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A Robust Opportunistic Relaying Strategy for Cooperative Wireless Communications

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Abstract

Using outdated channel state information (CSI) in an opportunistic relay selection (ORS) system may lead to a wrong selection of the best relay, which substantially deteriorates performance and degrades diversity order. In this article, therefore, we propose a robust cooperative scheme coined opportunistic space-time coding (OSTC) to combat the inaccuracy of CSI. A predefined number (i.e., N) of relays, instead of a single relay in ORS, are opportunistically selected from K cooperating relays. At these selected relays, N-dimensional orthogonal space-time block coding is employed to encode the regenerated signals in a distributed manner. Then, N branches of coded signals are simultaneously transmitted from the relays to the destination, followed by a simple maximum-likelihood decoding at the receiver. To evaluate its performance, the closed-form expressions of outage probability and ergodic capacity are derived, together with an asymptotic analysis that sheds light on the achievable diversity. Analytical and numerical results reveal that a full diversity of K is reaped by the proposed scheme when the knowledge of CSI is perfect. In the presence of outdated CSI, where the diversity of ORS degrades to one, a diversity of N can still be kept. Moreover, the achieved capacity of OSTC is remarkably higher than that of the existing schemes based on orthogonal transmission. From the perspective of multiplexing-diversity trade-off, the proposed scheme is the best solution until now.

Index Terms

Alamouti, cooperative diversity, decode-and-forward, generalized selection combining, opportunistic relaying, outdated channel state information (CSI), space-time coding.

I. Introduction

In radio channels [1], the multi-path fading due to constructive and destructive interferences of received signals is a severe impairment. It is challenging for the receiver to correctly detect a signal without some form of diversity.

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Since time and frequency resources in wireless systems are extremely scarce, a particularly appealing approach is the utilization of antenna arrays, such as multiple-input multiple-output (MIMO) [2] and massive MIMO [3], which can achieve higher diversity by simply installing additional antennas. Due to limitations of cost, power supply and hardware size at the carrier frequencies below 6GHz [4], it is impractical to exploit spatial diversity for mobile terminals in cellular systems or wireless nodes in *ad hoc* networks. Hence, cooperative communications [5] has been proposed to alleviate such a limitation by exploiting the broadcast nature of radio signals in *a relay channel* [6], [7], where multiple nodes can form a virtual array to cooperatively transmit their signals. Concretely, when a node sends a signal to its destination (e.g., a base station or wireless gateway), those neighboring nodes who overhear this signal could decode and retransmit the original signal. At the receiver, combining multiple copied versions of the original signal reaps an inherent spatial diversity, also referred to as cooperative diversity [8], without the need of antenna arrays.

Nowadays, it is practically impossible for mobile terminals or wireless nodes to transmit and receive signals simultaneously at the same frequency. The relays need to operate in a half-duplex mode where time- or frequency-division multiplexing is applied. Without loss of generality, we can assume that the signal transmission happens in two phases. In the broadcast phase, the source transmits its original signal in the source-relay channels while all relays listen. In the relaying phase, the relays decode and retransmit this signal in the relay-destination channels. However, a scheduling problem occurs: which relays should be selected and how to transmit the regenerated signals by the selected relays? In the literatures, several cooperative methods have been studied [9]–[14]. Generalized selection combining (GSC) [9], [10] that chooses N relays to transmit the regenerated signals in N orthogonal channels suffers from a substantial loss of spectral efficiency. To avoid this penalty, distributed beamforming based on simultaneous transmission has been taken into account [11], [12]. Given *a priori* knowledge of forward channels, the cooperating relays are capable of adjusting the phases of their transmit signals in order to being coherently combined at the receiver. However, such a beamforming is difficult to be practically implemented since radio-frequency oscillators at spatially-distributed relays are not necessarily synchronized, resulting in phase noises. Another approach called distributed space-time coding (DSTC) has also been proposed in [13], [14]. Although a full diversity can be achieved, designing such a code is infeasible since the number of distributed antennas is unknown and randomly varying. Moreover, a tight requirement on synchronization among simultaneously transmitting relays is difficult to be implemented with a large number of cooperating relays. In a nutshell, the aforementioned *multi-relay* selection methods are hard to be applied for practical systems.

In contrast, a *single-relay* approach referred to as opportunistic relay selection (ORS) [15] or opportunistic relaying has been extensively verified as a simple but efficient way to attain cooperative diversity. Although merely *a single* node with the best channel (in accordance to a given selection criterium) serves as relay, its performance is as same as that of DSTC, which uses an *all-participating* strategy and achieves a full diversity on the number of all cooperating relays [16]. From the viewpoint of multiplexing-diversity trade-off, ORS provides no performance loss compared to DSTC, while avoiding complex and practically-infeasible implementations of multi-relay selection methods.

Nevertheless, channel state information (CSI) at the time instant of relay selection may substantially differ from CSI at the instant of using the selected relays to transmit signals due to the channel fading and feedback delay. An imperfect CSI imposes the possibility of a wrong relay selection on ORS, which would drastically deteriorate its performance. The performance of opportunistic relaying in the presence of *outdated CSI* has been analyzed in previous works [17]–[26]. Vicario *et al.* derived a closed-form expression of outage probability for decode-and-forward (DF) ORS [17]. Seyfi *et al.* investigated the impact of feedback delay and channel estimation errors on the performance of DF ORS [18], [19]. Kim *et al.* evaluated the performance degradation with respect to symbol error probabilities in [20]. In the field of amplify-and-forward (AF) ORS, Torabi *et al.* analyzed the performance impact of outdated CSI in [21]–[24]. In [25], effects of the inaccurate CSI on partial and opportunistic relay selection have been presented. Besides, error probabilities for conventional and opportunistic relaying with channel estimation errors have been derived in [26]. In summary, the previous works draw the following conclusions: (i) ORS achieves a full diversity that is equal to the number of all relays in the cooperative system. (ii) But it is very vulnerable to the outdated CSI and its cooperative diversity is only one, i.e., no diversity, regardless of how many relays cooperate to retransmit. (iii) Unfortunately, this diversity is still limited to one when the outdated CSI is very close to the actual CSI, even if their correlation coefficient tends to one ($\rho \to 1$). From a practical point of view, therefore, it is worth designing a robust cooperative strategy to alleviate such a severe diversity loss owing to the outdated CSI.

To the best knowledge of the authors, only a few proposals to deal with this problem have appeared in the literature until now. A relay selection method employing geolocation information has been proposed in [27]. It was reported therein that this method can achieve a better performance than choosing relays in terms of the outdated CSI in some specific networks. Obviously, it makes sense only in a fixed wireless system rather than a mobile network. A strategy taking into account the knowledge of channel statistics have been proposed in [28]. Although its complexity is remarkably increased, this scheme only achieves a marginal performance gain and its diversity is limited to one, i.e., no diversity. Generalized selection combining [9] and its enhanced version called N plus normalized threshold opportunistic relay selection (N+NT-ORS) [29] have also been applied. However, these schemes require at least N channels to orthogonally transmit the regenerated signals from the selected relays to the destination, resulting in a spectral efficiency of only $1/N$.

