Hindawi
International Journal of Antennas and Propagation
Volume 2022, Article ID 5883490, 10 pages
https://doi.org/10.1155/2022/5883490

Research Article

A Novel Model for Calculating Uplink-Downlink Spectral Efficiency in Cooperative Communication MIMO Systems

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Received 9 January 2022; Revised 23 April 2022; Accepted 15 May 2022; Published 28 June 2022

Academic Editor: Sami Myllymäki

Cooperative communication that enables the use of relays between a base station (BS) and end users is an effective technique against fading to improve network performance, especially in increasing spectral efficiency (SE) and network coverage. However, systems that use cooperative communication have weaknesses in the structure, such as resistance to latency and an increase in the bandwidth of substitute users (SU), which can be improved by optimizing the relay selection method effectively. The system due to insufficient spacing between antennas and insufficient scattering in the channel has spatially faded that leads to spatial correlation. We use Kronecker statistical model correlated multiantenna channels to implement detection techniques and eliminate interference in cooperative communication. The validity of the Kronecker model lies in the fact that correlation coefficients of transmission are independent of the receiving antennas. In other words, the spatial correlation model separates both ends of the communication link. Therefore, using the minimum mean-squared-error (MMSE) technique, we have removed the need for optimal elimination of interference between SU and relay service provider or primary user (PU). Regardless of BS performance, the scope of this work is restricted to the layer after the BS in the interaction between the service providers and substitute users. The primary purpose of the presented method is to improve the spectral gain through the elimination of interference. Simulation results show about 10% of SE improvement along with considerable traffic gain.

1. Introduction

Point-to-point MIMO systems refer to communicating two multiple antennas devices with each other; in this case, for two terminals of link, multiantenna equipment is needed, increasing the cost of systems. Multiuser MIMO with single-antenna users is used, and multiplexing gain can be shared by all users. For the purpose of more enhancement in reliability, spectral and energy efficiency, and relatively simple processing in cellular wireless networks, massive multiple-input multiple-output (Massive MIMO) systems are used, which the base stations (BSs) equip with very large numbers of antennas; therefore, complexity and cost will be increased. Instead of that, a cooperative MIMO can be used as multiple devices group into virtual antenna arrays (VAAs). Within a VAA and between possibly different VAAs, multiple point-to-point links can exist; therefore, cooperative MIMO improves capacity, cell edge throughput, and coverage, although these systems have high complications and extensive signaling for forming cooperative devices. Three strategies used for relay-based MIMO include amplify-and-forward, decode-and-forward, and compress-and-forward techniques.

Relay networks have a good advantage in terms of energy savings and are mainly achieved by a short transmission range that reduces path loss and decreases transmission power. The amount of energy-saving is related to how the relay is selected. Considering the coordination overhead, as the number of cooperators increases, the energy efficiency of cooperative communication may decrease [1].

This issue is of particular importance in the fifth generation of cellular wireless communications, especially in the mmWave frequency range. Based on the nature of this frequency range and the lesser number of reflections, areas without coverage will gradually increase. Therefore, the use of tools and coverage improvement techniques is particularly important. Relay operations manage according to various criteria, for example, maximum SNR, best harmonic mean, nearest neighbor selection, and difference-based selection. Hybrid methods could be implemented by a combination of the above methods. In this regard, we have referred to the clustering of users in the peripheral environment of a relay user, located at the head of end users. Figure 1 shows the PUs in the head of clusters.

Kronecker model, also known as correlated multiple-input multiple-output (MIMO) channels, has theoretically been studied mainly in the context of the separator correlation model [2, 3], and the virtual representation framework for uniform linear arrays (ULAs) [4–7]. Spatial correlation is determined by the transfer of weights (complex excitation of the Tx array elements), direction, and polarization of the irradiated power. Transferred weights determine which elements of the array antenna will be activated and how their transmitted power would be managed for radiation. For example, radiation in specific directions may only activate some elements and leave others inactive, which affects the spatial correlation in the Rx array. This model provides accurate results for MIMO modeling in specific settings for the small number of antenna elements. However, several studies have been conducted on how different detectors are applied in cooperative communication in the fifth generation (5G) and heterogeneous networks [8]. Furthermore, the incorporation of the Kronecker model and virtual channel representation models can alleviate the effect of the joint correlation structure of the channel to enhance spectral efficiency [9, 10].

Many researchers have focused on the design of low-complexity detection algorithms for the generalized spatial modulation (GSM) system, for example, the compressive sensing (CS) [11–14], the ordered block (OB) MMSE [15, 16], the message passing [17], the Gaussian approximation [18, 19], and sphere decoding (SD) [8, 20, 21]. Dytso et al. [22] considered a Gaussian channel with one transmitter and two receivers in which the maximization of the input-output mutual information at the primary/intended receiver is subject to a disturbance constraint measured by the MMSE at the secondary/unintended receiver and derived new upper bounds on the input-output mutual information of this channel that held for vector inputs of any length. Some authors, such as Imam et al. [23], addressed interference cancellation in uplink multiuser (MU) MIMO system with an amplify and forward (AF) full-duplex (FD) relay, and an equivalent relay model is adopted to suppress the self-interference. Moreover, block diagonalization (BD) is applied to design postprocessor filters to null the MU interference and extract the direct and relayed links signals for performing the MMSE combination of the extracted signals. In [24, 25], the author uses two protocols and combines them with multiantenna users and MMSE-SIC detection in a downlink; the system can achieve an optimal spectral efficiency (SE) and suboptimal SE performance regardless of a number of the users in the system [26]. The performance of an uplink large-scale MIMO system with an MMSE-SIC detector is studied. In [27] particular, considers the coherent detection MIMO-MMSE-SIC of M-PSK signals in a flat Rayleigh fading environment, where after serial-to-parallel conversion, several substreams of symbols are simultaneously transmitted by using an antenna array, thereby increasing the spectral efficiency.

