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A Beamforming Technique Using Rotman Lens Antenna for Wireless Relay Networks

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Abstract: Rotman lens, which is a radio frequency beam-former that consists of multiple input and multiple output beam ports, can be used in industrial, scientific, and medical applications as a beam steering device. The input ports collect the signals to be propagated through the lens cavity toward the output ports before being transmitted by the antenna arrays to the destination in order to enhance the error performance by optimizing the overall signal to noise ratio (SNR). In this article, a low-cost Rotman lens antenna is designed and deployed to enhance the overall performance of the conventional cooperative communication systems without needing any additional power, extra time or frequency slots. In the suggested system, the smart Rotman lens antennas generate a beam steering in the direction of the destination to maximize the received SNR at the destination by applying the proposed optimal beamforming technique. The suggested optimal beamforming technique enjoys high diversity, as well as, low encoding and decoding complexity. Furthermore, we proved the advantages of our suggested strategy through both theoretical results and simulations using Monte Carlo runs. The Monte Carlo simulations show that the suggested strategy enjoys better error performance compared to the current state-of-the-art distributed multi-antenna strategies. In addition, the bit error rate (BER) curves drawn from the analytical results are closely matching to those drawn from our conducted Monte Carlo simulations.

Keywords: Performance analysis; smart antenna; Rotman lens antenna; multi-antenna systems; wireless relay networks cooperative diversity schemes; digital network coding; relay selection schemes

1 Introduction

In the recent years, several techniques have been proposed in the field of wireless communications to enhance the error performance of the whole system and its achievable throughput [1–6]. A group of these techniques works by increasing or optimizing the transmitted power, while another group is applying powerful forward error detection and correction techniques to increase the achievable gain. Latest techniques are using time, frequency, and space-diversity techniques in order to enhance the total diversity gain [7–12]. In time diversity, the BER performance can be improved by sending the same signal many times in several time periods [13–16]. While, in frequency diversity the error performance is enhanced by sending the same signal many times in several frequency bands. Also, space diversity schemes that are known as multiple input multiple output (MIMO) schemes can be used to enhance the error performance by broadcasting the same signal many times via different transmitting antennas using the same frequency band and time period, leading to the most powerful performance without requiring extra periods or frequency bands [17,18]. Later on, several schemes are suggested to improve both diversity order and coding gain by combining diversity techniques with coding algorithms including but not limited to space-frequency coding (SFC) schemes and space-time coding (STC) schemes [10,13–15]. Furthermore, special diversity techniques using beamforming schemes [11–12,17–19] are used to steer the transmitting antenna beams towards the destination terminal to enhance the BER performance and the throughput by maximizing the received signal to noise ratio (SNR), given that the BER performance of the multi-antenna systems suffer from the multiuser interference and channel impairments [1–9]. In addition, it is very well known that it is difficult to deploy several antennas at the same mobile station due to several limitations. Therefore, cooperative communication systems can be used to overcome this problem by randomly distributing a group of relay nodes between the two communicating parties [5–11,20,21]. Those relay nodes can be used in two modes of operation, either to amplify and forward (AF) the obtained signals or to detect the transmitted symbols before forwarding them to the receiving antennas. However, relay-nodes in wireless relay systems process the obtained signals before transmitting them to the destination terminals by merging the obtained copies of the transmitted signal received via several links to enhance the diversity order and coding gain. These schemes are well known as the spatial-diversity schemes [5–11]. Lately, several improved relaying methods have been introduced to obtain a high diversity and coding gain. For instance, the so called space-time diversity schemes for cooperative communication systems, in which the relay nodes are applying a space-time coding techniques, are found to enhance the performance in terms of BER and achievable data rate [9,13–15,22]. The distributed beamforming techniques, where the relay nodes are capable of forming a beam towards the destination to enhance the achievable SNR, are introduced in [9,11,12,23–25]. More specifically, the authors of [17] proposed a new beamforming approach by combining a single-group multicasting network with orthogonal space-time block coding in order to minimize the total transmitted power while maintaining the quality of service constraints. Article [11] proposed a new non-coherent beam-forming scheme for bi-directional cooperative communication systems where the angles of the obtained signals on the relay nodes are adjusted without needing CSI or training signals. In [24], a non-trivial combination between the differential diversity and the distributed beamforming techniques have been used to develop a simple distributed differential transmit beamforming technique that does not require CSI at any node while providing high BER, optimal end-to-end delay, and low decoding complexity. A bi-directional differential beamforming scheme have been proposed in [9] by utilizing differential phase shift keying modulation at the relay stations to enable beamforming without the knowledge of any instantaneous CSI. On the other hand, more non-beamforming techniques have been proposed without the knowledge of any instantaneous CSI [26–29]. The Rotman lens is a radio frequency (RF) beam-former that has multi-input and multi-output beam ports [30,31]. The input ports collect the RF signals to be propagated through the lens cavity toward the output ports before being transmitted by the antenna arrays [30]. The authors of [32] emphasize on the need to combine the use of Rotman lens with RF switching for superior performance compared to conventional phased arrays. One great advantage of Rotman lens is its capability to generate many beams without the need to physically moving the antenna system [33], therefore, its being widely used in the radar surveillance systems to see targets in multiple directions without changing the orientation of the antenna. Also, in [34] the authors found that using the low-cost Rotman lens in hybrid beamforming systems can achieve a superior performance, exhibit wideband capability compared to the high-cost phase shifters and the small-scale MIMO systems. In this article, a low-cost Rotman lens antenna is utilized in order to enhance the overall performance of the conventional cooperative communication systems without needing any additional power, extra time or frequency slots. In the suggested system, the smart Rotman lens antennas generate a beam steering in the direction of the destination to maximize the received SNR by applying the proposed optimal beamforming technique. The suggested optimal beamforming technique enjoys high diversity order and low encoding and decoding complexity. Furthermore, we proved the advantages of our suggested strategy through both theoretical results and simulations using Monte Carlo runs. The Monte Carlo simulations show that the suggested strategy enjoys better BER performance compared to the current distributed multi-antenna strategies. In addition, the BER curves drawn from the analytical results are closely matching those drawn from our conducted Monte Carlo simulations.