We propose a simple but effective scheme coined opportunistic space-time coding (OSTC) to combat the outdated CSI, while avoiding an unnecessary loss of spectral efficiency. A predefined number (i.e., N) of relays, rather than a single relay in the conventional ORS, are opportunistically selected from K cooperating relays according to the instantaneous CSIs of relay-destination channels. At these selected relays, N-dimensional orthogonal space-time block coding (OSTBC) [30]–[32] is employed to encode the regenerated signals. Then, N-branches coded signals are simultaneously transmitted from the relays to the destination, followed by a simple maximum-likelihood decoding based only on linear processing at the receiver. Using $N{=}2$ as an example, the Alamouti scheme [33], a unique space-time code achieving both full-rate and full-diversity with complex signal constellations, is applied at a pair of selected relays. In contrast to DSTC, where all relays participate in the signal's retransmission without any need of selection, only a fraction of relays are activated in the proposed scheme. Therefore, *opportunistic space-time* *coding* can be regarded as the combination of *opportunistic* relay selection and distributed *space-time coding*.

The main contributions of this paper can be summarized as follows:

1) A simple and robust opportunistic relaying scheme is proposed for decode-and-forward cooperative systems. It achieves a remarkable performance gain over all the existing schemes in the presence of outdated CSI. From the perspective of multiplexing-diversity trade-off, the proposed scheme is the best solution.
2) Closed-form expressions of outage probability and ergodic capacity for OSTC, ORS and GSC are comparatively derived via a moment generating function (MGF)-based performance analysis, together with an asymptotic result that clarifies the achievable diversity.
3) Monte-Carlo simulations are set up, and numerical results corroborate theoretical analyses.

The remainder of this paper is organized as follows. Section II introduces the system model of DF cooperative system. Section III presents the proposed scheme. In Section IV, its outage probability and diversity order are theoretically derived, followed by an analysis of ergodic capacity in Section V. Numerical results are given in Section VI. Finally, Section VII concludes this paper.

II. System Model

A. Decode-and-forward Cooperative System

We consider a dual-hop cooperative network [34] where a single source s communicates with a single destination d with the help of K decode-and-forward relays. Suppose that a direct link between the source and destination does not exist owing to a line-of-sight blockage. Because of severe signal attenuations in radio channels, a strong self-interference will be generated if a relay simultaneously transmits and receives signals at the same frequency. It is cost-inefficient to implement a full-duplex transmission upon mobile terminals or wireless nodes with the current radio technology. Consequently, the relays need to operate in a half-duplex mode, and time-division multiplexing (TDD) is assumed to be applied for the source-relay and relay-destination channels. It is generally assumed that all relays are equipped with a single antenna due to limitations of cost, power supply and hardware size on mobile terminals and wireless nodes.

Without loss of generality, the received signal in an arbitrary link $A{\to}B$ can be modeled as

$$y_{_B} = h_{_{A,B}} x_{_A} + z,$$

where $x_{_A}$ is a transmitted signal with power $E[|x_{_A}|^2]{=}P_{_A}$, and $E[\cdot]$ stands for the statistical mean. Assuming a Rayleigh channel with the *block fading*, its gain $h_{_{A,B}}$ is zero-mean circularly-symmetric complex Gaussian random variable with variance of $\Omega_{_{A,B}}$, i.e., $h_{_{A,B}}{\sim}\mathcal{CN}(0,\Omega_{_{A,B}})$. Besides, additive white Gaussian noise (AWGN) with zero-mean and variance of σ^2, i.e., $z{\sim}\mathcal{CN}(0,\sigma^2)$, is applied at the receiver. Node A could be the source $A{=}s$ or the k^{th} relay $A{=}k, k{\in}\{1,...,K\}$, while B denotes the k^{th} relay $B{=}k$ or the destination $B{=}d$. The instantaneous signal-to-noise ratio (SNR) is expressed as $\gamma_{_{A,B}}{=}|h_{_{A,B}}|^2P_{_A}/\sigma^2$ and the average SNR $\bar{\gamma}_{_{A,B}}{=}\Omega_{_{A,B}}P_{_A}/\sigma^2$.

In practice, the mobile terminals in a cellular network have an upper limit on the transmit power, which is denoted by P_u here. To simplify analysis, all links are assumed to be *independent and identically distributed (i.i.d.)* Rayleigh channels with a normalized gain of $\Omega_{A,B}{=}1$, i.e., $h{\sim}\mathcal{CN}(0,1)$. Therefore, the average received SNR for each link is equal to P_u/σ^2. In the scenario of cooperative systems, the aggregated power grows with the increased number of activated relays, imposing an unfairness on the comparison of different schemes. For instance, the aggregated power of $(N{+}1)P_u$ is consumed in the case of N selected relays compared to $2P_u$ for a single-relay scheme. We call it (*i*) *the practical power mode* where either the source or the relays transmit their signals with the fixed power P_u. In addition, we need to define (*ii*) *the theoretical power mode* [35] in order to facilitate a fair performance comparison for the different schemes. Given an end-to-end power constraint of P, we have $P_s{+}\sum_{k=1}^{K}P_k{=}P$, where P_s and P_k denote the source's and the k^{th} relay's power, respectively. With the transmit power P_s, a unified average SNR for all source-relay channels can be given by $\bar{\gamma}_s{=}P_s/\sigma^2$. If the activated relays use an identical power while $P_k{=}0$ for the unselected relays, a unified average SNR for relay-destination channels can be written as

$$\bar{\gamma}_{N} = \frac{P-P_s}{N\sigma^2},$$

or

$$\bar{\gamma}_{L} = \frac{P-P_s}{L\sigma^2}, \tag{1}$$

when the number of activated relays are N and L, respectively. Similarly, the average SNRs in *the practical power mode* are expressed as

$$\bar{\gamma}_{s} = \bar{\gamma}_{N} = \bar{\gamma}_{L} = \frac{P_u}{\sigma^2}. \tag{2}$$

B. The Outdated CSI

From a practical point of view, CSI at the time instant of selecting a relay may substantially differ from CSI at the instant of using the selected relay to transmit signals. Taking advantage of the outdated version of CSI $\hat{h}$ rather than the actual CSI h may lead to a wrong relay selection, which will drastically deteriorate the system performance. To quantify the inaccuracy of outdated CSI, the envelope of the correlation coefficient between h and $\hat{h}$ is defined as

$$\rho = \frac{|cov(h,\hat{h})|}{\mu_h\mu_{\hat{h}}},$$

where $cov(\cdot)$ and μ stand for the covariance of two random variables and the standard deviation, respectively. In accordance to [36], we have

$$h = \rho\hat{h} + \varepsilon\sqrt{1-\rho^2},$$

where the factor ε is a normalized Gaussian random variable, i.e., $\varepsilon{\sim}\mathcal{CN}(0,1)$. The actual CSI h and its outdated version $\hat{h}$ are joint Gaussian distributions. Thus, h conditioned on $\hat{h}$ is also Gaussian distributed:

$$h|\hat{h} \sim \mathcal{CN}(\rho\hat{h}, 1-\rho^2).$$

Due to the assumption of a normalized channel gain $\Omega_{A,B}{=}1$, the average SNR is simplified to $\bar{\gamma}_{A,B}{=}P_A/\sigma^2$, and the instantaneous SNR can be rewritten as $\gamma_{A,B}{=}|h_{A,B}|^2\bar{\gamma}_{A,B}$. As given in [37], $\gamma_{A,B}$ conditioned on its