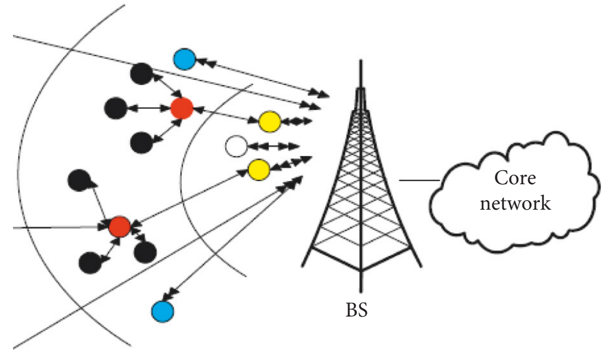

FIGURE 1: Head cluster users (red points: primary users and black points: secondary users).

As seen in most of these works, the combining vector method has been used to detect exchange channels between users and service providers. Due to the accuracy and importance of MMSE-based methods, it has higher efficiency and validity than other methods such as MR and ZF; still, MMSE-based matrix calculations are more complex and repetitive than other methods.

In the first section, we model the cooperative communication MIMO system with the central base station and coherence blocks for primary-relay users, and secondary users then achieve MMSE of the channel response based on the Kronecker statistical channel model. In step 3, we calculate the cooperative user's achievable SE in the uplink. We suppose PU is aware of the statistical information about the CSI of SUs. Linear MMSE detector by separating the independent string NK uses to maximize uplink SE of special string from user k. In Section 4, we calculate the achievable SE of cooperative users in the downlink receiver signal with the assumption the users do not have any instant CSI from BS and based on only the covariance channel matrix. Figures describe more details. Finally, we summarize our results in section 5.

2. System Model

Consider a time division duplex (TDD) MIMO system equipped with PU with antennas and K secondary users (SU) having N antennas (Figure 2). In this model, PUs act as relays between the K number of SUs and one BS. Assume that each coherence block (CB) contains S symbols, and each user in each CB remains unchanged. We consider N_r and N_t as numbers of receiver antennas and transmitter antennas, respectively. Then, the channel response of user k and PU relay is $H\varepsilon\mathbb{C}^{N_r\times N_t}$. The fading phenomenon is considered spatially fading due to the small distance of antenna elements and low channel scattering. In this model, we use the canonical Kronecker form to describe spatial correlation.

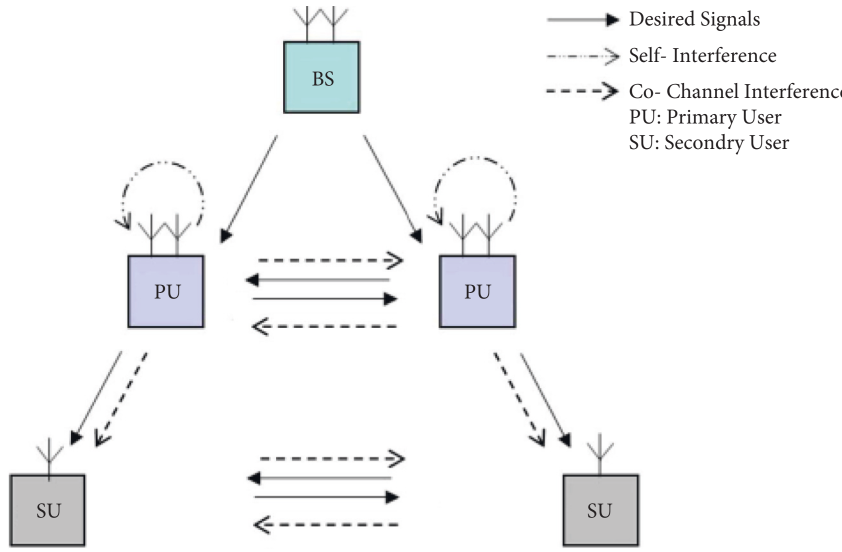

Figure 2: Schematic of the system model for downlink.

The Kronecker model has mainly developed for Rayleigh distributed channels having identically distributed (i.i.d.) zero-mean circularly symmetric complex Gaussian distributions. This model indicates a correlation on spatial diversity R_{MIMO} due to proximity antenna [7, 28, 29].

$$R_{Rx} = \frac{1}{Nr}\mathbb{E}\left[HH^T\right], \quad R_{Tx} = \frac{1}{Nt}\mathbb{E}\left[H^T H\right], \tag{1}$$

$$R_{MIMO} = R_{Tx} \otimes R_{Rx}, \tag{2}$$

where H, $\mathbb{E}[\cdot]$, R_{Rx}, and R_{Tx} are channel responses, expected value, receiver correlation, and transmitter correlation, respectively.

