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Receive Correlation-Based User Scheduling for Collaborative Spatial Multiplexing Systems

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***Abstract*—In this paper, we propose a user scheduling scheme to maximize the ergodic capacity of multi-user MIMO uplink systems. The proposed scheduling scheme only considers the use of the receive correlation matrix of users, not the instantaneous channel state information of users. The proposed user scheduling scheme is applied to *collaborative spatial multiplexing* systems specified in the IEEE 802.16e, where the base station receives two user signals at each time slot using two receive antennas. Analytic and numerical results show that the proposed user scheduling scheme outperforms conventional random user scheduling scheme in terms of the ergodic capacity without loss of opportunity fairness.**

I. Introduction

The capacity of a multi-user multiple-input multiple-output (MIMO) uplink system can be increased by using multiple antennas at the base station (BS) [1]–[4]. For example, the use of two receive antennas at the BS can almost double the capacity compared to the use of a single receive antenna, even when users use only a single antenna for transmission. It is well known that the capacity of a multi-user MIMO uplink system can be achieved by employing a minimum mean-squared error (MMSE)-successive interference cancellation (SIC) receiver that decodes the received signal from all users in a sequential manner [3], [4]. However, it may not be applicable to practical systems due to huge pilot signaling burden for channel estimation of all users [4], [5].

This problem can be alleviated by limiting the number of users in transmission to the number of receive antennas of the BS (i.e., available degrees of freedom) at each time slot [4]–[6]. As a consequence, much effort has been devoted to find a user scheduling scheme to maximize the capacity. If the BS has instantaneous channel state information (CSI) of all users, it can maximize the capacity [4], [7]. However, the instantaneous CSI of all users can be obtained at the expense of a large signaling overhead [8], and may not be accurate due to the channel outdated problem [9], making it impractical to use. Instead, the use of random scheduling without the CSI is often considered in practical systems, at the expense of performance degradation. As an alternative, the use of spatial correlation-based user scheduling has recently been considered [10], [11]. Slow variation properties of the spatial correlation enable to accurately predict it with low feedback signaling burden compared to the use of the instantaneous CSI [10]–[12]. However, conventional spatial correlation-based user scheduling schemes only consider the use of the transmit correlation, not the receive correlation [10], [11].

In this paper, we propose a new user scheduling that utilizes receive correlation to maximize the ergodic capacity of the uplink in multi-user MIMO systems. For simplicity of design and description, we consider a case where the BS has two receive antennas and allows only two users to transmit the signal at each time slot, and users each have a single transmit antenna. In fact, this case is considered as one of key multi-user MIMO techniques in the uplink of the IEEE 802.16e mobile-WiMAX system, so-called *collaborative spatial multiplexing* system [6]. To optimize the user scheduling in the collaborative spatial multiplexing mode, we first analyze the ergodic capacity of the collaborative spatial multiplexing system. Then, we find the condition to maximize the ergodic capacity assuming that the BS only knows the receive correlation matrix of all users. Finally, we propose a user scheduling scheme that can maximize the ergodic capacity of the collaborative spatial multiplexing system.

The remainder of this paper is organized as follows. Section II describes the system and channel model in consideration. The ergodic capacity of the collaborative spatial multiplexing system is analyzed in Section III. Section IV proposes a receive correlation-based user scheduling scheme that maximizes the ergodic capacity of the collaborative spatial multiplexing system. Section V verifies the performance of the proposed user scheduling scheme by computer simulation. Finally, conclusions are given in Section VI.

II. System and Channel Model

Consider the uplink of a multi-user MIMO wireless system, where the BS uses two antennas for the reception and each of M users uses a single antenna for the transmission. For collaborative spatial multiplexing [6], the BS receives the signal from two users at each time slot as illustrated in Fig. 1. Without loss of generality, we assume that user 1 and user 2 are scheduled to transmit the signal at any time slot. Let $\mathbf{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$ be the transmitted signal vector from the two users where the superscript T denotes transpose. Further, let $\mathbf{h}_m = \begin{bmatrix} h_{1m} & h_{2m} \end{bmatrix}^T$ be the channel vector from the user m to the BS, where $m = 1, 2$. Then, the channel matrix from the