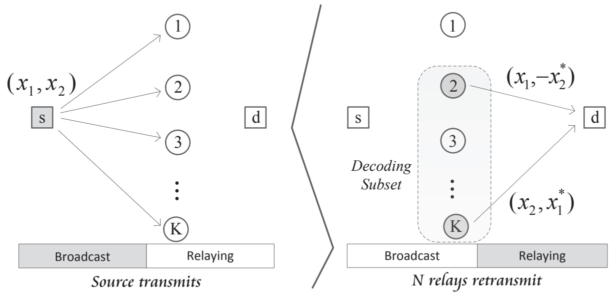


Fig. 1. Schematic diagram of OSTC. For illustration purposes, we use $N{=}2$ as an example. In the broadcast phase, the source transmits a pair of symbols (x_1, x_2) in two consecutive symbol periods. In the relaying phase, two relays with strongest CSIs in relay-destination channels are selected from the decoding subset, and the Alamouti scheme is applied to encode the regenerated symbols at this pair of relays. Then, a relay transmits $(x_1, -x_2^*)$ while another relay sends (x_2, x_1^*) *simultaneously at the same frequency*.

outdated version $\hat{\gamma}_{A,B}{=}|\hat{h}_{A,B}|^2\bar{\gamma}_{A,B}$ follows a noncentral Chi-square distribution with two degrees of freedom, whose probability density function (PDF) is

$$f_{\gamma_{A,B}|\hat{\gamma}_{A,B}}(\gamma|\hat{\gamma}) = \frac{1}{\bar{\gamma}_{A,B}(1-\rho^2)} e^{-\frac{\gamma+\rho^2\hat{\gamma}}{\bar{\gamma}_{A,B}(1-\rho^2)}} I_0\left(\frac{2\sqrt{\rho^2\gamma\hat{\gamma}}}{\bar{\gamma}_{A,B}(1-\rho^2)}\right), \tag{3}$$

where $I_0(\cdot)$ is $zero^{\text{th}}$ order modified Bessel function of the first kind.

III. Opportunistic Space-Time Coding

The fundamental principle of *opportunistic space-time coding* is that a predefined number of relays are *opportunistically* selected and the regenerated signals at the selected relays are transmitted simultaneously at the same frequency by means of *space-time block coding*.

Because of severe signal attenuations in wireless channels, the single-antenna relays have to operate in the half-duplex mode to avoid harmful self-interferences between the transmitter and receiver's circuits. Without loss of generality, TDD can be applied to orthogonalize the source-relay and relay-destination channels. The signal transmission is divided into two steps: the broadcast and relaying phases. In the broadcast phase, the source transmits and those relays who can correctly decode the original signal constitute a *decoding subset* $\mathcal{DS}$, which is assumed to contain L relays, $0{\leqslant}L{\leqslant}K$. Mathematically speaking,

$$\begin{aligned}\mathcal{DS} &\triangleq \{k : \frac{1}{2}\log_2(1+\gamma_{s,k}) \geqslant R\} \\ &= \{k : \gamma_{s,k} \geqslant 2^{2R}-1\} \\ &= \{k : \gamma_{s,k} \geqslant \gamma_{th}\},\end{aligned} \tag{4}$$

where R is an end-to-end target rate for the dual-hop cooperative network and $\gamma_{th}{=}2^{2R}{-}1$ denotes the threshold SNR. It is noted that the required rate for each hop doubles to $2R$ owing to the half-duplex transmission mode.

In the conventional ORS [16], the relay having the strongest SNR (interchangeable with CSI if the given transmit power for each relay is equal) in relay-destination channels is selected from $\mathcal{DS}$ to serve as the best relay denoted by $\tilde{k}$, i.e.,

$$\tilde{k} = \arg \max_{k\in\mathcal{DS}} \hat{\gamma}_{k,d},$$

where $\hat{\gamma}_{k,d}$ is the instantaneous SNR of relay-destination channel at the instant of selecting relay, which may be outdated compared to the actual SNR $\gamma_{k,d}$ at the instant of using the selected relay to transmit signals. In contrast, no relay selection process is performed in DSTC, where *all relays* belonging to $\mathcal{DS}$ are used to simultaneously transmit the regenerated signals by means of space-time coding. In this case, the number of participating antennas is unknown and randomly varying since $\mathcal{DS}$ dynamically changes with the fluctuation of radio channel. Instead of selecting a single relay in ORS or all-participating in DSTC, the proposed scheme chooses a predefined number (i.e., N) of relays in terms of the instantaneous SNR, i.e.,

$$\begin{aligned}\tilde{k}_1 &= \arg\max{}_{k\in\mathcal{DS}}\hat{\gamma}_{k,d},\\ \tilde{k}_n &= \arg\max{}_{k\in\mathcal{DS}-\{\tilde{k}_1,\ldots,\tilde{k}_{n-1}\}}\hat{\gamma}_{k,d}, \quad 2\leqslant n\leqslant N.\end{aligned} \tag{5}$$

In the relaying phase, an N-dimensional orthogonal space-time block code is applied to encode the regenerated signals at the selected relays $\tilde{k}_n$, $1\leqslant n\leqslant N$ in a distributed manner. N branches of coded signals are simultaneously transmitted by the selected relays at the same frequency, followed by a simple maximum-likelihood decoding based only on linear processing at the receiver. It is possible that the number of relays in a decoding subset is less than the predefined number of selected relays, i.e., $L<N$. In this case, all of L relays participate in signal retransmission directly in order to avoid a relay selection, which inevitably increases complexity, and to achieve a diversity gain as high as possible.

For illustration purposes, we utilize $N=2$ and the Alamouti scheme [33] to clarify the principle of the proposed scheme. In the broadcast phase, as illustrated in Fig.1, the source sends a pair of symbols (x_1, x_2) to all relays within two consecutive symbol periods, during which channel gains are regarded as constant due to the block fading assumption. Those relays who correctly decode the original signal constitute a decoding subset. In accordance to instantaneous SNRs of relay-destination channels, a pair of relays $(\tilde{k}_1, \tilde{k}_2)$ from this decoding subset are opportunistically selected as (5). In the relaying phase, the regenerated symbols (x_1, x_2) are encoded according to Alamouti scheme[1]:

$$(x_1, x_2) \Longrightarrow \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix}, \tag{6}$$

where the superscript $*$ denotes the complex conjugate. Then, a relay transmits the first branch of coded symbols $(x_1, -x_2^*)$, while another relay sends (x_2, x_1^*) simultaneously at the same frequency, analogous to the Alamouti

[1] There exists an equivalent form given by $\begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix}$.

scheme applying for two co-located antennas. At the destination, the received signals (y_1, y_2) in two consecutive symbol periods can be written as

$$\begin{aligned} y_1 =& h_{\tilde{k}_1,d}x_1 + h_{\tilde{k}_2,d}x_2 + z_1 \\ y_2 =& h_{\tilde{k}_2,d}x_1^* - h_{\tilde{k}_1,d}x_2^* + z_2. \end{aligned} \tag{7}$$