In uplink communication, Nr is the number of the receiver PU antenna elements M, and Nt is the number of the transmitter SU antenna elements N. In (2), "⊗" represents the multiplier of Kronecker. In other words, the correlation is between the transmitter and receiver elements. After applying the operator ⊗ in (2), we will have the channel response of the whole system in the form of (3) [30]. We consider a downlink in a wireless narrowband system based on Rayleigh fading MIMO by considering a relay transmitter with N_t antennas and users with the N_r antennas. The model assumes that the statistical nature of the separation exists and is presented according to the classical Kronecker model as follows [31]:

$$H_k = R_{r,k}^{(1/2)} H_{i.i.d} R_{t,k}^{(1/2)}, \tag{3}$$

where $R_{t,k} \in \mathbb{C}^{N_t * N_t}$ represents the spatial correlation matrix in user k and $R_{r,k} \in \mathbb{C}^{N_r * N_r}$ represents the spatial correlation matrix in PU for the link of the k_{th} user. The large-scale fading parameter exists in $R_{r,k}$ and can be considered as $(1/M)tr(R_{r,k})$ that tr(.) is the trace of a non-negative self-adjoint operator and shows the sum of elements on the main diagonal (the trace of a matrix is the sum of its eigenvalues, and it is invariant with concerning a change of basis).

We consider the $R_{t,k}$ based on eigenvalues, so $R_{t,k} = U_k \Gamma_k U_k^H$ in this expression $U_k \in \mathscr{C}^{N_t \times N_t}$ is a unitary matrix, and $\Gamma_k = \text{diag}\{\mu_{k,1}, \ldots, \mu_{k,N_t}\}$ is eigenvalues.

To estimate all PU MIMO channels in the uplink, the $T = N * K$ number of orthogonal pilot signals are required. $F_k \in \mathbb{C}^{N_t * K}$ represents the pilot sequence signal in the uplink. Assuming that each PU is aware of only the channel state information (CSI) value of each user's CSI, this includes the PU concerning BS [30, 32, 33], which is out of our debate, and we merely model the communication between PU and SU. In this case, based on the nature of using the Kronecker model and the need to minimize the value of MMSE in the channel approximation, $tr(F_k F_k^H) \leq \text{TP}_k$ where $F_k = U_k L_k^{(1/2)} V_k^T$ and P_k is the maximum power level of the transmitter. The maximum number of users is K, and $L_k = \text{diag}\{L_{k,1}, \ldots, L_{k,N_t}\}$ is the power distribution on the N_t channel, which is on the diameter of the matrix L, and $V_k \in \mathbb{C}^{T * N_t}$ with the condition $V_k^H V_k = \text{TI}_{N_t}$ and based on the orthogonality, if $k \neq l$, then $V_k^H V_l = 0 k \neq l$. Because other PUs should not interfere with each other, and at any time, a user cluster containing k number of users interacts with only one PU. In this case, the received signal in the PU, Y, will be as follows [34]:

$$\begin{aligned} Y &= \sum_{k=1}^{K} H_k F_k + n \\ &= \sum_{k=1}^{K} G_k D_k^{1/2} V_k^T + n, \quad Y \in \mathbb{C}^{N_r \times T}, \end{aligned} \tag{4}$$

where n is additive Gaussian noise; we define the matrices G_K, D_K as $G_k = R_{r,k}^{1/3} H_{i.i.d} U_{t,k}, D_k = \Gamma_k L_k$ for use in matrix operations. In this case, the amount of received noise has been considered as vec(n) and $\text{vec}(n) \sim CN(0, \sigma^2 I_{\text{TM}})$, where $\sigma^2 I_{\text{TM}}$ denotes additive receive noise and $\text{vec}(\cdot)$ is the vectorization operator; the vec operator is an operator that transforms a matrix into a column vector by vertically stacking the columns of the matrix. In addition, it assumes that PU is aware of statistical information related to D_k [30], and by referring to this, the MMSE approximation of $\hat{g} = \text{vec}(G_k)$ can be formulated:

$$\hat{g}_k = \left(D_k^{(1/2)} \otimes R_{r,k}\right)\left\{\left(D_k \otimes R_{r,k}\right) + \frac{\sigma^2}{T} I_{\text{MN}}\right\}^{-1} b_k. \quad (5)$$

By use of (5), the value of the $\hat{G}$ channel response could be calculated, and by using MMSE, the difference with the channel response H could be minimized. This equation $b_k = \text{vec}((1/T)Y_k V_k^*) = \text{vec}(G_k D_k^{(1/2)} + (1/\sqrt{T})nV_k^*)$ and the expression $(\sigma^2/T)I_{\text{MN}}$ denote Gaussian noise with zero mean and variance σ^2, respectively. Orthogonally, the mathematical expectation $\hat{g}_{k,i}\hat{g}_{k,j}^H$ is calculated as follows:

$$\mathbb{E}\left\{\hat{g}_{k,i}\hat{g}_{k,j}^H\right\} = \begin{cases} \Phi_{k,i}, & i = j, \\ 0, & i \neq j, \end{cases} \quad (6)$$

where $\Phi_{k,i}$ is the MMSE of the channel response between PU and k^{th} SU as the client and $\Phi_{k,i}$ is equal to $\Phi_{k,i} = d_{k,i}R_{r,k}(d_{k,i}R_{r,k} + (\sigma^2/T)I_M)^{-1}R_{r,k}$. With this amount as vector combining, we examine the spectral efficiency in uplink and downlink between PU and SU.