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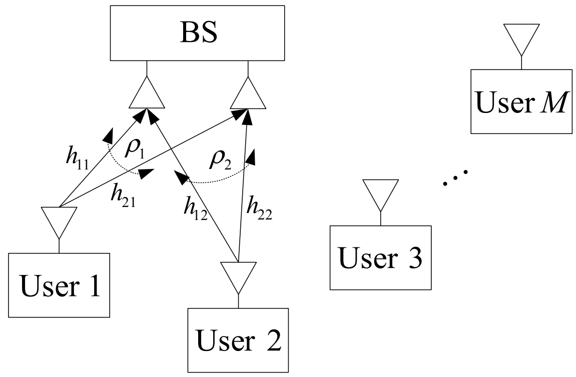
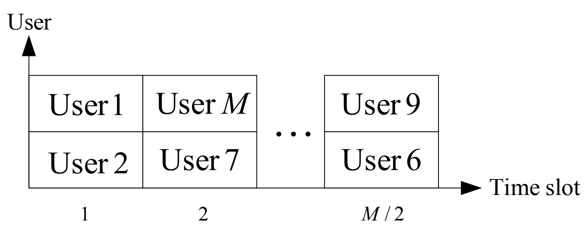


(a) Signal transmission at any time slot



(b) User scheduling example in the collaborative spatial multiplexing system

Fig. 1. Model of collaborative spatial multiplexing system.

two users to the BS can be represented as $\mathbf{H}=\begin{bmatrix}\mathbf{h}_1 & \mathbf{h}_2\end{bmatrix}$. We also assume that additive noise $\mathbf{n}=\begin{bmatrix}n_1 & n_2\end{bmatrix}^T$ is added at the BS, where n_1 and n_2 are independent and identically distributed (i.i.d.) zero-mean Gaussian random variables with the same variance N_0. Then the received signal vector at the BS can be represented as [3]

$$\begin{aligned}\mathbf{y} &= \sum_{m=1}^{2}\mathbf{h}_m x_m + \mathbf{n} \\ &= \mathbf{Hx}+\mathbf{n}.\end{aligned} \tag{1}$$

When the channels are spatially correlated, the channel matrix $\mathbf{H}$ can be generated using a complex white Gaussian random matrix $\mathbf{H}_w$ whose entries are i.i.d. zero-mean Gaussian random variables with unit-variance, i.e., [13]

$$\operatorname{vec}(\mathbf{H}) = \mathbf{R}^{1/2}\operatorname{vec}(\mathbf{H}_{\mathrm{w}}) \tag{2}$$

where $\operatorname{vec}(\mathbf{H})$ denotes an operator staking matrix $\mathbf{H}$ into a vector columnwise (i.e., $\operatorname{vec}(\mathbf{H})=\begin{bmatrix}\mathbf{h}_1^T & \mathbf{h}_2^T\end{bmatrix}^T$), and $\mathbf{R}^{1/2}$ denotes the Hermitian positive definite square root of the channel correlation matrix (i.e., $\mathbf{R}=\mathbf{R}^{1/2}\mathbf{R}^{*/2}$). Here, the superscript $*$ denotes conjugate transpose. Since users are not physically co-located in a real environment, we assume that no transmit correlation exists between the users [14]–[16]. In other words, the columns of $\mathbf{H}$ are uncorrelated as

$$E\left\{\mathbf{h}_1\mathbf{h}_2^*\right\} = E\left\{\mathbf{h}_2\mathbf{h}_1^*\right\} = \mathbf{O} \tag{3}$$

where $\mathbf{O}$ is a zero matrix whose entries are zero. Thus, the channel correlation matrix $\mathbf{R}$ of the collaborative spatial multiplexing system can be represented as [13], [16]

$$\begin{aligned}\mathbf{R} &= E\left\{\operatorname{vec}(\mathbf{H})\operatorname{vec}(\mathbf{H})^*\right\} \\ &= \begin{bmatrix} E\left\{\mathbf{h}_1\mathbf{h}_1^*\right\} & E\left\{\mathbf{h}_1\mathbf{h}_2^*\right\} \\ E\left\{\mathbf{h}_2\mathbf{h}_1^*\right\} & E\left\{\mathbf{h}_2\mathbf{h}_2^*\right\} \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{R}_1 & \mathbf{O} \\ \mathbf{O} & \mathbf{R}_2 \end{bmatrix}\end{aligned} \tag{4}$$