According to [33], the transmitted symbols (x_1, x_2) can be recovered simply through a linear combining of (y_1, y_2) as

$$\begin{aligned} x_1' =& h_{\tilde{k}_1,d}^* y_1 + h_{\tilde{k}_2,d}y_2^* \\ x_2' =& h_{\tilde{k}_2,d}^* y_1 - h_{\tilde{k}_1,d}y_2^*. \end{aligned} \tag{8}$$

Substituting (7) into (8), yields

$$\begin{aligned} x_1' =& (|h_{\tilde{k}_1,d}|^2 + |h_{\tilde{k}_2,d}|^2)x_1 + \tilde{z}_1 \\ x_2' =& (|h_{\tilde{k}_1,d}|^2 + |h_{\tilde{k}_2,d}|^2)x_2 + \tilde{z}_2. \end{aligned} \tag{9}$$

Since $h_{\tilde{k}_1,d}$ and $h_{\tilde{k}_2,d}$ can be easily acquired by a channel estimation at the receiver, the transmitted signals are successfully recovered by a simple maximum-likelihood decoding based only on linear processing. Note that the impact of channel estimation errors on the signal detection is not considered in this article since it is negligible compared with the effect of outdated CSI. Denoting the power of relays $\tilde{k}_1$ and $\tilde{k}_2$ as $P_{\tilde{k}_1}$ and $P_{\tilde{k}_2}$, respectively, the instantaneous capacity of relay-destination channel for OSTC when N=2 is computed as

$$C_0^{(2)} = \log_2\left(1 + \frac{|h_{\tilde{k}_1,d}|^2 P_{\tilde{k}_1}}{\sigma^2} + \frac{|h_{\tilde{k}_2,d}|^2 P_{\tilde{k}_2}}{\sigma^2}\right), \tag{10}$$

where $\log_2(\cdot)$ stands for the binary logarithm.

We return to the general cases where N-dimensional OSTBC is applied for N selected relays. According to [31], OSTBC can reap a full diversity for an arbitrary dimension of N, but only the Alamouti scheme achieves both full-rate and full-diversity with complex signal constellations. For N=3 and 4, there exists a capacity loss since a maximal rate of $3/4$ is realized. To get a higher diversity of N>4, only a rate of $1/2$ can be kept. Similar to (10), the capacity of relay-destination channel for an arbitrary number of N can be given by

$$C_0^{(N)} = \beta_N \cdot \log_2\left(1 + \sum_{n=1}^{N} \frac{|h_{\tilde{k}_n,d}|^2 P_{\tilde{k}_n}}{\sigma^2}\right), \tag{11}$$

where the factor β_N reflects the maximal rate achieved by an N-dimensional OSTBC, which is summarized as

$$\beta_n = \begin{cases} 1, & n = 1,2 \\ 0.75, & n = 3,4 \\ 0.5, & n > 4 \end{cases} \tag{12}$$

The capacity loss of OSTBC also affects the threshold SNR defined in (4), which needs to be accordingly modified to

$$\gamma_{th}^n = 2^{2R/\beta_n} - 1. \tag{13}$$

IV. Outage Probability and Diversity Analysis

In this section, closed-form expressions of outage probabilities for the proposed scheme and the conventional ORS are derived by means of an MGF-based performance analysis approach, together with an asymptotic analysis that sheds light on their achievable diversity orders.

A. Outage Probability

In the information theory, an *outage* is defined as that the instantaneous channel capacity falls below a target rate R, i.e., $C<R$, where a reliable communication is impossible whatever coding used. The probability measuring such an outage is defined as outage probability [1], which is an important performance metric over fading channels, i.e.,

$$P_{out}(R)=\Pr\left\{\log_2(1+\gamma)<R\right\},$$

where $\Pr$ is the notation of mathematical probability.

1) OSTC with the Outdated CSI: Recalling the definition of a decoding subset, which is a collection of relays whose instantaneous capacity of source-relay channel is larger than the target rate of $2R$ due to the half-duplex mode. In the proposed scheme, a predefined number of relays are opportunistically selected from the decoding subset in terms of instantaneous SNRs in relay-destination channels. At these selected relays, the regenerated signals are space-time encoded and simultaneously transmitted. At the receiver, multiple branches of coded signals are coherently combined by means of a simple maximum-likelihood decoding. If all relays fail to decode the original signal in source-relay channels or the overall received SNR at the destination is less than the threshold SNR, an outage occurs. The outage probability of OSTC in the presence of outdated CSI is derived as follows.

Because of the channel fading, the number of relays in a decoding subset varies randomly, i.e., $L\in[0,K]$. Denoting all decoding subsets that contain L relays by a set $\mathcal{DS}_L$, we have $\mathcal{DS}_L=\{\mathcal{DS}_L^p:\ p=1,...,|\mathcal{DS}_L|\}$, where $\mathcal{DS}_L^p$ is the p^{th} element of $\mathcal{DS}_L$ and $|\cdot|$ represents the cardinality of the set. That is to say, $\mathcal{DS}_L$ contains $|\mathcal{DS}_L|$ elements and an arbitrary element $\mathcal{DS}_L^p$ is a decoding subset having L relays. Conditioned on $\mathcal{DS}_L^p$, OSTC's outage probability can be computed as

$$P_{ostc}(\gamma_{th})=\sum_{L=0}^{K}\sum_{p=1}^{|\mathcal{DS}_L|}\Pr(outage|\mathcal{DS}_L^p)\Pr(\mathcal{DS}_L^p), \tag{14}$$

where $\Pr(\mathcal{DS}_L^p)$ denotes the occurrence probability of a specific decoding subset $\mathcal{DS}_L^p$, and $\Pr(outage|\mathcal{DS}_L^p)$ is the outage probability conditioned on $\mathcal{DS}_L^p$. Recalling the aforementioned assumption that all channels are *i.i.d.* Rayleigh faded, values of $\Pr(\mathcal{DS}_L^p)$ are identical for any $p\in\{1,...,|\mathcal{DS}_L|\}$, and as well $\Pr(outage|\mathcal{DS}_L^p)$. Hence, (14) can be simplified to

$$P_{ostc}(\gamma_{th})=\sum_{L=0}^{K}\Pr\left(outage||\mathcal{DS}|=L\right)\Pr\left(|\mathcal{DS}|=L\right), \tag{15}$$

where $\Pr(|\mathcal{DS}|=L)$ denotes the probability that the current decoding subset has L relays.