3. Cooperative Users Achievable SE in Uplink

Consider the system as a multiple access MIMO channel. If the received signal Y in the service user is equal to

$$Y = \sum_{k=1}^{K} G_k F_k' S_k + n, \quad (7)$$

where S is the information vector of the symbols sent from SU to PU, $S_k \in CN(0, I_N)$, and $n \in CN(0, \sigma^2 I_M)$. Matrices S, G, when the PU is mindful of the perfect CSI of SU, i.e., each transmitter is cognizant of its CSI. In total, the PU is aware of the statistical information about the CSI of SUs so that the precoding matrix can be formed with the eigenvector [30, 34].

So we can get the precoding matrix. In this case, each transmitter in the PU has only its own statistical CSI, the precoding directions of each user that maximizes the total capacity with its particular spatial correlation matrix vectors. This assumption is expressed like double scattering and is consistent with the prevailing reality based on the results [35, 36].

We assume that the receiver has imperfect CSI, while each transmitter only has access to its own statistical CSI. Consider the matrix F_k, $k = 1, \ldots K$, as the precoding of the user matrix in the uplink, where $F_k' = U_k P_k^{1/2}$, P_k is a diagonal matrix in the form: $P_k = \text{diag}\left\{p_{k,1}, \ldots, p_{k,N}\right\}$, and $F_k' \in C^{N \times N}$. Therefore, (7) has been rewritten as follow based on the matrix of eigenvalues:

$$Y = \sum_{k=1}^{K} H_k F_k' S_k + n = \sum_{k=1}^{K} G_k \Gamma_k^{1/2} P_k^{1/2} S_k + n_k. \quad (8)$$

Now, if we consider the mutual information between S and Y as a conditional probability and $S = [s_1, \ldots, s_k]$ and the channel response estimated under imperfect CSI in (5), then the conditional probability governing the relation (9) will be

$$\begin{aligned} I(Y, \hat{G}; S) &\geq \sum_{k=1}^{K} \mathbb{E}\left\{\log_2\left|I_N + Q_k \hat{G}_k^H \sum_k \hat{G}_k\right|\right\} \cong \sum_{k=1}^{K} R_{ul,k}^{sic}, \\ Q_k &= \Gamma_k P_k \sum_k \\ &= \left(\sum_{l \neq k} \hat{G}_l Q_l \hat{G}_l^H + Z + \sigma^2 I_M\right)^{-1}, \\ Z &= \sum_{l=1}^{K}\sum_{n=1}^{N} \lambda_{l,n} p_{l,n}\left(R_{r,l} - \Phi_{l,n}\right). \end{aligned} \quad (9)$$

In (9), the changes of the average channel compared to the approximation of the channel are calculated, where "$|\cdot|$" represents the matrix determinant and N is the number of exchange strings between PU and SUs.

In (9), the lower bound signal capacity using the MMSE-SIC detector can be described as achievable SE for k_{th} primary user (PU) based on information theory with the condition of uncorrelated Gaussian couser interference.

For example, from the user k, the signal of S_k strings in the form of imperfect CSI, uncorrelated Gaussian signal is received through the channel with imperfect CSI $\hat{G}_k Q_k^{(1/2)}$. This signal passes through the factor $n_k = Y - \hat{G}_k Q_k^{1/2} S_k$ is broken as an uncorrelated interference factor that has the covariance of the matrix $(\sum_k)^{-1}$, in which by applying the MMSE-SIC procedure to the S_k strings, the value of SE is ergodic, based on the (9). Equation (9) is the general form of achievable SE [37, 38] in MIMO systems.

When the SIC procedure is computable, the number of N stream data can be transferred to SU_k and now can use the linear MMSE detector to separate the independent string NK. Based on [39], a linear MMSE detector can maximize uplink SE for the i_{th} string for k_{th} user as $f_{k,i} = \sqrt{\lambda_{k,i} p_{k,i}} \sum \hat{g}_{k,i}$. Linear detector application $f_{k,i}$ to the signal in (7) causes an achievable SE for user k as follows:

$$R_{\text{UL},k}^{\text{MMSE}} = \sum_{i=1}^{N} \mathbb{E}\left\{\log_2\left(1 + \text{SINR}_{k,i}^{\text{UL}}\right)\right\}. \quad (10)$$

SINR value of the i_{th} string in (10) is equal to

$$\text{SINR}_{k,i}^{\text{UL}} = \frac{\lambda_{k,i} p_{k,i}\left|f_{k,i}^H \hat{g}_{k,i}\right|^2}{\mathbb{E}\left\{f_{k,i}^H\left(\text{YY}^H - \lambda_{k,i} p_{k,i} \hat{g}_{k,i} \hat{g}_{k,i}^H\right) f_{k,i} | \hat{G}\right\}}. \quad (11)$$

It seems that the condition of: $R_{\text{UL},k}^{\text{MMSE}} \leq R_{\text{UL},k}^{\text{SIC}}$ is required to effectively eliminate user string interference via $f_{k,i}$; see Appendix A for (11).