2 System Model

Given that the Rotman lens is considered as a radio-frequency beam former that consists of N input terminals and M output terminals [30]. The received signals at the N input terminals will flow via the Rotman-lens to the M output terminals before reaching the transmitting antennas. The required phase and amplitude distributions can be obtained using the formulas of the optical path length equality by calculating the needed locations of the input and output terminals, and the transmission-line lengths as well. Rotman lens is capable of producing a steering beam of different phases by exciting the corresponding input/output ports, as well as, producing multiple beams by exciting the multiple input/output ports simultaneously. The use of Rotman lens is an efficient way to design low-cost smart antennas as it provides a true time delay leading to a larger spectrum, and a low insertion loss allowing to be easily fabricated at low cost [30].

In our proposed cooperative communication system, a unidirectional network composed of a transmitter T equipped with a single antenna, a receiver D equipped with a single antenna, and smart Rotman lens relay with a group of M receive antennas and N transmit antennas. The transmitter and the relay are equipped each with a Rotman lens in order to focus their beam-forms. As a first step, the transmitter T broadcasts the information toward the array of smart relay node. The smart relay amplifies and forwards (AF) the information toward the terminal node D. One should note here that all the antennas (T, R and D) have limited average transmission powers. In addition, we also denote the channel gains as f_r (from T to$\mathcal{R}_r$) and g_r (from D to$\mathcal{R}_r$). The magnitude, the floor formula that rounds in the direction of zero, the Frobenius norm, and the expectation are denoted by $|.|$, $\lfloor\cdot\rfloor$, $||\cdot||$ and,$E(.)$, respectively. Also, Fig. 2 illustrates the implementation of the Rotman lens with M-input ports and N-output ports within the relay node.

Figure 1: System model showing the two communicating parties and the smart relay node

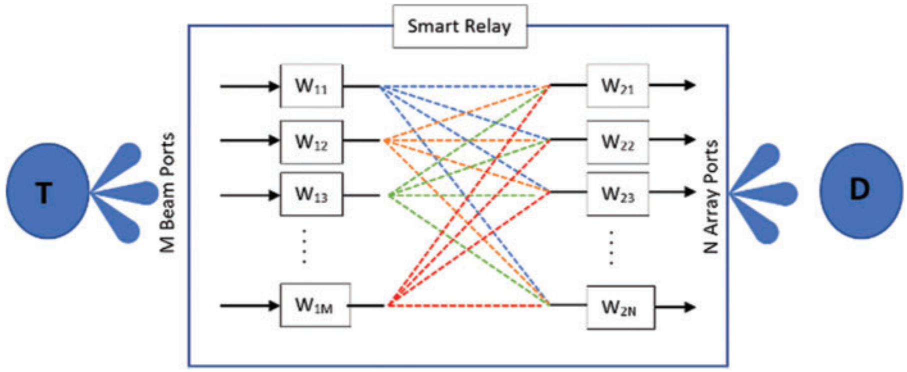

Figure 2: Smart relay Node showing the use of Rotman lens with M-input ports and N-output ports

3 The Proposed Beamforming Technique Using Rotman Lens Antenna

The relationship between the input signal vector and the output signal vector is characterized by the Rotman lens matrix as given in the below equations:

$$\mathbf{z}_{\mathcal{R}} = \mathbf{w}_1\mathbf{w}_2\mathbf{y}_{\mathcal{R}} \tag{1}$$