where $\mathbf{R}_m$ denotes the receive correlation matrix of user m defined as

$$\begin{aligned}\mathbf{R}_m &= E\left\{\mathbf{h}_m\mathbf{h}_m^*\right\} \\ &= \begin{bmatrix} E\left\{h_{1m}h_{1m}^*\right\} & E\left\{h_{1m}h_{2m}^*\right\} \\ E\left\{h_{2m}h_{1m}^*\right\} & E\left\{h_{2m}h_{2m}^*\right\} \end{bmatrix} \\ &= \begin{bmatrix} 1 & \rho_m \\ \rho_m^* & 1 \end{bmatrix}.\end{aligned} \tag{5}$$

Here, $m=1,2$ and $\rho_m\left(=\alpha_m e^{j\theta_m}\right)$ is the receive correlation coefficient of user m, where α_m ($0\le\alpha_m<1$) and θ_m ($0<\theta_m\le 2\pi$) denote the amplitude and the phase of the receive correlation coefficient, respectively.

III. Ergodic Capacity of Collaborative Spatial Multiplexing Systems

In this section, we analyze the impact of receive correlation on the ergodic capacity of collaborative spatial multiplexing system. Without loss of generality, we assume that user 1 and user 2 are scheduled at time slot t, and that the BS can get the channel of the scheduled two users (i.e., user 1 and user 2). The channel of the scheduled two users can be estimated by using their dedicated pilot symbols [6]. Then, the BS can get the ergodic capacity by means of an MMSE-SIC process, given by [3], [4]

$$\begin{aligned}C(t) &= E\left\{\log_2\det\left(\mathbf{I}+\sum_{m=1}^{2}\gamma_m\mathbf{h}_m\mathbf{h}_m^*\right)\right\} \\ &= E\left\{\log_2\det\left(\mathbf{I}+\mathbf{H\Gamma H}^*\right)\right\}\end{aligned} \tag{6}$$

where $\mathbf{I}$ is an identity matrix, $\mathbf{\Gamma}$ is a diagonal matrix whose m-th diagonal element γ_m represents the average signal-to-noise ratio (SNR) of user m, which equals $P_m/2N_0$, and $P_m/2$ denotes the average transmit power of user m for $m=1,2$.

Using the concave property of the logarithmic function and after some mathematical development, it can be shown that the ergodic capacity (6) is bounded by (refer to Appendix)

$$C(t)\le\log_2\left(1+2(\gamma_1+\gamma_2)+2\gamma_1\gamma_2\left(1-\alpha_1\alpha_2\cos\left|\theta_1-\theta_2\right|\right)\right). \tag{7}$$

It can be seen that the ergodic capacity of the collaborative spatial multiplexing system highly depends on the phase difference between the receive correlation coefficients of the scheduled users (i.e., $|\theta_1 - \theta_2|$). Moreover, the ergodic capacity of the collaborative spatial multiplexing system can be maximized by finding users whose receive correlation coefficients have a phase difference close to π (i.e., $|\theta_1 - \theta_2| \to \pi$), and an amplitude product close to one (i.e., $\alpha_1 \alpha_2 \to 1$).

IV. Proposed Receive Correlation-Based User Scheduling Scheme

We consider receive correlation-based user scheduling that can maximize the ergodic capacity of the collaborative spatial multiplexing system. We assume that the BS utilizes only the receive correlation matrix of all users without the instantaneous CSI of all users. To provide opportunity fairness to all M users, we also assume that each of two users is scheduled once every $M/2$ time slots in an average sense, i.e., twice every M time slots. Then, there can be a total S numbers of user scheduling cases, where

$$S = \prod_{t=1}^{M/2} \binom{2t}{2} \Big/ \left(\frac{M}{2}\right)!. \quad (8)$$

We find an optimum user scheduling case that maximizes the upper bound of the ergodic capacity given by (7). Let $\widehat{C}_s(t)$ be the upper bound (7) corresponding to the s-th user scheduling case at time slot t, where $s = 1, \dots, S$ and $t = 1, \dots, M/2$. Then, the optimum scheduling case can be determined by

$$s_{\text{opt}} = \arg\max_{s} \frac{2}{M} \sum_{t=1}^{M/2} \widehat{C}_s(t), \quad s = 1, \dots, S. \quad (9)$$