4. Achievable SE of Cooperative Users in Downlink

For simplicity, we assume that CSI feedback from the reference BS does not reach the SU. Of course, this is a common assumption in MIMO because we have not considered any CSI improvement strategy and only consider cooperative communication via PU. In addition, by using CSI feedback, only 25% of users through could be improved cooperative communication. Therefore, in this case, users do not have any instant CSI, and our reference, in this case, is only the covariance form in the form $\overline{G}_k \cong \Gamma_k^{(1/2)}\mathbb{E}\{G_k^H W_k\}\Omega_l^{(1/2)}$ to know that the effective average will be the channel response, where $W_k \in \mathscr{C}^{N_t \times N_r}$ is the downlink precoding matrix of user k and $\Omega_k = \operatorname{diag}\{w_{k,i}, \ldots, w_{k,N_r}\}$ indicates the add-on power for N stream for users. The total power of SU is equal to P_k, and the signal received in SU is equivalent to

$$Y = H_k^H \sum_{l=1}^{K} W_l \Omega_l^{(1/2)} S_l + n_k \in \mathscr{C}^{N\times 1}, \quad (12)$$

where $S_l \sim NC(0, I_M)$ are desired signals for the end user l and the $n_k \sim CN(0, \sigma^2 I_N)$ the received added noise. Without losing the generality of the work, consider that user k uses the eigenvalue matrix of its correlation matrix, U_k^H. For detection in the first step of channel correlation matching, the received signal Z_k is equal to

$$\begin{aligned} Z_k &= U_k^H Y_k \\ &= \Gamma_K^{(1/2)} H_k^H \sum_{l=1}^{K} W_l \Omega_l^{(1/2)} S_l + U_k^H n_k. \end{aligned} \quad (13)$$

In (13), we need to calculate the lower bound mutual information between Z_k, S_k, that is, $I = (Z_k; S_k)$, to calculate the minimum channel capacity to join SE.

According to the definition of mutual information based on entropy:

$$I(Z_k; S_k) = h(S_k) - h(S_k Z_k). \quad (14)$$

If $S_k \sim NC(0, I_N)$, then $h\ (S_k) = \log_2|\pi e I_N|$. However, by applying MMSE to S_k value:

$$\hat{S}_k = \overline{G}_k^H \left[\Gamma_k^{(1/2)}\mathbb{E}\left\{G_k^H \sum_{l=1}^{K} W_l W_l^H \Omega_l\right\}\Gamma_k^{(1/2)} + \sigma^2 I_N\right]^{-1} Z_k. \quad (15)$$

Now we calculate $\tilde{S}_k = S_k - \hat{S}_k$ as the error estimate S_k concerning $h(S_k|Z_k)$, the entropy of the upper bound of the Gaussian vector with zero mean, which is the covariance matrix, is as follows:

$$h(S_k|Z_k) \le \log_2|\pi e \mathbb{E}|\left\{\tilde{S}_k \tilde{S}_k^H\right\} = \log_2\left|\pi e\left(I_N - \overline{G}_k^H A_k \overline{G}_k\right)\right|. \quad (16)$$

And $\mathbb{E}\{\cdot\}$ is the expectation of the stochastic channel realizations. In (14), by placing the equations, we have the values of $h(S_k)$ and $h(S_k Z_k)$:

$$I(Z_k; S_k) \ge \log_2\left|I_N + \overline{G}_k^H \overline{A}_k \overline{G}_k\right| \approx R_{\mathrm{DL},k}^{\mathrm{SIC}}, \quad (17)$$

$$Z_k S_k \overline{A}_k \overline{A}_k = \left(\left[\Gamma_k^{(1/2)}\mathbb{E}\left\{G_k^H \sum_{l=1}^{K} W_1 W_1^H \Omega_1\right\}\Gamma_k^{(1/2)} + \sigma^2 I\right] - G_k \overline{G}_k^H\right)^{-1}. \quad (18)$$

Equation (17) shows mutual information between Z_k, and S_k. In addition, in (13), the MMSE estimate has been applied to the received signal; in this case, the combination vector (CV), $\mathrm{CV}_{k,i}$, will be equal to

$$CV_{\mathrm{k,i}} = A_k g_{k,i}, \quad (19)$$

where the CV vector represents the combining vector (g) and $\overline{g}_{k,i}$ represents the $i^{\mathrm{th}} i_{th}$ column of the $\overline{G}_k$ matrix. Knowing $\overline{\mathrm{G}}_k$, we can apply the MMSE estimate for the i_{th} string to the downlink and obtain the SE value with the MMSE linear estimate, which in (18) is equal to $A_k = \overline{A}_k^{-1} + G\overline{G}_k^H$. By applying this approximation, the value of user SE downlink k is equivalent to

$$R_{dl\ ,k}^{\mathrm{MMSE}} = \sum_{i=1}^{N} \mathbb{E}\left\{\log_2\left(1 + \mathrm{SINR}_{k,i}^{dl}\right)\right\}. \quad (20)$$

The SINR value of user k in the downlink could be calculated by (21):

$$\mathrm{SINR}_{k,i}^{dl} = \frac{\left|r_{k,i}^H \overline{g}_{k,i}\right|^2}{r_{k,i}^r \mathbb{E}\left\{Z_k Z_k^H\right\} r_{k,i} - \left|r_{k,i}^H \overline{g}_{k,i}\right|^2}. \quad (21)$$

The MMSE-SIC detector performs better than the MMSE detector in the downlink. To compare the MMSE-SIC and linear MMSE method's performance in a cooperative communication system, we extract uplink and downlink SE diagrams in this system.

