Location-aided Transmit Strategy in Bidirectional Relay over MISO Rician Channels

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Abstract— **In this paper, performance of location-aided transmit strategy in bidirectional relay networks over Rician fading channel is studied. This work is based on a three node relay system, where on the relay node, multiple antennas are deployed, and single antenna on other nodes. The idea of the location-aided transmit strategy is to acquire angle–of-arrival (AoA) of signal through relative location of devices, and to make use of the AoA in designing transmit beamformers. It is presented in this paper that this practical method for low-cost systems yields good system performance in terms of spectral efficiency when Line-of-Sight components exist in the propagation channel. In addition, the achievable rate performance of such relay network system in the broadcasting phase, which is impacted by Rician κ-factor and the relative position between devices, are analyzed.**

Keywords- Array signal processing, Bidirectional Relay, Cross-layer optimization, Location Awareness, Rician K-factor

I. INTRODUCTION

Nowadays location-awareness is one of the most attracting technologies in wireless communication systems. With the development of Internet-of-Things, more and more devices and applications are able to provide their geographical locations, and Location-based Services (LBS) are therefore developed. It is reported that only in China the market of LBS is about 3.8 Billion Yuan [1]. In most of the wireless systems, location information is obtained through the localization and tracking technologies. A lot of researches and studies in the field of localization and tracking technologies have been done in last several years, such as the European Union funded projects, Pervasive Ultra-wideband Low Spectral Energy Radio Systems (Pulsers) and Coexisting Short Range Radio by Advanced Ultra-Wideband Radio Technology (EUWB). In these researches, advanced algorithms and applications are developed and implemented. It is reported that accurate localization algorithm [2] with ultra-wideband (UWB) radio can get estimation accuracy around 10cm. However, how to make use of location information is still a new topic. In some studies location information is used for routing or relay selection, such as geographic random forwarding [3] [4]. However most of them are focusing on higher level applications. In our study, relative location information of devices is used in physical layer, such as calculate the AoA of received signal, and then build the transmit beamformer.

AoA estimation is a mature field with a solid theoretical basis and a large number of practical applications. Normally the AoA of received signal is estimated through complicated algorithm, such MUSIC, ESPRIT, and maximum likelihood (ML) methods. A lot of literatures can be found in papers and text books [5]. But all these AoA estimation methods are with high complexity to implement, and they are not suitable for low-cost systems, such as in wireless sensor networks.

In single path none fading channel, AoA of the received signal is identically to the relative location of the devices [6]. In a rich scattering environment, AoA of signal cannot be directly substituted by relative location of devices, especially when there is no Line-of-Sight (LOS) component in the channel. However in some cases, the received signal contains both LOS and None-Line-of-Sight (NLOS) components, which can be modeled by a Rician fading channel. In Rician fading channel the AoA of the received signal has relationship with device's location due to the existence of LOS component. The strength of the LOS component is determined by Rician factor κ (see Section II.A). When $\kappa = 0$, channel degrades to full Rayleigh fading, and as $\kappa \to \infty$ the channel becomes deterministic and gives rise to an AWGN channel [7]. Performance on localization accuracy in scattering environment with mixed LOS and NLOS channel is studied in [8] – [10]. Studies on MIMO capacity over Rician fading channel can be found in [11],[12], and the capacity for MIMO broadcast channel is studied in [13] – [16]. In our study, the location application in bidirectional relay is focused. In a bidirectional relay system, communication protocol has normally two phases, first is multiple-access phase (MAC) and second is bidirectional broadcast phase (BC). We will study achievable rate pair performance of the bidirectional broadcasting in BC phase with the location-aided transmit strategy.

The paper is organized as follows. In Section II a relay network system with three nodes and multiple antennas is modeled, and the location-aided transmit strategy is introduced. In Section III achievable rate performance impacted by the relative position and Rician factor κ of the channel are analyzed, and Section IV concludes the work.