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ \vdots \\ z_N \end{bmatrix} = \begin{bmatrix} w_{21} \\ w_{22} \\ w_{23} \\ \vdots \\ w_{2N} \end{bmatrix} \times \begin{bmatrix} w_{11} & w_{12} & w_{13} & \dots & w_{1M} \end{bmatrix} \times \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{bmatrix}, \tag{2}$$

where $\mathbf{y}_{\mathcal{R}}$ and $\mathbf{z}_{\mathcal{R}}$ are the vectors representing the input and the output signals respectively, such that

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ \vdots \\ z_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} w_{21}w_{11} & w_{21}w_{12} & w_{21}w_{13} & \cdots & w_{21}w_{1M} \\ w_{22}w_{11} & w_{22}w_{12} & w_{22}w_{13} & \cdots & w_{22}w_{1M} \\ w_{23}w_{11} & w_{23}w_{12} & w_{23}w_{13} & \cdots & w_{23}w_{1M} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ w_{2N}\,w_{11} & w_{2N}\,w_{12} & w_{2N}\,w_{13} & \cdots & w_{2N}\,w_{1M} \end{bmatrix}_{N\times M} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{bmatrix}_{M\times 1}, \tag{3}$$

$$\mathbf{z}_{\mathcal{R}} = \mathbf{W}_{\mathcal{R}}\mathbf{y}_{\mathcal{R}} = \mathbf{w}_1\mathbf{w}_2\mathbf{y}_{\mathcal{R}}\,, \tag{4}$$

where $\mathbf{W}_{\mathcal{R}}$ is an NxM matrix that represents the links between the input and the output of the Rotman lens [4]. In order to maximize the received signal to noise ratio at the receiver side the above matrix should be optimized. Given that the transmitter T sends the information symbol s_{T} to the relay node with a Rotman lens as per the below equation:

$$\mathbf{y}_{\mathcal{R}} = \sqrt{P_T}\,\mathbf{f}\,s_T + \mathbf{n}_{\mathcal{R}}, \tag{5}$$

where s_T denotes the transmitted symbol, $\mathbf{y}_R = [y_1 \quad y_2 \quad y_3 \dots \quad y_M]^T$ represents the received signal vector at the Rotman lens $\mathcal{R}$, $\mathbf{f} = [f_1 \quad f_2 \quad f_3 \dots \quad f_M]^T$ represents the channel vector between the transmitter and the Rotman lens $\mathcal{R}$, and $\mathbf{n}_{\mathcal{R}} = [n_1 \quad n_2 \quad n_3 \dots \quad n_M]^T$ represents the noise vector at the Rotman lens $\mathcal{R}$ and P_T is the total power of the transmitter. Noise signals are drawn from a white Gaussian distribution with an average time domain value of zero and variance σ^2. Now, Rotman lens $\mathcal{R}$ receives and retransmits the signal toward D after processing it to reduce the overall complexity. The Rotman lens $\mathcal{R}$ maximizes the received SNR as all received signals at the destination will be added coherently in-phase. The impact of using the Rotman lens on the received signal can be reflected using the weight vectors $\mathbf{w}_1$ and$\mathbf{w}_2$, such that $\mathbf{z}_{\mathcal{R}} = \mathbf{W}_{\mathcal{R}}\mathbf{y}_{\mathcal{R}} = \mathbf{w}_1\mathbf{w}_2\mathbf{y}_{\mathcal{R}}$. The signal at the receiver side is given in the below equation:

$$y_D = \sqrt{\alpha P_{\mathcal{R}}}\,\mathbf{g}\,\mathbf{z}_{\mathcal{R}} + n_D, \tag{6}$$

where $\mathbf{g} = [\mathrm{g}_1 \quad g_2 \quad g_3 \ldots \quad \mathrm{g}_N]$ is the CSI vector between the receiver and the smart Rotman lens antennas, α is scaling factor to control the transmitted power, and n_D represents the noise signal at the destination, then:

$$y_D = \sqrt{\boldsymbol{\alpha}\ P_{\mathcal{R}}}[g_1 \quad g_2 \quad g_3 \ldots \quad \mathrm{g}_N] \begin{bmatrix} w_{21} \\ w_{22} \\ w_{23} \\ \vdots \\ w_{2N} \end{bmatrix} \times \begin{bmatrix} w_{11} & w_{12} & w_{13} & \ldots & w_{1M} \end{bmatrix} \times \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{bmatrix} + n_D, \tag{7}$$

$$= \sqrt{\alpha\ P_{\mathcal{R}}}\ \mathbf{g}\ \mathbf{w}_2\ \mathbf{w}_1\ \mathbf{y}_{\mathcal{R}} + n_{D,} \tag{8}$$

$$= \sqrt{\alpha\ P_T P_{\mathcal{R}}}\ \mathbf{g}\ \mathbf{w}_2\ \mathbf{w}_1 \mathbf{f}\ s_T + \sqrt{\alpha\ P_{\mathcal{R}}}\mathbf{g}\ \mathbf{w}_2\ \mathbf{w}_1 \mathbf{n}_{\mathcal{R}} + n_D, \tag{9}$$