5. Channel State Information (CSI)

First, the channel should be estimated in real wireless systems. Then this estimated channel will be used in forward and reverse links. If the estimation has a difference with the exact channel, the channel information, named imperfect CSI, can be modeled by means of a Gauss–Markov uncertainty of the form:

$$G_W = \sqrt{1 - \beta^2 \hat{G}_W} + \beta n, \quad (22)$$

where $G_W \in\in CN$ (0, I) is the true Gaussian part of the channel matrix, $\hat{G}_W \in\in CN$ (0, I) is the imperfect observation of G_W available to the nodes, and $n \in\in CN$ (0, I) is an i.i.d. Gaussian noise. Partial CSI characterizes β has values of $0 < \beta < 1$ for partial CSI when $\beta = 0$ we have perfect CS and $\beta = 1$ corresponds to no CSI knowledge. β is a function of different system parameters. Using MMSE channel estimation, β is a function of pilot symbol SNR [40].

Supposing β equals zero, so using perfect channel knowledge leads to

(1) Have all certain CSI for optimal signal detection

(2) Do not have any decrease in SINR related to CSI

Using $\beta = 1$ and partial channel knowledge cause to

(1) Have no particular detection signal

(2) Have reduced SINR

In this work, we use MMSE-SIC, so the pilot symbols affect β. The number of needed pilot sequences is related to the number of all K users, number of N user antennas, and number of M PU antennas; if pilot sequences increase more than expected, preserving the orthogonality will be hard that would lead to pilot contamination. Our PUs have imperfect CSI. In actual work, by changing and settling N, M, and K, we can have semiperfect CSI. But, when the number of cells is considered additionally, more increase in cellular network dimension aggravates pilot contamination; also, in this case, reducing other parameters can diminish it.

Figure 3 shows the SE values for uplink and downlink using the MMSE-SIC and linear MMSE methods, which are plotted for the estimated solution and the simulated result. These values have been plotted for the incremental range of the number of cooperative user antennas or PU antennas and the number of exchanged strings $N = 1$ and $N = 3$, respectively, where the number of users is $K = 10$. As shown in Figure 3, by an increase in N, the SE value increases with the detectors in question, and this increase can be improved effectively by increasing the number of PU antennas. However, there are limitations in relative addition due to manufacturing technology and portable user volume. There are several antennas in each PU and SU, so in this article, we have considered the number of PU antennas as M and the number of SU antennas as N. Total number of all users is K. As depicted in Figure 3, in MMSE- SIC uplink estimation method, for $N = 3$ and $M \geq 5$, SE will be a little more than 8 bit/s/Hz and for $N = 1$and $M \geq 5$ SE ≥ 6.4 bit/s/Hz, so will have an improvement of about 20% in SE.

Figure 4 shows the total value of SE that can be obtained as a function of NK, calculated, and plotted for the

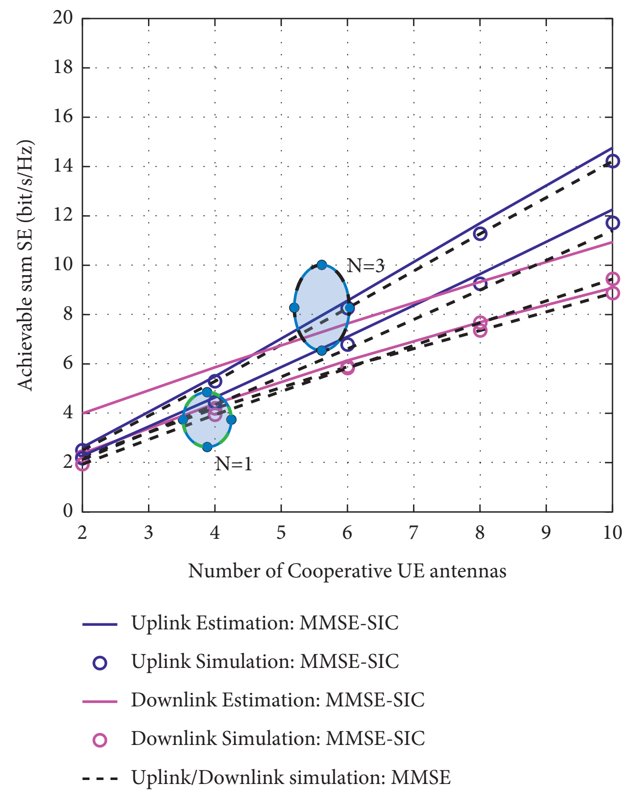

FIGURE 3: The total amount of obtained SE as a function of the number of PU antennas for. $M = 2, \ldots, 10$ in uplink, downlink for $N = \{1{,}3\}$, $k = 10$.

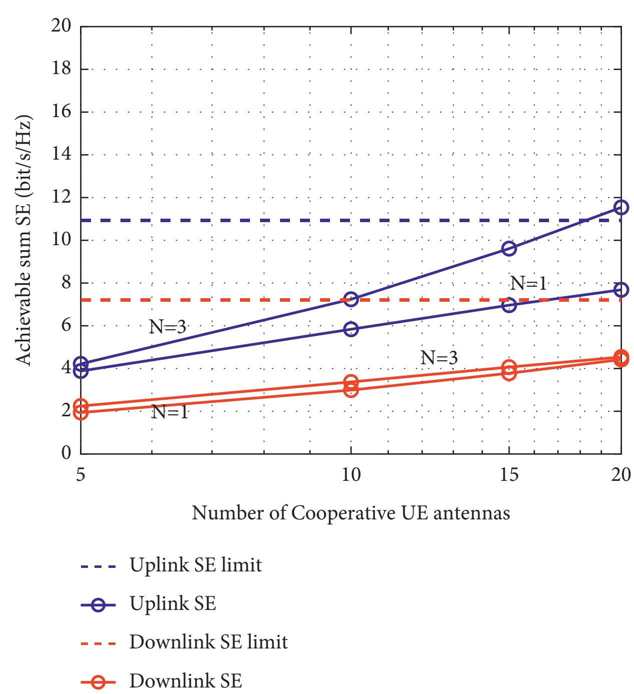

FIGURE 4: Total SE obtained as a function of $N = \{1{,}3\}$, $K = 10$ and $\mathbf{M} = 5, \ldots, 20$.