V. Performance Evaluation

The performance of the proposed user scheduling scheme is verified by computer simulation with analytic results in terms of the ergodic capacity of the collaborative spatial multiplexing system. We consider user scheduling based on the receive correlation in a collaborative spatial multiplexing system, where $M = 4$ users have the same SNR, i.e., $\gamma_m = \gamma$ for $m = 1, \dots, 4$, and the receive correlation coefficient whose amplitude is the same, i.e., $\alpha_m = \alpha$, and whose phase is uniformly distributed on $(0, 2\pi]$, i.e., $\theta_m = m\pi/2$. Then, there can be $S = 3$ possible user scheduling cases for the scheduling of 4 users in $M/2 = 2$ time slots, i.e., $\{(1,2),(3,4)\}$, $\{(1,3),(2,4)\}$ and $\{(1,4),(2,3)\}$, where the numbers denote the user index. Using the upper bound (7), the upper-bound of the ergodic capacity corresponding to these three scheduling cases can be calculated as

$$\frac{1}{2}\sum_{t=1}^{2} \widehat{C}_1(t) = \log_2\left(1 + 4\gamma + 2\gamma^2\right), \quad (10)$$

$$\frac{1}{2}\sum_{t=1}^{2} \widehat{C}_2(t) = \log_2\left(1 + 4\gamma + 2\gamma^2\left(1+\alpha^2\right)\right), \quad (11)$$

$$\frac{1}{2}\sum_{t=1}^{2} \widehat{C}_3(t) = \log_2\left(1 + 4\gamma + 2\gamma^2\right). \quad (12)$$

Thus, it can easily be found that the second scheduling case (i.e., $\{(1,3),(2,4)\}$) is the optimum scheduling case (i.e., $s_{\text{opt}} = 2$) that can maximize the ergodic capacity of this collaborative spatial multiplexing system, since the phase difference between the receive correlation coefficients of the scheduled users is π.

Fig. 2 depicts the ergodic capacity associated with these three scheduling cases when $\alpha = 0.5$ and $\alpha = 0.9$. It can be seen that the second scheduling case provides the largest ergodic capacity among these scheduling cases, as being expected. It can also be seen that the capacity gap between the scheduling cases given by

$$\begin{aligned}\frac{1}{2}\sum_{t=1}^{2} \widehat{C}_2(t) - \frac{1}{2}\sum_{t=1}^{2} \widehat{C}_1(t) &= \frac{1}{2}\sum_{t=1}^{2} \widehat{C}_2(t) - \frac{1}{2}\sum_{t=1}^{2} \widehat{C}_3(t) \\ &= \log_2 \frac{1 + 4\gamma + 2\gamma^2\left(1+\alpha^2\right)}{1 + 4\gamma + 2\gamma^2}\end{aligned} \quad (13)$$

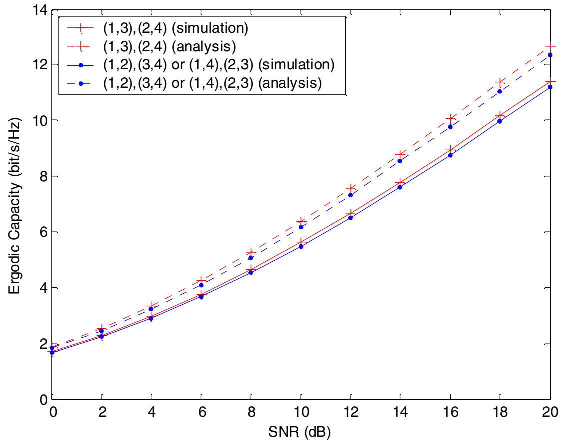
agrees well with the simulation results and that the analytic bounds are appropriate for the design. Moreover, it is interesting to note that the analytic ergodic capacity gap (13) approaches 1 bit/s/Hz as SNR and α approaches infinity and one, respectively, i.e.,

$$\begin{aligned}\lim_{\substack{\gamma\to\infty \\ \alpha\to 1}} \left[\frac{1}{2}\sum_{t=1}^{2} \widehat{C}_2(t) - \frac{1}{2}\sum_{t=1}^{2} \widehat{C}_1(t)\right] &= \lim_{\substack{\gamma\to\infty \\ \alpha\to 1}} \left[\frac{1}{2}\sum_{t=1}^{2} \widehat{C}_2(t) - \frac{1}{2}\sum_{t=1}^{2} \widehat{C}_3(t)\right] \\ &= 1 \text{ bit/s/Hz.}\end{aligned} \quad (14)$$