Here, the signal is represented by the term $\sqrt{P_T P_{\mathcal{R}}}\ \mathbf{g}\ \mathbf{w}_2\ \mathbf{w}_1\mathbf{f}\ s$ and the noise is represented by the term$\sqrt{P_{\mathcal{R}}}\mathbf{g}\ \mathbf{w}_2\ \mathbf{w}_1\mathbf{n}_{\mathcal{R}} + n_D$. Consequently, the received SNR can be written as:

$$SNR = \frac{E\left\{\left|\left|\sqrt{P_{\mathcal{R}} P_T}\ \mathbf{g}\ \mathbf{w}_2\ \mathbf{w}_1 \mathbf{f}\ s_T\right|\right|^2\right\}}{E\left\{\left|\left|\sqrt{\alpha P_{\mathcal{R}}}\mathbf{g}\ \mathbf{w}_2\ \mathbf{w}_1 \mathbf{n}_{\mathcal{R}} + n_D\right|\right|^2\right\}}. \tag{10}$$

Given that the Rotman lens is going to adjust the phase shifts of all the received signals to optimize the SNR at the destination. Moreover, we assume that $w_{1i} = e^{j\theta_{1i}}$ and $w_{2i} = e^{j\theta_{2i}}$. Then, Eq. (9) can be updated as the following:

$$y_D = \left(\sqrt{\alpha P_{\mathcal{R}} P_T} \sum\nolimits_{i=1}^{M} f_i e^{j\theta_{1i}}\right) \left(\sum\nolimits_{i=1}^{N} g_i e^{j\theta_{2i,r}}\right) s_T + \sqrt{\alpha P_{\mathcal{R}}} \left(\sum\nolimits_{i=1}^{M} g_i e^{j\theta_{1i}}\right) \left(\sum\nolimits_{i=1}^{N} e^{j\theta_{2i}} n_{\mathrm{i}}\right) + n_D. \tag{11}$$

Leading to SNR at the receiver side given as:

$$\beta = \frac{E\left\{\left|\left|\left(\sqrt{\alpha P_{\mathcal{R}} P_T} \sum_{i=1}^{M} f_i e^{j\theta_{1i}}\right) \left(\sum_{i=1}^{N} e^{j\theta_{2i}} g_i\right)\right|\right|^2\right\}}{E\left\{\left|\left|\sqrt{\alpha P_{\mathcal{R}}} \left(\sum_{i=1}^{M} g_i e^{j\theta_{1i}}\right) \left(\sum_{i=1}^{N} e^{j\theta_{2i}}\ n_{\mathrm{i}}\right) + n_D\right|\right|^2\right\}}, \tag{12}$$

where $E\left\{|s_T|^2\right\} = 1$ and

$$E\left\{\left|\left|\left(\sum\nolimits_{i=1}^{M} f_i e^{j\theta_{1i}}\right) \left(\sum\nolimits_{i=1}^{N} e^{j\theta_{2i}} g_i\right)\right|\right|^2\right\} \le E\left\{\left(\sum\nolimits_{i=1}^{M} |f_i|^2\right) \left(\sum\nolimits_{i=1}^{N} |g_i|^2\right)\right\}. \tag{13}$$

Now, in order to maximize β given in (12), Eq. (13) must be hold equal. This can be achieved if:

$$\theta_{1i} = \angle f_i = \frac{f_i}{|f_i|}, \tag{14}$$

$$\theta_{2i} = \angle g_i = \frac{g_i}{|g_i|}. \tag{15}$$

Also, the power scaling factor α presented in (7) used to ensure an average transmitted power of $P_{\mathcal{R}}$ at the Rotman lens can be represented as:

$$\alpha = \sqrt{\frac{P_{\mathcal{R}}}{\left(P_T\ \sigma_f^2 + \sigma^2\right)}}, \tag{16}$$

where σ_f^2 represents the variance of the channel between the transmitter and the Rotman lens antennas and σ^2 denotes the noise variance. Substituting (14)–(16) in (12), then the value of SNR can be expressed as:

$$\beta = \frac{P_{\mathcal{R}} P_{T_1}\ ||f||^2\ \ ||g||^2}{\sigma^2\left(P_T\ \sigma_f^2 + P_{\mathcal{R}}\ ||g||^2 + \sigma^2\right)}. \tag{17}$$

Therefore, during the second phase, the received signal can be written as:

$$y_D = \sqrt{\alpha P_{\mathcal{R}} P_T}\left(\sum\nolimits_{i=1}^{M} |f_i|\right)\left(\sum\nolimits_{k=1}^{N} |g_k|\right) s_T + \sqrt{\alpha P_{\mathcal{R}}}\left(\sum\nolimits_{i=1}^{M} g_i e^{j\theta_{1i}}\right)\left(\sum\nolimits_{i=1}^{N} e^{j\theta_{2i}} n_{\mathrm{i}}\right) + n_{D,} \tag{18}$$

$$y_D = \sqrt{\alpha P_{\mathcal{R}} P_T}\ ||\mathbf{f}||\ ||\mathbf{g}||\ s_T + \sqrt{\alpha P_{\mathcal{R}}\ ||\mathbf{g}||}\left(\sum\nolimits_{i=1}^{N} e^{j\theta_{2i}} n_i\right) + n_D. \tag{19}$$

