system to reduce interference and increase battery life of portable devices and that shows the importance of the proposed method.

IV. CONCLUSION

In this paper, we proposes a novel scheme of cooperative relaying network based on data exchange between relays before forwarding it to destination. In the proposed scheme the relay, with the highest *SNR* in the source-relays link, engages into cooperation by forwarding its received signal to the other relays. Also, we developed a virtual antenna array processing at the non-selected relays to estimate the transmitted signal by using both signals coming from source and the 'best' relay. It was shown by computer simulation that at reasonable transmit power levels, the proposed method has significant better outage behaviour and average throughput than conventional methods using one or two time slots for transmission.

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[1] Since all nodes stations are assumed to have unity noise variance, than low total transmit power is equivalent to low *SNR* condition.