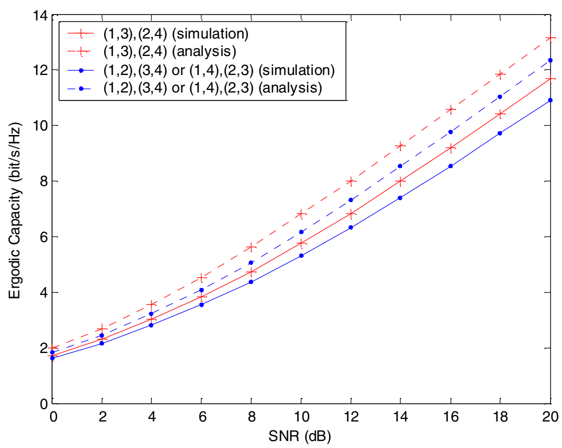
which also agrees well with the simulation results, e.g., 0.99 bit/s/Hz at an SNR of 30 dB when $\alpha = 0.99$.

Fig. 3 depicts the ergodic capacity of the collaborative spatial multiplexing system according to the SNR with the use of the proposed user scheduling, i.e., the second scheduling case, when $\alpha = 0.5$ and $\alpha = 0.9$. For reference, the ergodic capacity of random user scheduling without CSI is also depicted. It can be seen that the proposed user scheduling scheme outperforms the random user scheduling scheme and the performance gap increases in proportion to α^2. For example, the ergodic capacity gap at an SNR of 20 dB is 0.21 bit/s/Hz and 0.49 bit/s/Hz when $\alpha = 0.5$ and $\alpha = 0.9$, respectively. It can also be seen that the analytic ergodic capacity gap between the two user scheduling schemes, given as from (7)

$$\begin{aligned}\widehat{C}_{\text{proposed}} - \widehat{C}_{\text{random}} &= \frac{1}{2}\sum_{t=1}^{2} \widehat{C}_2(t) - \frac{1}{6}\sum_{s=1}^{3}\sum_{t=1}^{2} \widehat{C}_s(t) \\ &= \frac{2}{3}\log_2 \frac{1 + 4\gamma + 2\gamma^2\left(1+\alpha^2\right)}{1 + 4\gamma + 2\gamma^2}\end{aligned} \quad (15)$$



(a) $\alpha_m = 0.5$ and $\theta_m = m\pi/2$ for $m = 1, \ldots, 4$



(b) $\alpha_m = 0.9$ and $\theta_m = m\pi/2$ for $m = 1, \ldots, 4$

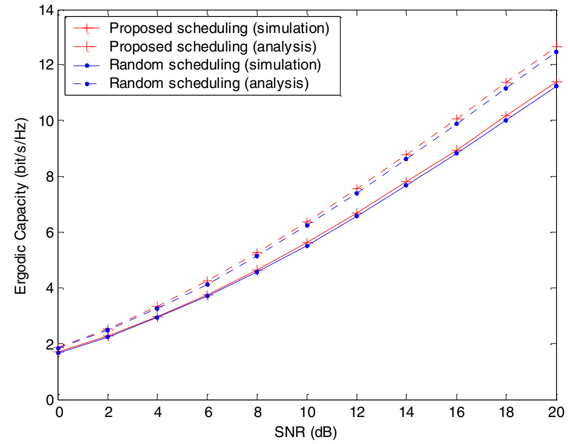
Fig. 2. Ergodic capacity according to the scheduling cases when $M = 4$.

agrees well with the simulation results. Especially, it is interesting to note that the analytic ergodic capacity gap (15) approaches 2/3 bit/s/Hz as SNR and α approaches infinity and one, respectively, i.e.,