II. System Model, Channel and Transmit Strategy

A. System and Channel Capacity

We consider a three-node relay network as shown in Figure 1. And we assume that channel information is perfectly known at both the transmitter and receiver sides. The source nodes S_1 and S_2, out of each other's communication range, have messages to exchange. They communicate through a relay node R that is within communication range of both S_1 and S_2. R has M transceiver antennas, and S_1 and S_2 has single transceiver antenna. In the BC phase of the bidirectional relay, system is a MISO broadcasting system. The baseband system model can be represented by

$$y_i = \boldsymbol{x}^{\mathrm{H}} \boldsymbol{h}_i + n_i, \quad i = 1, 2, \tag{1}$$

where $y_i \in \mathbb{C}$ denotes the received signal, $\boldsymbol{h}_i \in \mathbb{C}^{M\times 1}$ is the channel gain vector, $\boldsymbol{x} \in \mathbb{C}^{M\times 1}$ is the broadcasting input, $n_i \in \mathbb{C}$ is complex additive white Gaussian noise with zero mean and covariance σ^2 at S_i, i is the source node index and $(\cdot)^{\mathrm{H}}$ denotes Hermitian transpose.

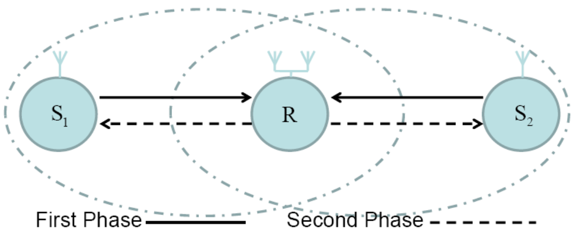

Figure 1. Three node relay network with multiple antennas on the relay node and one antenna on each source node.

The input signal $\boldsymbol{x}$ in BC phase is the composition of message from S1 and S2 in MAC phase, so each of them can decode the interested information using their own transmitted message from the received signal. Let us assume that the transmitter has an average power constraint of P, i.e. $\mathrm{tr}(\boldsymbol{Q}) \le P$, with $\boldsymbol{Q} := \mathbb{E}\{\boldsymbol{x}\boldsymbol{x}^{\mathrm{H}}\}$ .The capacity region of the broadcasting channel is found [15] to be

$$C_{\mathrm{BDBC}} = \bigcup \mathrm{dpch}\left(\left[C_1(\boldsymbol{Q}), C_2(\boldsymbol{Q})\right]\right), \tag{2}$$

where $C_i(\boldsymbol{Q}) := \log\det\left(1 + \frac{1}{\sigma^2}\boldsymbol{h}_i^{\mathrm{H}}\boldsymbol{Q}\boldsymbol{h}_i\right), i = 1, 2,$ and $\mathrm{dpch}(\cdot)$ is defined as downward positive comprehensive hull in [15]. When channel is Rician fading,

$$\boldsymbol{h}_i = \sqrt{\frac{\kappa_i}{1+\kappa_i}}\boldsymbol{h}_i^{\mathrm{sp}} + \sqrt{\frac{1}{1+\kappa_i}}\boldsymbol{h}_i^{\mathrm{sc}}, \quad i = 1, 2, \tag{3}$$

where the Rician factor κ_i reflects the ratio of energy in the specular path to energy in scattering path. $\boldsymbol{h}_i^{\mathrm{sp}}$ is the deterministic specular component, and $\boldsymbol{h}_i^{\mathrm{sc}}$ is the Rayleigh fading channel gain vector, i.e. its entries are i.i.d zero-mean complex Gaussian random variables with unit variance.

Let us assume that a uniform linear array (ULA) is deployed on the relay node and propagation takes place in the horizontal plane containing the tips of all antennas on relay node and two source nodes. The ULA has M antenna elements with separation of $d_{\mathrm{t}} = \Delta\lambda_{\mathrm{c}}$, where $\Delta = 1/2$ is the normalized separation to carrier wavelength λ_{c}. Let us further assume that the dimension of the antenna array is much smaller than the distances between the relay node and the source nodes. The distance from reference element in the antenna array to the antenna at S_i is denoted as d_i, the AoA of signal from each source node S_i to the relay node is denoted as $\phi_i, i = 1, 2$. And the array manifold vector is defined as,

$$\boldsymbol{a}(\phi) = \left[1 \ldots e^{-\mathrm{j}2\pi k\Delta\sin(\phi)} \ldots e^{-\mathrm{j}2\pi(M-1)\Delta\sin(\phi)}\right]^{\mathrm{T}}, \quad k = 0, \ldots, M-1. \tag{4}$$

where $(\cdot)^{\mathrm{T}}$ means transpose. The specular component is $\boldsymbol{h}_i^{\mathrm{sp}} = e^{-j\theta_i}\mathbf{a}(\phi_i), i = 1, 2,$ where $\theta_i = 2\pi d_i/\lambda_{\mathrm{c}}$ is initial phase of received signal on the reference antenna element. Substituting (3), (4) into (2) yields the capacity of MISO bidirectional broadcasting over Rician fading channel of