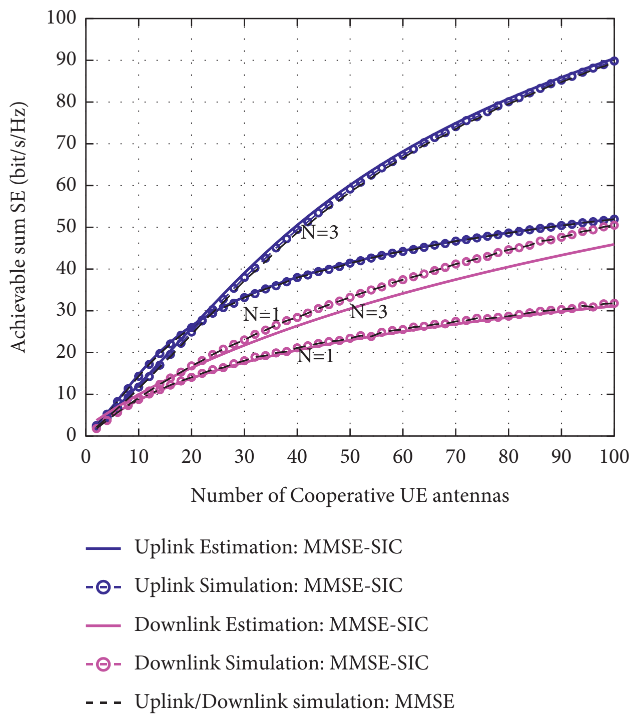

FIGURE 5: The total amount of obtained SE as a function of the number of PU antennas. $M = 2, \ldots, 100$ in uplink, downlink for $N = \{1{,}3\}$, $k = 10$.

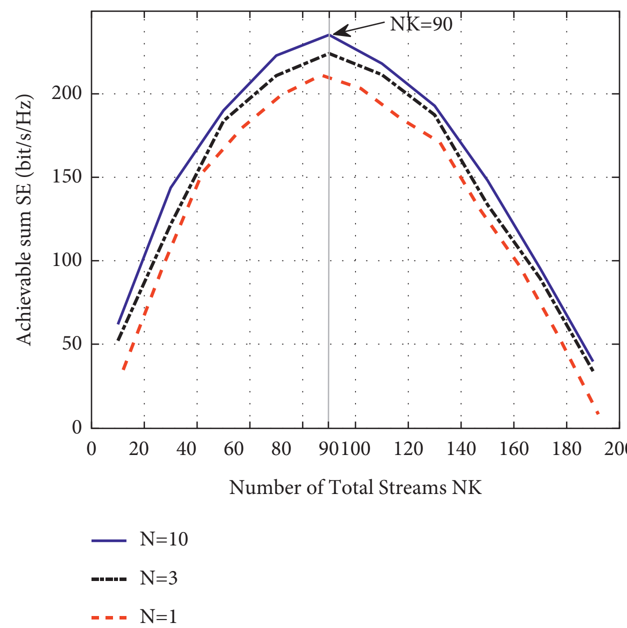

FIGURE 6: The total amount of SE can be obtained as a function of NK for $N = 1{,}3{,}10$ and $\mathbf{M} = 200$.

approximate lower boundary value of the channel capacity for uplink and downlink, respectively. According to Figure 4, as the number of antennas at primary-relay users increases, the amount of SE in the uplink for $N = 3$ approaches the highest possible level of SE. Still, this event occurs around $M = 20$, which is due to the limitations of manufacturing technology of an increasing number of user antenna. On the other hand, for $N = \{1{,}3\}$, with an increase in the number of users receiving antennas and N, no significant change is obtained near the resulting SE to the absolute limit of SE. The following are two ways to overcome this:

(1) Increasing the number of strings from $N = 3$ to, $N = 5$ for example

(2) Reducing the number of users from $K = 10$ to $K = 5$

With this assumption, cognitive radio (CR) possibility should be considered, and based on beam forming (BF), the maximization of SE in DL should be discussed. Accordingly, modulation effects should be applied in the communication between the primary users to use the SE maximization rate for the subsequent layers by directing the beam in the clusters and using it to the secondary user as the headers of the secondary users.

In Figures 3 and 4, where we considered limitations of manufacturing technology with $M = 10$, 20, it seems we do not have considerable improvement at downlink SE, but when in Figure 5, the number of cooperative user antennas increases to 30 and higher and an appreciable increase will occur in downlink SE in addition to uplink SE improvement to more than 20%. Also, the figure indicates that this incremental relation is not linear.

Figure 6 shows that with the hypothetical increase of NK, that is, the number of exchange strands and K, the amount of SE decreases again from a particular value at the peak of the matter and shows that increasing these two parameters, not only does not increase but tends them to zero; this is a detection method that can effectively increase SE in conventional NK.