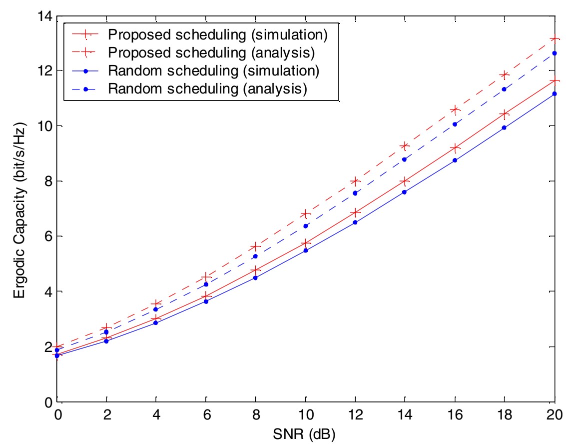
$$\lim_{\substack{\gamma \to \infty \\ \alpha \to 1}} \left[\widehat{C}_{\text{proposed}} - \widehat{C}_{\text{random}} \right] = 2/3 \text{ bit/s/Hz} \tag{16}$$

which also agrees well with the simulation results, e.g., 0.65 bit/s/Hz at an SNR of 30 dB when $\alpha = 0.99$.

Finally, we consider user scheduling in a collaborative spatial multiplexing system with $M = 20$ users. We assume that 10 users have a receive correlation coefficient of $\alpha_m = 0.5$ with phase uniformly distributed over $(0, 2\pi]$, (i.e., $\theta_m = m\pi/5$) for $m = 1, \ldots, 10$, and of the rest 10 users have a receive correlation coefficient of $\alpha_m = 0.9$ with phase $\theta_m = (m-10)\pi/5$, for $m = 11, \ldots, 20$. Fig. 4 depicts the ergodic capacity of the collaborative spatial multiplexing system according to the SNR with the use of the proposed user scheduling scheme. It can be seen that the proposed user scheduling scheme outperforms the random user scheduling scheme as the SNR increases, providing an ergodic capacity gap of 0.54 bit/s/Hz when the SNR is 20 dB.



(a) $\alpha_m = 0.5$ and $\theta_m = m\pi/2$ for $m = 1, \ldots, 4$



(b) $\alpha_m = 0.9$ and $\theta_m = m\pi/2$ for $m = 1, \ldots, 4$

Fig. 3. Comparison of the ergodic capacity when $M = 4$.

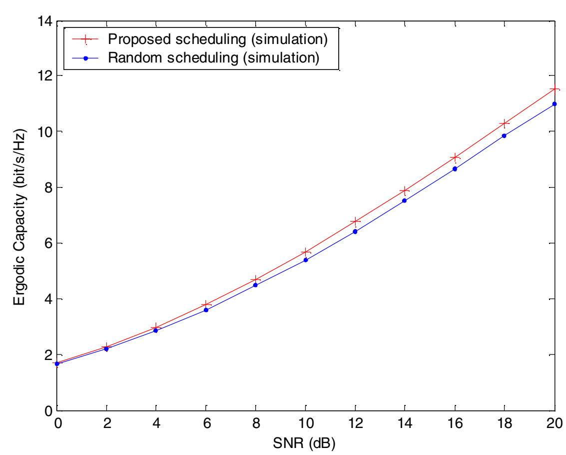


Fig. 4. Comparison of the ergodic capacity when $M = 20$.

VI. CONCLUSION

We have considered user scheduling of a collaborative spatial multiplexing system based on the receive correlation. The proposed user scheduling scheme has been optimized to maximize the ergodic capacity. Analyzing the ergodic capacity of the collaborative spatial multiplexing system in an upper bound manner, we have found the optimum scheduling condition. The numerical results have shown that the proposed user scheduling is quite effective in the presence of receive correlation, noticeably outperforming conventional random user scheduling without deteriorating the opportunity fairness.

APPENDIX

DERIVATION OF UPPER BOUND (7)

Using $\det(\mathbf{I}+\mathbf{AB})=\det(\mathbf{I}+\mathbf{BA})$ [1], (6) can be rewritten as

$$C(t)=E\left\{\log_2\det\left(\mathbf{I}+\mathbf{\Gamma}\mathbf{H}^*\mathbf{H}\right)\right\}. \tag{17}$$

Applying the Jensen's inequality, it can be shown that (17) is upper-bounded by

$$C(t)\le\log_2 E\left\{\det\left(\mathbf{I}+\mathbf{\Gamma}\mathbf{H}^*\mathbf{H}\right)\right\}. \tag{18}$$