$$C_i^{\kappa}(\boldsymbol{Q}) = \log\left(1 + \frac{1}{\sigma^2}\frac{\kappa_i}{1+\kappa_i}\left(\boldsymbol{h}_i^{\mathrm{sp}}\right)^{\mathrm{H}}\boldsymbol{Q}\boldsymbol{h}_i^{\mathrm{sp}} + \frac{1}{\sigma^2}\frac{1}{1+\kappa_i}\left(\boldsymbol{h}_i^{\mathrm{sc}}\right)^{\mathrm{H}}\boldsymbol{Q}\boldsymbol{h}_i^{\mathrm{sc}}\right), \quad i = 1, 2. \tag{5}$$

B. Transmit Strategy and Achievable Rate

In point-to-point communication, optimum beamforming vector is along the AoA of the received signal. However in multiple user case, it is impossible to find one beamforming vector that is coherent to all users. It has been proven in [15], [16] that the transmission with one beam is the optimal strategy for bidirectional broadcasting with two users. In our study, transmit beamforming is also based on one beam. Let us denote the beamforming vector as $\boldsymbol{w} = 1/\sqrt{M} \cdot \boldsymbol{a}(\phi)$, the estimated LOS component of channel is denoted as $\hat{\boldsymbol{h}}_1^{\mathrm{sp}} = h_1\boldsymbol{a}(\hat{\phi}_1)$ and $\hat{\boldsymbol{h}}_2^{\mathrm{sp}} = h_2\boldsymbol{a}(\hat{\phi}_2)$, where h_1 and h_2 are estimated channel gain on the reference antenna element, and $\hat{\phi}_1$ and $\hat{\phi}_2$ are estimation of ϕ_1 and ϕ_2 through relative location of devices. The optimization problem is to find maximized sum rate of two source node

$$\max_{\phi}\left(\begin{array}{l}\alpha\log\left(1 + \frac{1}{\sigma^2}\hat{\boldsymbol{h}}_1^{\mathrm{H}}\boldsymbol{w}\boldsymbol{w}^{\mathrm{H}}\hat{\boldsymbol{h}}_1\right)\\ +(1-\alpha)\log\left(1 + \frac{1}{\sigma^2}\hat{\boldsymbol{h}}_2^{\mathrm{H}}\boldsymbol{w}\boldsymbol{w}^{\mathrm{H}}\hat{\boldsymbol{h}}_2\right)\end{array}\right), \tag{6}$$

subject to average power constraint P. α is a factor used to balance the quality of transmission between S1 and S2. When $\alpha = 1$, it means the beamforming vector is to optimize achievable rate for S1, and when $\alpha = 0$, the optimization is for

S2. To keep a fair transmission, $\alpha = 1/2$ shall be used. The optimization problem can be solved through basic trigonometry [6]. The optimized transmit beamforming vector is derived as

$$\boldsymbol{w}_{\mathrm{Loc}} = \frac{1}{\sqrt{M}}\left[1 \ldots e^{-\mathrm{j}2\pi k \Delta_{\mathrm{t}} \cos(\phi_{\mathrm{Loc}})} \ldots e^{-\mathrm{j}2\pi (M-1) \Delta_{\mathrm{t}} \cos(\phi_{\mathrm{Loc}})}\right]^{\mathrm{T}}, \quad (7)$$
$$k = 0, \ldots, M-1.$$

The applied angle of the transmit beamforming vector ϕ_{Loc} is calculated as defined in [6].

$$\phi_{\mathrm{Loc}} = \begin{cases} \pi - \pi\triangle\left(\hat{\Omega}_1 + \hat{\Omega}_2\right), & \text{if } \cos\left(\pi\triangle\left(\hat{\Omega}_1 - \hat{\Omega}_2\right)\right) < 0 \\ \pi + \pi\triangle\left(\hat{\Omega}_1 + \hat{\Omega}_2\right), & \text{if } \cos\left(\pi\triangle\left(\hat{\Omega}_1 - \hat{\Omega}_2\right)\right) > 0, \\ 0, & \text{if } \cos\left(\pi\triangle\left(\hat{\Omega}_1 - \hat{\Omega}_2\right)\right) = 0 \end{cases} \quad (8)$$

where $\hat{\Omega}_1 := \cos\left(\hat{\phi}_1\right)$ is the directional cosine of $\hat{\phi}_1$ and $\hat{\Omega}_2 := \cos\left(\hat{\phi}_2\right)$ is that of $\hat{\phi}_2$.