Using the maximum likelihood (ML) technique to decode the information at the receiver side as per the below equation:

$$\tilde{s}_T = \arg\min_s \|y_d - \sqrt{\alpha P_{\mathcal{R}} P_T}\left(||\mathbf{f}||^2\right)\left(||\mathbf{g}||^2\right) s\|^2. \tag{20}$$

$\tilde{s}_T$ represents the estimated value of the transmitted symbol. Keeping in mind that in case the user decodes the message received from the direct link, the symbol $\tilde{s}_T$ can be given as:

$$\tilde{s}_T = \arg\min_s \left\|y_D - \sqrt{\alpha P_{\mathcal{R}} P_T}\left(\|\mathbf{f}\|^2\right)\left(\|\mathbf{g}\|^2\right) s\right\|^2 + \left\|y_{dl} - \sqrt{P_T} f_0 s\right\|^2, \tag{21}$$

Where $y_{dl} = \sqrt{P_T} f_0 s_T + n_{dl}$, where f_0 represents the direct link between the transmitter and the receiver and n_{dl} is the noise obtained at the receiver through the direct link. It's worth mentioning here that a linear symbol-wise decoder with a very low decoding complexity can be used to decode the received information symbols.

4 BER Performance Analysis

In this section, using the assumptions presented in Section 2 and without any prior channel knowledge in the whole system, the analytical BER performance of the suggested technique is introduced. For simplicity, we will consider that $M = N = R$. Therefore, the conditional BER formula of the differential or conventional strategies for flat fading channels is given by [11,35,36] as follows

$$P_b(\gamma) \approx \frac{1}{2^{2(R+1)}\pi}\int_{-\pi}^{\pi} f(\theta)\ exp\left(-\alpha(\theta)\gamma\right) d\theta, \tag{22}$$

where

$$f(\theta) = \frac{b^2}{2\,\alpha(\theta)}\sum\nolimits_{r=1}^{R+1}\binom{2R+1}{R}\left(\left(\beta^{-R} - \beta^{R+2}\right)\ \cos\left(R\left(\theta + \frac{\pi}{2}\right)\right)\right.$$
$$\left. - \left(\beta^{-R+1} - \beta^{R+1}\right)\ \cos\left((R+1)\left(\theta + \frac{\pi}{2}\right)\right)\right), \tag{23}$$

$$\alpha(\theta) = \frac{b^2\left(1 + 2\beta\sin(\theta) + \beta^2\right)}{2}. \tag{24}$$

Here, $\beta = \frac{a}{b}$ is a constant controlled by the modulation order which is depending on the values of a and b, e.g., for BPSK $a = 10^{-3}$, $b = \sqrt{2}$ and for 4-PSK, $a = \sqrt{2-\sqrt{2}}$, $b = \sqrt{2+\sqrt{2}}$, and $\gamma = \gamma_s + \sum_{r=1}^{R}\gamma_r$ where γ_s and γ_r represent the SNR of the channel between the transmitter T and the receiver D and the SNR of the indirect channel between T and D through the rth Rotman lens antenna available in the relay node, respectively, where

$$\gamma_r = \frac{P_{\mathcal{R}}P_T\left|f_r\right|^2\left|g_r\right|^2}{\sigma^2\left(P_T\sigma_f{}^2 + P_{\mathcal{R}}\left|g_r\right|^2 + \sigma^2\right)}, \tag{25}$$

$$\gamma_s = \frac{P_T\left|f_0\right|^2}{2\sigma^2}. \tag{26}$$

Now, the average BER, calculated through finding the average of the conditional formula $P_b(\gamma)$ expressed by (22) with respect to the random variables using the moment generation function (MGF) technique [11,35,36], can be expressed as

$$P_b \approx \frac{1}{2^{2(R+1)}\pi}\int_{-\pi}^{\pi} f(\theta)\ \mathrm{M}_{\gamma_s}(\theta)\ \prod_{r=1}^{R}\mathrm{M}_{\gamma_r}(\theta)\,d\theta, \tag{27}$$

where $\mathrm{M}_{\gamma_r}(\theta)$ represents the moment generation function (MGF) of the instantaneous SNR γ_r, given that r ∈ {s, 1, · · ·, R}. With Rayleigh independent fading channels, $|f_r|^2$, $|g_r|^2$and $|f_0|^2$ are independent exponential random variables with parameter $1/\sigma_f^2$, $1/\sigma_g^2$ and $1/\sigma_0^2$ respectively. Thus, we have