The instantaneous SNR of each source-relay Rayleigh channel is exponentially distributed, i.e., $\gamma_{s,k}{\sim}EXP\left(\frac{1}{\bar{\gamma}_s}\right)$, where $\bar{\gamma}_s$ is a unified average SNR as mentioned in (1) and (2). Its cumulative distribution function (CDF) can be given by

$$F_{\gamma_{s,k}}(x) = 1 - e^{-\frac{x}{\bar{\gamma}_s}}, \quad x > 0. \tag{16}$$

From (4) and (16), the probability that a relay correctly decodes the original signal and falls into $\mathcal{DS}$ can be obtained, which is equal to $1{-}F_{\gamma_{s,k}}(\gamma_{th})$. Following the definition of Binomial distribution, we can get the occurrence probability of successfully decoding L out of K relays, i.e.,

$$\Pr(|\mathcal{DS}| = L) = \binom{K}{L}\left(e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^L\left(1 - e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K-L}. \tag{17}$$

In the relaying phase, N-dimensional OSTBC is applied to encode the regenerated signals at the selected relays. It is possible that the number of relays in the current decoding subset is less than the predefined number of selected relays, i.e., $L{<}N$. Without any need of relay selection, all of L relays are directly used to transmit the regenerated signals. The outage probability $\Pr\left(outage||\mathcal{DS}|{=}L\right)$ in (15) is required to be derived conditioned on different numbers of L, as follows:

a) L=0: In this case, all relays fail to decode the source's signal, which is an outage, i.e.,

$$\Pr(outage|L = 0) = 1. \tag{18}$$

b) $1{\leqslant}L{\leqslant}N$*:* When the number of available relays in $\mathcal{DS}$ is not larger than the predefined number N, the relay selection process is not needed and all of L relays directly participate in the signal relaying by means of L-dimensional OSTBC, e.g., using the Alamouti scheme in the case of $L{=}2$. A special case is $L{=}1$ where a unique relay is available in the decoding subset and space-time coding is not required. The instantaneous capacity of relay-destination channel can be given by

$$C_0^{(L)}{=}\beta_L \cdot \log_2\left(1{+}\sum_{n=1}^{L}\frac{|h_{\tilde{k}_n,d}|^2 P_{\tilde{k}_n}}{\sigma^2}\right),$$

where $h_{\tilde{k}_n,d}$ is the channel gain from relay $\tilde{k}_n$ to the destination, and $P_{\tilde{k}_n}$ is the transmit power of relay $\tilde{k}_n$. For each Rayleigh relay-destination channel, its SNR is exponentially distributed, i.e., $\gamma_{k,d}{\sim}EXP(\frac{1}{\bar{\gamma}_{k,d}})$, where $\bar{\gamma}_{k,d}$ denotes the average SNR from k^{th} relay to the destination, and $\bar{\gamma}_{k,d}{=}\bar{\gamma}_L$ according to (1) and (2). The total received SNR at the destination can be denoted by $\gamma_{tot}^L{=}\sum_{n=1}^{L}|h_{\tilde{k}_n,d}|^2 P_{\tilde{k}_n}/\sigma^2$, which is the sum of a group of *i.i.d.* exponential random variables. As we know, γ_{tot}^L is still a random variable and follows *Erlang* distribution, whose CDF can be given by

$$F_\gamma(x) = 1 - \sum_{n=1}^{L}\frac{1}{(n-1)!}e^{-\frac{x}{\bar{\gamma}_L}}\left(\frac{x}{\bar{\gamma}_L}\right)^{n-1}, \tag{19}$$

where $(n{-}1)!$ is the notation of factorial that is the product of all the integers from 1 to $n{-}1$. Due to the capacity loss of OSTBC, the threshold SNR in (13) is now $\gamma_{th}^L{=}2^{2R/\beta_L}{-}1$ and the outage probability equals to $F_\gamma(\gamma_{th}^L)$, that is

$$\Pr(outage|L{\leqslant}N) = 1 - \sum_{n=1}^{L}\frac{1}{(n{-}1)!}e^{-\frac{\gamma_{th}^L}{\bar{\gamma}_L}}\left(\frac{\gamma_{th}^L}{\bar{\gamma}_L}\right)^{n-1}. \tag{20}$$

$$\begin{aligned}P_{ostc}(\gamma_{th}) &= \left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K} \\ &+ \sum_{L=1}^{N}\binom{K}{L}\left(e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{L}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K-L}\left(1-\sum_{n=1}^{L}\frac{1}{(n-1)!}e^{-\frac{\gamma_{th}^{L}}{\bar{\gamma}_L}}\left(\frac{\gamma_{th}^{L}}{\bar{\gamma}_L}\right)^{n-1}\right) \\ &+ \sum_{L=N+1}^{K}\binom{K}{L}\left(e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{L}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K-L}\left(\frac{2^{-Q}e^{A/2}}{\gamma_{th}^{N}}\sum_{q=0}^{Q}\binom{Q}{q}\sum_{p=0}^{P+q}\frac{(-1)^p}{\xi_p}\mathcal{R}\left\{\frac{\mathcal{M}_{\gamma}\left(\frac{A+2\pi jp}{2\gamma_{th}^{N}}\right)}{\frac{A+2\pi jp}{2\gamma_{th}^{N}}}\right\}\right) \quad (27)\end{aligned}$$

$$\begin{aligned}P_{ors}(\gamma_{th}) &= \left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K} \\ &+ Ke^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K-1}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_1}}\right) \\ &+ \sum_{L=2}^{K}\binom{K}{L}\left(e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{L}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K-L}\left(\frac{2^{-Q}e^{A/2}}{\gamma_{th}^{N}}\sum_{q=0}^{Q}\binom{Q}{q}\sum_{p=0}^{P+q}\frac{(-1)^p}{\xi_p}\mathcal{R}\left\{\frac{\mathcal{M}_{\gamma}\left(\frac{A+2\pi jp}{2\gamma_{th}^{N}}\right)}{\frac{A+2\pi jp}{2\gamma_{th}^{N}}}\right\}\right) \quad (28)\end{aligned}$$

$$\begin{aligned}C_{ostc} &= \sum_{L=1}^{N}\frac{\beta_L}{\ln(2)(1+\beta_L)}\binom{K}{L}\left(e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{L}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K-L}\sum_{t=1}^{T}-L\bar{\gamma}_L w_t\Lambda(s_t)\left(\frac{1}{1+s_t\bar{\gamma}_L}\right)^{L+1} \\ &+ \sum_{L=N+1}^{K}\frac{\beta_N\bar{\gamma}_N L(L-N)!}{\ln(2)(1+\beta_N)}\binom{L-1}{N-1}\binom{K}{L}\left(e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{L}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_s}}\right)^{K-L} \\ &\times \sum_{t=1}^{T}\sum_{m=0}^{L-N}\frac{(-1)^{m+1}w_t\Lambda(s_t)}{m!(L-N-m)!}\left(\frac{1}{1+s_t\bar{\gamma}_N}\right)^{N}\left(\frac{N-1}{\eta(s_t)}+\frac{(N+m(1-\rho^2))(1+s_t\bar{\gamma}_N)}{\eta^2(s_t)}\right) \quad (29)\end{aligned}$$

It is noted that the outage probabilities (18) and (20) are independent of the outdated CSI, since the relay selection is not utilized in the case of $L \leqslant N$.

c) $L > N$: If the number of available relays in $\mathcal{DS}$ is more than the predefined number N, an opportunistic relay selection is required. Namely, N relays $\tilde{k}_1, \tilde{k}_2, ..., \tilde{k}_N$ who have the large SNRs in relay-destination channels are chosen from a decoding subset in the presence of outdated CSI. At the selected relays, N-dimensional OSTBC is applied to encode the regenerated signals in a distributed manner. Then, these N branches of coded signals are simultaneously transmitted from the relays to the destination at the same frequency. Using a simple maximum-likelihood decoding, the total SNR at the receiver is obtained as $\gamma_{tot}^{N} = \sum_{n=1}^{N} |h_{\tilde{k}_n,d}|^2 P_{\tilde{k}_n}/\sigma^2$.