The designed beamforming vector (7) is to maximize the sum date rate as defined in (6). With $\boldsymbol{w}_{\mathrm{Loc}}$, the achievable rate pair of each source node is $\left[R_1, R_2\right]$, where

$$R_i = \log\left(1 + \frac{1}{\sigma^2}\boldsymbol{h}_i^{\mathrm{H}} \boldsymbol{w}_{\mathrm{Loc}} \boldsymbol{w}_{\mathrm{Loc}}^{\mathrm{H}} \boldsymbol{h}_i\right). \quad (9)$$

This AoA based beamforming is on the assumption that the LOS component domains the channel. The $\boldsymbol{w}_{\mathrm{Loc}}$ is optimal only if there is no NLOS component. When NLOS is stronger, which means rich scattering exists in the environment, (7) yields suboptimal performance. However, alternative transmit strategy of space-time coding can be used to exploit the spatial diversity [18] without complicated adaption. Due to the space constraints, adaptive switch of the beamforming strategy and space-time coding scheme will not be discussed here.

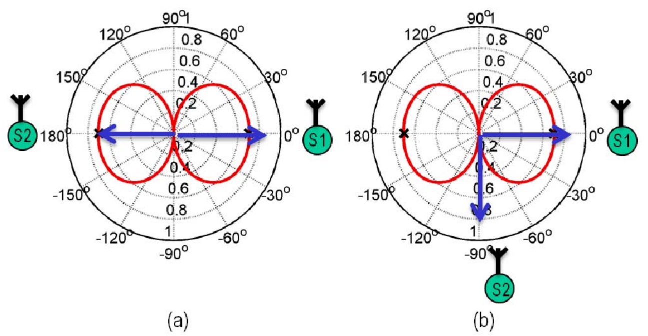

Figure 2. Transmit beamforming patterns in the BC phase of bidirectional relaying. M=2 antenna elements on the array. The relative position of S1 and S2. (a) coherent position, (b) orthogonal position.

III. Impact on Performance

The $\boldsymbol{w}_{\mathrm{Loc}}$ in (7) is optimized under the assumption that channels are $\boldsymbol{h}_1 = h_1\boldsymbol{a}\left(\phi_1\right)$ and $\boldsymbol{h}_2 = h_2\boldsymbol{a}\left(\phi_2\right)$, where the fading part of the channel has been neglected. With strong fading part in the channel, system performance with applying $\boldsymbol{w}_{\mathrm{Loc}}$ degrades. In this section, performance of transmit strategy impacted by Rician factor κ and relative position of devices are studied.

A. *Impact by relative position of devices*

In [6] three types of relative position of the devices are defined. Two out of which are extreme cases, namely coherent position and orthogonal position. They are corresponding to lower and upper bound of the performance. When two sources are in coherent position, AoA of signal from S1 and S2 have imaged direction, one beamforming vector is optimal to S1 and S2. As illustrated in Figure 2. (a), S1 and S2 are located in the imaged position to the normal line of the ULA, main lobe of the beam can point to S1 and S2 at the same time. In Figure 2. (b), S1 and S2 are in orthogonal position. In general case, relative position of S1 and S2 are not the two aforementioned extreme situations. The one beam strategy is to make main lobe of the beamer point neither to S1 and S2, but to the direction of ϕ_{Loc}.

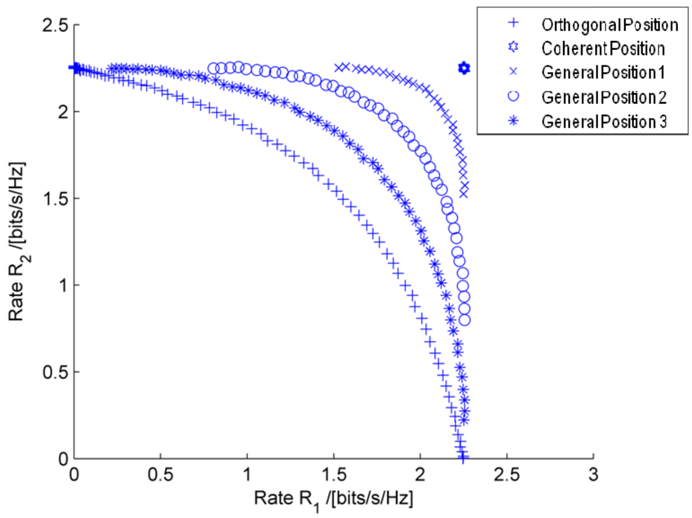

Figure 3. Achievable rate pair impacted by the relative position of S1 and S2 in the BC phase of bidirectional relaying