$$\mathrm{M}_{\gamma_s}(\theta) = \frac{1}{1 + K_0(\theta)}, \tag{28}$$

Where $K_0(\theta) = \frac{P_T\,\alpha(\theta)\,\sigma_0^2}{\sigma^2}$ and $\mathrm{M}_{\gamma_s}(\theta)$ represents MGF of γ_s. Like (28), $\mathrm{M}_{\gamma_r}(\theta)$given in (29) is calculated by integrating with respect to both (exponential) random variables $|f_r|^2$ and $|g_r|^2$. Thus,

$$\mathrm{M}_{\gamma_r}(\theta) = \frac{1}{1 + K_f}\left[1 + A(\theta)\int_0^{\infty}\frac{\exp\left(-u/\sigma_g^2\right)}{u + R_r(\theta)}du\right], \tag{29}$$

$$A(\theta) = \frac{1}{1 + K_f}\frac{P_T\,\sigma_f^2 + \sigma^2}{\sigma_g^2 P_{\mathcal{R}}}, \tag{30}$$

$$R_r(\theta) = \frac{P_T\,\sigma_f^2 + \sigma^2}{P_{\mathcal{R}}\left(1 + K_f(\theta)\right)}, \tag{31}$$

where $K_f(\theta) = \frac{P_T\,\alpha(\theta)\,\sigma_f^2}{\sigma^2}$. Finally, by substituting (28) and (29) into (27), we end up with a BER expression that involves only double integration. Then, the BER expression in (27) can be upper bounded by the bound in (29). We can see from (31) that $R_r(\theta)$ reaches its minimum value when $\alpha(\theta)$ attains its maximum at $\theta = \frac{\pi}{2}$ where $\alpha(\theta) \le \frac{b^2\left(1+\beta^2\right)}{2}$. Therefore, the minimum value of $R(\theta)$ is given by

$$R_r(\theta) \ge R_{r,\,min} = \frac{P_T\,\sigma_f^2 + \sigma^2}{P_{\mathcal{R}}}\left[1 + \frac{P_T\,\sigma_f^2\,b^2\,\left(1+\beta^2\right)}{2\sigma^2}\right]^{-1}. \tag{32}$$

Substituting $R_{min}(\theta)$ in (27), leads to the BER upper bound as given by

$$P_b \le \frac{1}{2^{2(R+1)}\pi}\int_{-\pi}^{\pi}\frac{f(\theta)}{1+K_0(\theta)}\prod_{r=1}^{R}\frac{1}{1+K_f(\theta)}\times[1+A(\theta)Z_r(\theta)]\,d\theta, \tag{33}$$

where $Z_{r,max}(\theta) = \int_0^\infty \frac{\exp\left(-u/\sigma_g^2\right)}{u+R_{r,min}(\theta)}du.$ If a large SNR is considered, i.e., $K_0 \gg 1$ and $K_f \gg 1$, $1/(1+K_f)$becomes $1/K_f$ and $1/(1+K_0)$ becomes $1/K_0$ in (33). For the sake of simplicity, we can also consider that $\sigma_f^2 = \sigma_0^2$, then, the formula expressed in (32) is given by

$$P_b \le \left(\frac{2\sigma^2}{P_T\,\sigma_f^2}\right)^{R+1}\times G_{r,max}(\theta), \tag{34}$$

$$G_{r,max}(\theta) = \frac{1}{2^{2(R+1)}\pi}\int_{-\pi}^{\pi}\frac{f(\theta)}{\alpha(\theta)^{R+1}}[1+A(\theta)Z_{r,max}(\theta)]\,d\theta. \tag{35}$$

$G_{r,max}(\theta)$and (R + 1) given by (34) and (35) represent the coding gain and diversity order. Therefore, the suggested system with R Rotman lens antennas and direct link between the transmitter and receiver enjoys a diversity order which is equal to (R + 1), i.e., the full diversity order . Like (33), $\alpha(\theta)$ is lower bounded by assuming that $\theta = \frac{\pi}{2}$ in (24). Thus, $\alpha(\theta) \ge \frac{b^2(1-\beta^2)}{2}$. Therefore, BER expression given in (34) can be bounded as follows

$$P_b \ge \frac{1}{2^{2(R+1)}\pi}\int_{-\pi}^{\pi}\frac{f(\theta)}{1+K_0(\theta)}\prod_{r=1}^{R}\frac{1}{1+K_f(\theta)}\times[1+A(\theta)Z_{r,\,min}(\theta)]\,d\theta, \tag{36}$$

$$Z_{r,min}(\theta) = \int_0^\infty \frac{\exp\left(-u/\sigma_g^2\right)}{u+R_{r,\,max}(\theta)}du, \tag{37}$$

$$R_r(\theta) \le R_{r,\,max} = \frac{P_T\,\sigma_f^2+\sigma^2}{P_{\mathcal{R}}}\left[1+\frac{P_T\,\sigma_f^2\,b^2\,\left(1-\beta^2\right)}{2\sigma^2}\right]^{-1}. \tag{38}$$