In general, the typical approach to derive an outage probability is to first find the received SNR's PDF $f(\gamma)$ and then integrate over this PDF as:

$$P_{out}(\gamma_{th}) = \int_0^{\gamma_{th}} \log_2(1+\gamma) f(\gamma) d\gamma. \quad (21)$$

However, $f(\gamma)$ is not available in a simple and closed form, so that the PDF-based performance analysis becomes mathematically intractable. To be specific, $f(\gamma)$ in OSTC is a nonlinear function of the instantaneous SNRs $\gamma_{1,d}, \gamma_{2,d}, ..., \gamma_{K,d}$ and their outdated versions $\hat{\gamma}_{1,d}, \hat{\gamma}_{2,d}, ..., \hat{\gamma}_{K,d}$. Also, N relays are required to be opportunistically chosen from a decoding subset according to the outdated SNRs, but the total SNR at the receiver is the combination of the actual SNRs of these selected relays, which is called *NchooseK* problem here. Due to this nonlinearity and *NchooseK* problem, the derivation of a closed-form expression for outage probability is tedious, if not infeasible. In contrast, MGF of the total SNR can be obtained in a simple form. Hence, the closed-form expression can be derived through an MGF-based performance analysis approach. As in [38], a numerical technique to approximate an outage probability directly from MGF is proposed, i.e.,

$$P_{out}(\gamma_{th}) = \frac{2^{-Q}e^{A/2}}{\gamma_{th}} \sum_{q=0}^{Q} \binom{Q}{q} \sum_{p=0}^{P+q} \frac{(-1)^p}{\xi_p} \times \mathcal{R}\left\{ \frac{\mathcal{M}_\gamma\left(\frac{A+2\pi jp}{2\gamma_{th}}\right)}{\frac{A+2\pi jp}{2\gamma_{th}}} \right\} + E(A,P,Q), \tag{22}$$

where $j^2 = -1$, $\mathcal{R}\{\cdot\}$ denotes the real part, $\mathcal{M}_\gamma(\cdot)$ is MGF of the total SNR, and A, P and Q are numerical parameters, which satisfy the condition that the error term $E(A,P,Q)$ is negligible compared to the outage probability. As recommended in [38], using $A=10\ln 10$, $P=21$ and $Q=15$ can result in $E(A,P,Q)<10^{-10}$. Besides, the coefficient ξ_p is defined as

$$\xi_p = \begin{cases} 2, & p=0 \\ 1, & p=1,2,... \end{cases}$$

From (22), we know that $\Pr(outage|L>N)$ could be obtained once the MGF of γ_{tot}^N is available. Making full use of a *probability space partition* approach proposed in [10] and [29], this MGF can be derived as follows.

Lemma 1: In the case of $L>N$, the moment generating function for the total SNR γ_{tot}^N can be expressed as

$$\mathcal{M}_\gamma(s) = L(L-N)!\binom{L-1}{N-1}\left(\frac{1}{1+s\bar{\gamma}_N}\right)^{N-1} \times \sum_{m=0}^{L-N} \frac{(-1)^m}{m!(L-N-m)!} \cdot \frac{1}{\eta(s)}, \tag{23}$$

where the average SNR $\bar{\gamma}_N$ is defined in (1) and (2), and

$$\eta(s) = N(1+s\bar{\gamma}_N) + m[1+s\bar{\gamma}_N(1-\rho^2)]. \tag{24}$$

Proof: See Appendix A. ■

Substituting (23) into (22), the outage probability of OSTC in the case of $L>N$ is obtained as

$$\Pr(outage|L>N) = \frac{2^{-Q}e^{A/2}}{\gamma_{th}^N} \sum_{q=0}^{Q} \binom{Q}{q} \times \sum_{p=0}^{P+q} \frac{(-1)^p}{\xi_p} \mathcal{R}\left\{ \frac{\mathcal{M}_\gamma\left(\frac{A+2\pi jp}{2\gamma_{th}^N}\right)}{\frac{A+2\pi jp}{2\gamma_{th}^N}} \right\}, \tag{25}$$

where the threshold SNR is $\gamma_{th}^{N}=2^{2R/\beta_N}-1$ in terms of (13).

Looking back to (15), it can be transformed into an equivalent form of

$$\begin{aligned} P_{ostc}(\gamma_{th}) = & \Pr(outage|L=0)\cdot\Pr(|\mathcal{DS}|=0) \\ & + \sum_{L=1}^{N}\Pr(outage|L\leqslant N)\cdot\Pr(|\mathcal{DS}|=L) \\ & + \sum_{L=N+1}^{K}\Pr(outage|L>N)\cdot\Pr(|\mathcal{DS}|=L), \end{aligned} \tag{26}$$

where $\Pr(|\mathcal{DS}|=L)$ and $\Pr\left(outage||\mathcal{DS}|=L\right)$ are already figured out, so that $P_{ostc}(\gamma_{th})$ can be derived as follows.

Theorem 1: In the presence of outdated CSI, the overall outage probability for the proposed scheme in *i.i.d.* Rayleigh channels can be given in a closed form by (27).

Proof: By substituting (17), (18), (20) and (25) into (26), yields (27). ■

2) ORS with the Outdated CSI: Interestingly, the proposed scheme can be transformed to the conventional ORS if the number of selected relays is $N=1$. Accordingly, the outage probability of ORS denoted by $P_{ors}(\gamma_{th})$ can be obtained by substituting $N=1$ into (27). Its closed-form expression is illustrated in (28).

The outage probability of ORS in the presence of outdated CSI has already been derived in [17] by using the conventional PDF-based performance analysis. The PDF-based expression can be found in Equ. (2) of [17]. It is easy to verify that ORS's outage probability given by MGF-based expression in (28) tightly matches PDF-based expression in [17]. This corroborates our theoretical analyses in this section.

B. Asymptotic Diversity Analysis

From the outage probabilities of (27) and (28), it is still difficult to make an insightful comparison for different cooperative systems. Hence, it is worth providing an asymptotic analysis in high SNR regime to compare their achievable diversity, as the definition of $d{=}-\lim_{\bar{\gamma}\to\infty}\log(P_{out})/\log(\bar{\gamma})$ in [17]. Both ORS [17] and GSC [29] can achieve a full diversity of K with the prefect CSI. However, their diversity are decreased to 1 and N, respectively, in the presence of outdated CSI. For the proposed scheme, we have

Theorem 2: The achievable diversity order of the proposed scheme is

$$d=\begin{cases} N, & \rho<1 \\ K, & \rho=1 \end{cases}$$

Proof: See Appendix B. ■

V. Capacity Analysis

The ergodic capacity is defined as [1]:

$$C=\int_0^\infty \log_2(1+\gamma)f(\gamma)d\gamma,$$

that is another key performance metric to indicate the highest rate at which a signal can be transmitted over a radio channel with a negligible error probability. As mentioned in the previous section, $f(\gamma)$ is difficult to be obtained in a simple and closed form. To avoid intractability of PDF-based performance analysis, we take advantage of an MGF-based approach [39], as follows:

Lemma 2: The ergodic capacity can be calculated through the MGF of the received SNR, given by:

$$C = \frac{1}{\ln(2)} \sum_{t=1}^{T} w_t \Lambda(s_t) \left[\frac{\partial}{\partial s} M_\gamma(s) \Big|_{s \to s_t} \right], \tag{30}$$

where ln denotes the natural logarithm, $\frac{\partial}{\partial s}$ expresses the partial derivative with respect to s, T is a truncation index (setting T=200 is accurate enough for SNRs lower than 30dB), $\Lambda(x)$ stands for a special function called Meijer's G[2],

$$\Lambda(s) = -G_{2,1}^{0,2} \left[\begin{matrix} 1,1 \\ 0 \end{matrix} \middle| \frac{1}{s} \right], \tag{31}$$

and the coefficients s_t and w_t are defined as

$$s_t = \tan\left[\frac{\pi}{4}\cos\left(\frac{2t-1}{2T}\pi\right) + \frac{\pi}{4}\right],$$
$$w_t = \frac{\pi^2 \sin\left(\frac{2t-1}{2T}\pi\right)}{4T\cos^2\left[\frac{\pi}{4}\cos\left(\frac{2t-1}{2T}\pi\right)+\frac{\pi}{4}\right]}.$$

Proof: The detailed derivation can refer to [39]. ■

Subsequently, we make full use of this MGF-based approach to figure out the proposed scheme's capacity. Meanwhile, the closed-form capacity expressions for ORS and GSC are also derived, which are still not available in the literature until now.

A. Capacity of OSTC

According to [40], the end-to-end ergodic capacity of the proposed scheme can be computed conditioned on the decoding subset:

$$C = \sum_{L=0}^{K} \sum_{p=1}^{|\mathcal{DS}_L|} C(\mathcal{DS}_L^p) \Pr(\mathcal{DS}_L^p), \tag{32}$$

where $\Pr(\mathcal{DS}_L^p)$ is the occurrence probability of an arbitrary decoding subset $\mathcal{DS}_L^p$, and $C(\mathcal{DS}_L^p)$ is the end-to-end capacity conditioned on $\mathcal{DS}_L^p$. Thanks to the assumption of *i.i.d.* channels, $\Pr(\mathcal{DS}_L^p)$ as well as $C(\mathcal{DS}_L^p)$ are identical for all $p \in \{1, ..., |\mathcal{DS}_L|\}$. Analogous to (15), (32) is simplified into

$$C = \sum_{L=0}^{K} C^L \Pr(|\mathcal{DS}|=L), \tag{33}$$

[2]The expressions of capacity given in the prior works of [21]- [24] all contain the exponential integral $\int_1^\infty t^{-1}e^{-\lambda t}dt$, whose result isn't closed-form and is still a function of variable λ. In contrast, the result of Meijer's G function is a numerical number, e.g., $G_{2,1}^{0,2}\left[\begin{matrix}1,1\\0\end{matrix}\middle| 1\right] \approx 0.2193839$, leading to a closed-form expression. The mathematical softwares such as MATHEMATICA® and MATLAB® have already implemented Meijer's G in their in-build function library, which can be invoked directly. That is the motivation of using the MGF-based method in this article.

where $\Pr(|\mathcal{DS}|{=}L)$ is the occurrence probability indicating that the current decoding subset has L relays, which is already given in (17). C^L denotes the end-to-end capacity when the decoding subset has $|\mathcal{DS}|{=}L$ relays. The capacity C^L can be derived conditioned on the number of L as follows:

a) $L{\leqslant}N$: If the number of available relays in $\mathcal{DS}$ is not larger than the predefined number N, all of L relays directly participate in the signal retransmission without the need of relay selection. For a Rayleigh-faded channel, its MGF with respect to the received SNR $\gamma_{\tilde{k}_n,d}$ is given by

$$\mathcal{M}_{\gamma_n}(s) = \frac{1}{1+s\bar{\gamma}_{\tilde{k}_n,d}},$$

where $\bar{\gamma}_{\tilde{k}_n,d}$ is the average SNR from relay $\tilde{k}_n$ to the destination. At the receiver, the total SNR can be denoted by $\gamma_{_{tot}}^L{=}\sum_{n=1}^{L}|h_{\tilde{k}_n,d}|^2 P_{\tilde{k}_n}/\sigma^2$. According to [39], the MGF of $\gamma_{_{tot}}^L$ is equal to the multiplication of the MGFs for all links, i.e., $\mathcal{M}_{\gamma}^L(s){=}\prod_{n=1}^{L}\mathcal{M}_{\gamma_n}(s)$. We have

$$\mathcal{M}_{\gamma}^L(s) = \prod_{n=1}^{L}\frac{1}{1+s\bar{\gamma}_{\tilde{k}_n,d}}. \tag{34}$$

If all activated relays use the same transmit power over *i.i.d.* Rayleigh channels, all relay-destination links have a unified average SNR of $\bar{\gamma}_{_L}$, as defined in (1) and (2). Thus, (34) can be further simplified to

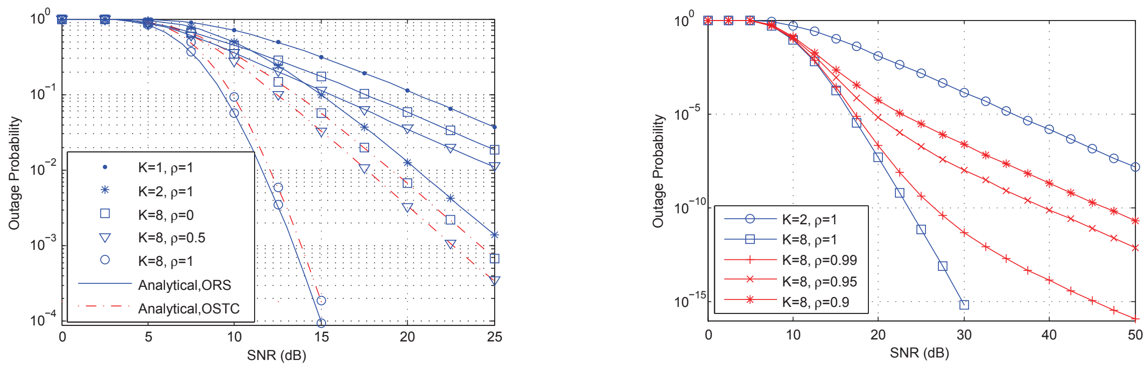
$$\mathcal{M}_{\gamma}^L(s) = \left(\frac{1}{1+s\bar{\gamma}_{_L}}\right)^L. \tag{35}$$