In Figure 3. achievable rate pair of S1 and S2 in different relative positions are illustrated. X-axis shows the achievable rate of source S1, and Y-axis shows the achievable rate of S2. The hexagon point in the most top right corner of the figure shows the maximum achievable rate for S1 and S2 in coherent position, where AoA pair $(\phi_1, \phi_2) = \left(0^\circ, 180^\circ\right)$ is used. Each of the source nodes can reach their maximum rate with $\boldsymbol{w}_{\mathrm{Loc}}$. The curve with the cross mark shows rate pair when S1 and S1 are in their orthogonal position, i.e. the simulated AoA pair is $\left(0^\circ, 90^\circ\right)$. This is the worst case the proposed transmit strategy can have and can be treated as the lowest bound of the system performance. The left three curves are for general cases, the AoA pairs used for inner to outer curves are, $\left(0^\circ, 105^\circ\right)$, $\left(0^\circ, 120^\circ\right)$ and $\left(0^\circ, 150^\circ\right)$. The bigger area a rate pair curves encircle, the more correlated two channels (Relay to S1, Relay to S2) are. In relay networks, it is reasonable that the two source nodes are approximately point symmetry to relay node with high possibility, which corresponds to area with high achievable rate for both S1 and S2. In other words, the proposed strategy is suitable to be used in relay networks.

B. Impact by Rician factor

Let us assume that the localization is perfect and without estimation error. In this case, the $\boldsymbol{w}_{\mathrm{Loc}}$ is calculated according to real direction $\hat{\boldsymbol{h}}_1 = \boldsymbol{h}_1^{\mathrm{sp}}$ and $\hat{\boldsymbol{h}}_2 = \boldsymbol{h}_2^{\mathrm{sp}}$. The achievable rate pair that impacted by the Rician κ factor is shown in Figure 4. In this simulation, the source S1 and S2 are in their orthogonal position as shown in Figure 2. (b). The three curves are with three different Rician κ factor equals to 2, 4, and 16, respectively. The bigger the Rician κ factor is, the better the performance of the achievable rate is. In the case of $\kappa = 16$, the rate of our proposed strategy is quite close to the channel capacity. Therefore, the location-aided transmit strategy is suitable to the Rician fading channel, especially when there is strong LOS component. When the scattering fading is dominant in the channel, this strategy will not work. As already mentioned above, in rich scattering environment, the space-time coding scheme on relay node is preferred.

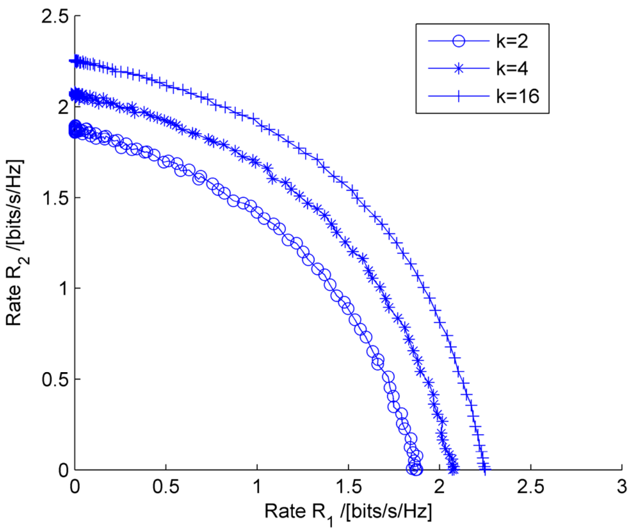

Figure 4. Achievable rate pair impacted by Rician factor κ

IV. COLCLUSION

In this work, achievable rate performances of location-aided transmit beamforming impacted by Rician κ-factor and the relative position of source nodes are studied. Analysis and simulation results show that the proposed method works well when there is a strong LOS component in the propagation channel. When $\kappa = 16$, the rate of our proposed strategy is quite close to the channel capacity. In this work, ideal localization is assumed. However, localization error will also degrade the performance. In the future work, the impact of inherent errors in localization on the rate performance is going to be examined.

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