If a large SNR is considered, i.e., $K_0 \gg 1$ and $K_f \gg 1$, $1/(1+K_f)$becomes $1/K_f$ and $1/(1+K_0)$ becomes $1/K_0$ in (33). For the sake of simplicity, we can also consider that $\sigma_f^2 = \sigma_0^2$, then, the formula expressed in (36) is given by

$$P_b \ge \left(\frac{2\sigma^2}{P_T\,\sigma_f^2}\right)^{R+1}\times Q_{r,min}(\theta), \tag{39}$$

$$Q_{r,min}(\theta) = \frac{1}{2^{2(R+1)}\pi}\int_{-\pi}^{\pi}\frac{f(\theta)}{\alpha(\theta)^{R+1}}[1+A(\theta)Z_{r,min}(\theta)]\,d\theta\,. \tag{40}$$

5 Results and Discussion

This section presents the analytical and simulated performance results explained before in Section 4. Figs. 3, 4 and 5 show the BER performance of the cooperative communication system shown in Fig. 1 which has a single transmitter T, a single destination D, with and without considering the direct communication channel between them, as well as, a smart Rotman antennas imbedded at the relay node (R= 1 and 2) performing the AF protocol using one or two bits per channel use (bpcu). In these figures, the proposed technique is compared with the state-of-the-art coherent and non-coherent techniques proposed in [9–14]. In all the simulation figures, Rayleigh flat-fading channels are considered, and the total power used in the whole system is distributed uniformly between the transmitter P_T and the smart Rotman relay $P_{\mathcal{R}}$ such that $P_{\mathrm{T}} = P_{\mathcal{R}}$, and that the whole transmitted power from the smart Rotman relay $P_{\mathcal{R}}$ is uniformly distributed on its transmitting antennas. To compare the BER performance of our proposed strategy with the BER performance of the state-of-the art strategies suggested in [9–14] as a function of the total SNR, a Monte Carlo method with 10^6 iterations is used to draw the curves available in Figs. 3, 4 and 5. Fig. 3 illustrates the BER performance of the proposed strategy assuming there is no direct channel between the transmitter T and the receiver D. Therefore, two Rotman antennas are located at an intermediary relay node (R= 2) performing the AF protocol using one bpcu. In the latter situation, the suggested strategy is compared with the state-of-the-art coherent and non-coherent strategies proposed in [9–14]. Fig. 3 shows that the suggested strategy outperforms all the state-of-the art two-, there-, and four-phase distributed space time coding strategies suggested in [10,13,14], as well as, all the distributed beamforming strategies proposed in [9,11,12]. In Fig. 4, the BER is displayed *vs.* the SNR. In this figure, the proposed strategy, using two bpcu and two antennas at the smart relay node (R= 2), assuming there is no direct channel between the transmitter T and the receiver D, is compared with the strategies proposed in [9–14]. Fig. 4 shows that the suggested strategies again enjoys a better performance than the current two-, there-, and four-phase distributed space time coding strategies proposed in [10,13,14], as well as, all the distributed beamforming strategies proposed in [9,11,12]. Note that the smart lens antennas can also be improved by modifying the electromagnetic field localization [19,37,38].

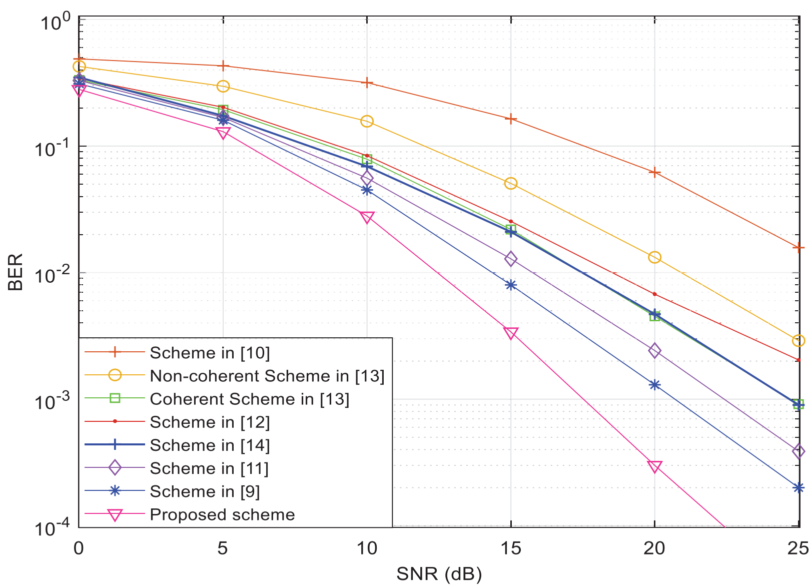

Figure 3: BER *vs.* SNR for different cooperative diversity strategies using the AF protocol with 1bpcu and $\mathbf{R} = 2$