The downlink performance is compared in Figure 6 for $N \in \{1, 3, 10\}$. Figure 6 shows that for any given NK, scheduling NK multiantenna users is always beneficial. The optimal NK is around 100, which requires 100 active users per coherence block if $N = 1$. With multiantenna users, more realistic user numbers are sufficient to reach the sweet spot of $\mathrm{NK} \approx 100$. Therefore, additional user antennas are beneficial to increase the spatial multiplexing in lightly and medium-loaded systems.

6. Conclusion

Separating correlated PU and SU antennas is of vital importance. To this end, we use Kronecker statistical model for channel. We examined and analyzed the extent to which SE can be acquired in a cooperative communication system with each user aware of its own CSI. By estimating CSI in uplink and downlink, we obtained the lower bound value for the total capacity in ergodic form per user by the MMSE-SIC method. We compared these values with the values obtained by the MMSE method. This comparison shows that the MMSE-SIC detection method, such as the linear MMSE method, is highly efficient and can handle users equipped with multiantennas in cooperative communication. In addition, we showed that the SE increases effectively with increasing N. This increase will be to a certain extent. Then decreases again with increasing NK, where this process is independent of the detection method. The results of SE improvement are presented in uplink and downlink. Calculation results show that additional user antennas are particularly beneficial for SE enhancement when there are few active users in the system. Ten percent of SE improvement and an additional 3–5 data stream numbers are the gain of the proposed detection technique.

Appendix

A. Proof of. $\mathrm{SINR}_{k,i}^{\mathrm{UL}}$

Received signal in the PU relay is $\hat{S}_k$, precoding matrix user $F_k' F_k$, $k=1, \ldots$ K. Applying linear detector $f_{k,i} = \sqrt{\lambda_{k,i} p_{k,i}} \sum \hat{g}_{k,i}$ to uplink the received signal in PU (A.1) maximizes uplink SE for the $i^{\mathrm{th}} i_{th}$ string for $k^{\mathrm{th}} k_{th}$ user in MMSE detection: $S_k \sim NC(0, I_N)$, $\hat{S}_k$ is estimated transmitted signal [41].

$$Y = \sum_{k=1}^{K} H_k F_k' S_k + n = \sum_{k=1}^{K} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} S_k + n_k, \tag{A.1}$$

$$\begin{aligned}\hat{S}_k &= f_{k,i}^H Y = f_{k,i}^H \left[\sum_{k=1}^{K} H_k F_k' S_k + n \right] \\ &= f_{k,i}^H \left[\sum_{k=1}^{K} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} S_k + n_k \right].\end{aligned} \tag{A.2}$$

We can estimate noise as $n = Y - \sum_{k=1}^{K} G_k \Gamma_k^{1/2} P_k^{1/2} S_k$; therefore, $f_{k,i}^H n f_{k,i} = f_{k,i}^H [Y - \sum_{k=1}^{K} G_k \Gamma_k^{1/2} P_k^{1/2} S_k] f_{k,i}$, so it can be obtained as $n = f_{k,i}^H [Y - \sum_{k=1}^{K} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} S_k] f_{k,i}$.

Knowing SNR = (P_s/P_n) that P_s and P_n are signal and noise powers, respectively, in calculating the power of noise using its variance, the uncertainty of the channel will be considered.

$$\begin{aligned}P_s &= \left(\Gamma_k^{(1/2)} P_k^{(1/2)}\right)^{(1/2)} \left| f_{k,i}^H \hat{g}_{k,i} \right|^2 = \lambda_{k,i} p_{k,i} \left| f_{k,i}^H \hat{g}_{k,i} \right|^2 \\ P_n &= E\left[nn^H\right] = E\left[\left(f_{k,i}{}^H \left(Y - \sum_{k=1}^{K} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} S_k \right) f_{k,i} \right) \left(f_{k,i}{}^H \left(Y - \sum_{k=1}^{K} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} S_k \right) f_{k,i} \right)^H \right] \\ &= f_{k,i}^H \left[E\left[\mathrm{YY}^H\right] - E\left[\sum_{k=1}^{K} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} \right] \right] f_{k,i} \\ &= E\left[f_{k,i}^H \left(\mathrm{YY}^H - \sum_{k=1}^{K} G_k \Gamma_k^{(1/2)} P_k^{(1/2)} \right) f_{k,i} \right],\end{aligned} \tag{A.3}$$

where $\hat{g}_k = \mathrm{vec}(\hat{G}_k)$, $\hat{g}_{k,i}$ is i_{th} column of $\hat{G}_k$.

We have

$$P_n = E\left[\left(f_{k,i}^H \left(\mathrm{YY}^H - \lambda_{k,i} p_{k,i} \hat{g}_{k,i} \hat{g}_{k,i}^H \right) f_{k,i} \right) | \hat{G} \right]. \tag{A.4}$$

Thus, the ultimate SNR in uplink is achieved as follows:

$$\mathrm{SINR}_{k,i}^{\mathrm{UL}} = \frac{\lambda_{k,i} p_{k,i} \left| f_{k,i}^H \hat{g}_{k,i} \right|^2}{\mathbb{E}\left\{ f_{k,i}^H \left(\mathrm{YY}^H - \lambda_{k,i} p_{k,i} \hat{g}_{k,i} \hat{g}_{k,i}^H \right) f_{k,i} | \hat{G} \right\}}. \tag{A.5}$$

Data Availability

The data used in the study are available in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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