Or, (18) can explicitly be represented as

$$\begin{aligned}C(t)&\le\log_2 E\left\{\det\left(\begin{bmatrix}1+\gamma_1\left(|h_{11}|^2+|h_{21}|^2\right) & \gamma_1\left(h_{11}^*h_{12}+h_{21}^*h_{22}\right)\\ \gamma_2\left(h_{12}^*h_{11}+h_{22}^*h_{21}\right) & 1+\gamma_2\left(|h_{12}|^2+|h_{22}|^2\right)\end{bmatrix}\right)\right\}\\ &=\log_2\left(\begin{aligned}&1+\gamma_1\left(E\left\{|h_{11}|^2\right\}+E\left\{|h_{21}|^2\right\}\right)\\ &+\gamma_2\left(E\left\{|h_{12}|^2\right\}+E\left\{|h_{22}|^2\right\}\right)\\ &+\gamma_1\gamma_2\left(\begin{aligned}&E\left\{|h_{11}|^2|h_{22}|^2\right\}+E\left\{|h_{12}|^2|h_{21}|^2\right\}\\ &-E\left\{h_{11}h_{12}^*h_{21}^*h_{22}\right\}-E\left\{h_{11}^*h_{12}h_{21}h_{22}^*\right\}\end{aligned}\right)\end{aligned}\right).\end{aligned} \tag{19}$$

It can be seen from (5) that

$$E\left\{|h_{11}|^2\right\}=E\left\{|h_{21}|^2\right\}=E\left\{|h_{12}|^2\right\}=E\left\{|h_{22}|^2\right\}=1. \tag{20}$$

Since [17, p. 1119]

$$E\left\{h_{ab}h_{cd}^*h_{ef}h_{gh}^*\right\}=E\left\{h_{ab}h_{cd}^*\right\}E\left\{h_{ef}h_{gh}^*\right\}+E\left\{h_{ab}h_{gh}^*\right\}E\left\{h_{cd}^*h_{ef}\right\}, \tag{21}$$

(3), and (5), it can be shown that

$$\begin{aligned}E\left\{|h_{11}|^2|h_{22}|^2\right\}&=E\left\{|h_{11}|^2\right\}E\left\{|h_{22}|^2\right\}+E\left\{h_{11}h_{22}^*\right\}E\left\{h_{11}^*h_{22}\right\}\\ &=1,\end{aligned} \tag{22}$$

$$\begin{aligned}E\left\{|h_{12}|^2|h_{21}|^2\right\}&=E\left\{|h_{12}|^2\right\}E\left\{|h_{21}|^2\right\}+E\left\{h_{12}h_{21}^*\right\}E\left\{h_{12}^*h_{21}\right\}\\ &=1,\end{aligned} \tag{23}$$

$$\begin{aligned}E\left\{h_{11}h_{12}^*h_{21}^*h_{22}\right\}&=E\left\{h_{11}h_{12}^*\right\}E\left\{h_{22}h_{11}^*\right\}+E\left\{h_{11}h_{21}^*\right\}E\left\{h_{12}^*h_{22}\right\}\\ &=\rho_1\rho_2^*,\end{aligned} \tag{24}$$

$$\begin{aligned}E\left\{h_{11}^*h_{12}h_{21}h_{22}^*\right\}&=E\left\{h_{12}h_{11}^*\right\}E\left\{h_{21}h_{22}^*\right\}+E\left\{h_{12}h_{22}^*\right\}E\left\{h_{11}^*h_{21}\right\}\\ &=\rho_2\rho_1^*.\end{aligned} \tag{25}$$

Substituting (20) and (22)–(25) into (19), (18) can be rewritten as

$$C(t)\le\log_2\left(1+2(\gamma_1+\gamma_2)+\gamma_1\gamma_2\left(2-\rho_1\rho_2^*-\rho_1^*\rho_2\right)\right). \tag{26}$$

Since $\rho_m=\alpha_m e^{j\theta_m}$ for $m=1,2$, (26) can be rewritten as

$$C(t)\le\log_2\left(1+2(\gamma_1+\gamma_2)+2\gamma_1\gamma_2\left(1-\alpha_1\alpha_2\cos|\theta_1-\theta_2|\right)\right). \tag{27}$$

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