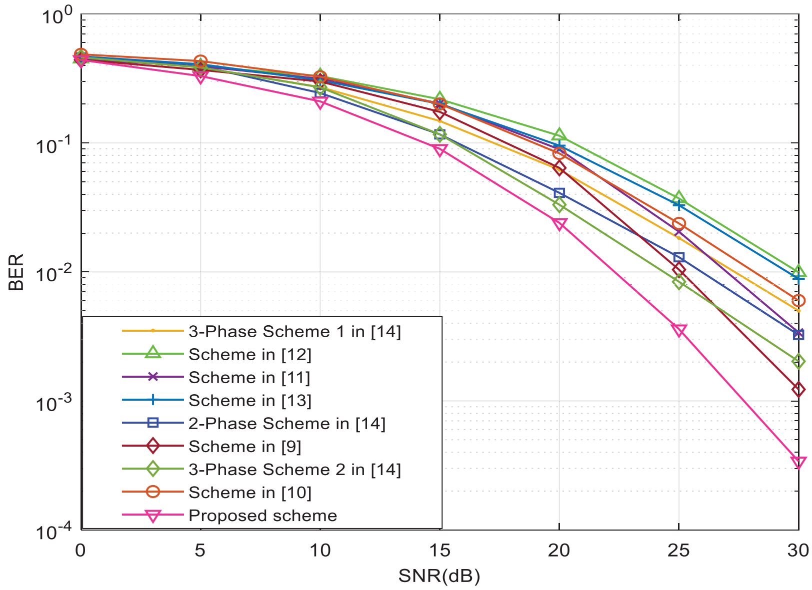

Figure 4: BER *vs.* SNR for different cooperative diversity strategies using the AF protocol with 2bpcu and $\mathbf{R} = 2$

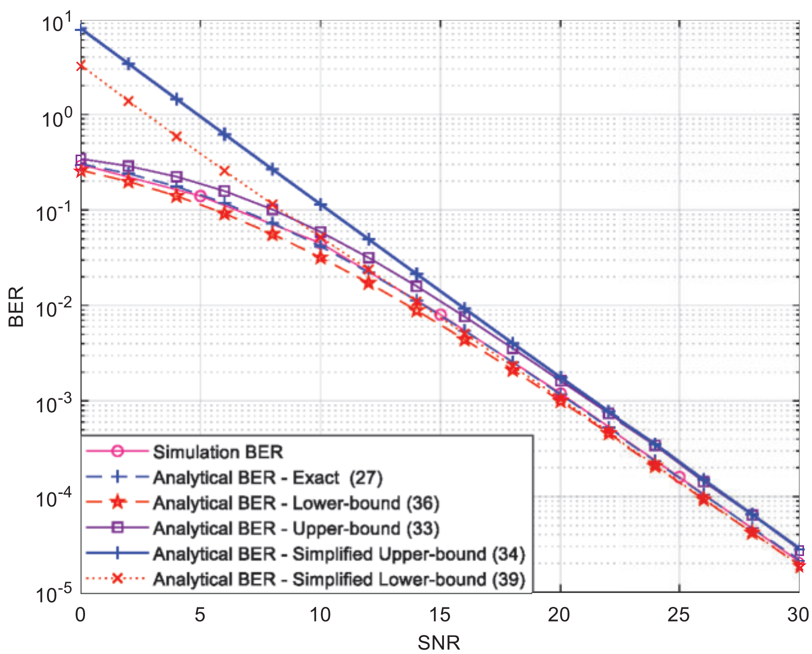

Figure 5: BER *vs.* SNR using the AF protocol with 4-PSK modulations and $\mathrm{R} = 1$

Fig. 5 considers the scenario when we have a cooperative communication system using only one relay carrying one smart Rotman antenna and a direct channel from the source to destination is considered. Fig. 5 shows the analytical and simulated performance in terms of BER of the suggested technique at the destination using 4-PSK modulation. Moreover, Fig. 5 clearly shows that the performance in terms of BER using Monte Carlo simulation of the suggested strategy matches the analytical performance in terms of BER calculated using the formulas given in Section 4. From Figs. 3, 4 and 5, we can clearly observe that our proposed strategy outperforms all the best-known strategies [9–14].

6 Conclusion

In this article, a low-cost Rotman lens antenna is utilized in order to enhance the performance of the conventional cooperative communication networks without requiring any extra power, or additional time or frequency slots. In the suggested system, the smart Rotman lens antennas form a beam in the direction of the destination to maximize the received SNR at the destination by performing optimal beamforming technique. The suggested optimal beamforming technique enjoys high diversity order and low encoding and decoding complexity. Furthermore, we proved the advantages of our suggested strategy through both theoretical results and simulations using Monte Carlo runs. The Monte Carlo simulations show that the suggested strategy enjoys better BER performance as compared to the current state-of-the-art distributed multi-antenna strategies. In addition, the BER curves drawn from the analytical results are closely matching to those drawn from our conducted Monte Carlo simulations.

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