Different from the end-to-end capacitiy C^L for the dual-hop channels, the capacity of relay-destination channel is denoted by C_0^L. Substituting (35) into (30), C_0^L rather than C^L can be figured out. It is noted that there exists a capacity loss owing to the utilization of orthogonal space-time block coding, which is indicated by the factor of β_L in (12). Moreover, the dual-hop cooperative system uses an extra time slot for the broadcast phase. This can be modelled by a modified factor of $\beta_L/(1{+}\beta_L)$. That is to say, the end-to-end capacities for the case of $L{\leqslant}N$ can be computed as

$$C^L = \frac{\beta_L}{1+\beta_L}C_0^L. \tag{36}$$

b) $L{>}N$: When the number of available relays in $\mathcal{DS}$ is more than the predefined number N, the relay selection is applied to choose N relays with strong SNRs. At the selected relays, the regenerated signals are encoded by N-dimensional OSTBC and simultaneously transmitted to the destination. Using a simple maximum-likelihood decoding at the receiver, the total SNR can be obtained as $\gamma_{_{tot}}^N{=}\sum_{n=1}^{N}|h_{\tilde{k}_n,d}|^2 P_{\tilde{k}_n}/\sigma^2$, whose MGF is (23). The first partial derivative of (23) is

$$\begin{aligned}\frac{\partial\mathcal{M}_{\gamma}(s)}{\partial s}{=}&\bar{\gamma}_{_N}L(L-N)!\binom{L-1}{N-1}\left(\frac{1}{1+s\bar{\gamma}_{_N}}\right)^N\\ &\times\sum_{m=0}^{L-N}\frac{(-1)^{m+1}}{m!(L-N-m)!}\\ &\cdot\left(\frac{N{-}1}{\eta(s)}+\frac{(N+m(1{-}\rho^2))(1+s\bar{\gamma}_{_N})}{\eta^2(s)}\right).\end{aligned} \tag{37}$$



(a) (b)

Fig. 2. (a) Outage probability of OSTC and ORS as a function of the average SNR $\bar{\gamma}=P/\sigma^2$ in the case of $K=8$ and $N=2$; (b) Outage probability of OSTC in high SNR using $K=8$ and $N=2$. Numerical results are marked by **markers** while analytical results by **curves**.

Substituting (37) into (30), the capacity of relay-destination channel is obtained. Analogous to (36), a modified factor $\beta_N/(1+\beta_N)$ is needed to model the effect of dual-hop relaying, yielding the end-to-end capacity:

$$\begin{aligned} C^N =& \frac{\beta_N}{1+\beta_N} \cdot \frac{\bar{\gamma}_N L(L-N)!}{\ln(2)} \binom{L-1}{N-1} \\ &\times \sum_{t=1}^{T} \sum_{m=0}^{L-N} \frac{(-1)^{m+1} w_t \Lambda(s_t)}{m!(L-N-m)!} \left(\frac{1}{1+s_t\bar{\gamma}_N}\right)^N \\ &\times \left(\frac{N-1}{\eta(s_t)} + \frac{(N+m(1-\rho^2))(1+s_t\bar{\gamma}_N)}{\eta^2(s_t)}\right). \end{aligned} \tag{38}$$

Looking back to (33), the required occurrence probabilities $\Pr(|\mathcal{DS}|=L)$ as well as the capacities C^L and C^N are all available. This gives the following theorem:

Theorem 3: In the presence of outdated CSI, the end-to-end ergodic capacity for the proposed scheme over *i.i.d.* Rayleigh channels can be calculated in a closed form by (29).

Proof: Substituting (17), (36) and (38) into (33), yields (29). ■

B. Capacity of GSC

The signal transmission of GSC is also divided into two steps: the broadcast and relaying phases. The source transmits and those relays who can correctly decode the original signal constitute a decoding subset $\mathcal{DS}$. N relays with large SNRs in relay-destination links are selected from $\mathcal{DS}$. The regenerated signals at the selected relays are transmitted in N orthogonal channels from the relays to the destination, i.e., only one relay sends at each time while the others keep silence. Using maximal ratio combining at the receiver, the total received SNR using GSC is $\gamma_{tot}=\sum_{n=1}^{N}|h_{\tilde{k}_n,d}|^2 P_{\tilde{k}_n}/\sigma^2$, which is identical to that of OSTC. It can be verified that the MGF with respect to γ_{tot} in GSC is as same as that of OSTC and can also be expressed by (23). The key difference between these two schemes is that $N+1$ orthogonal channels are totally used for the end-to-end signal transmission by GSC, whereas the number of required channels is merely 2 in the proposed scheme thanks to the utilization of space-time coding.

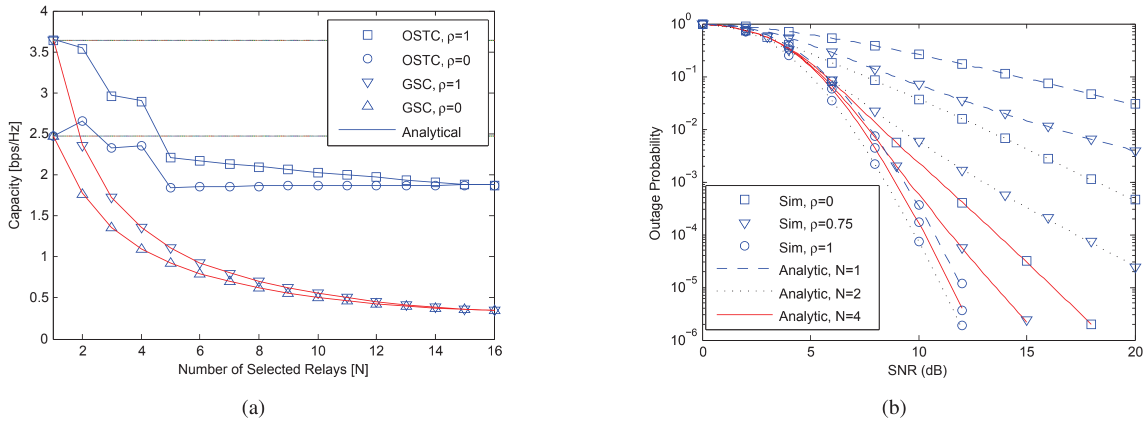


Fig. 3. (a) Capacity comparison of OSTC, ORS and GSC as a function of the number of selected relays $N\in[1,16]$ in the case of $K=16$ and $\bar{\gamma}=20$dB; (b) Outage probability of OSTC and ORS as a function of the average SNR P_u/σ^2 for *the practical power mode* in the case of $K=10$. Numerical results are marked by **markers** while analytical results by **curves**.

Corollary 1: The outage probability of GSC scheme is identical to that of OSTC given in (27), i.e.,

$$P_{gsc}(\gamma_{th}) = P_{ostc}(\gamma_{th}).$$

The ergodic capacity of GSC can be obtained by replacing the factors $\beta_L/(1+\beta_L)$ and $\beta_N/(1+\beta_N)$ in (29) by $1/(L+1)$ and $1/(N+1)$, respectively.

According to [29], N+NT-ORS scheme is transformed to GSC if a normalized threshold $u=1$ is used. For brevity, we only analyze GSC in this article since the mechanism and achievable performance of these two schemes are quite similar.

C. Capacity of ORS

As mentioned in Section IV, the proposed OSTC scheme can be transformed into the conventional ORS if the number of selected relays is decreased to $N=1$. Accordingly, we can figure out ORS's capacity simply by setting $N=1$ in (29):

$$C_{ors} = C_{ostc}\Big|_{N=1}.$$

VI. Numerical Results

We make use of Monte-Carlo simulations to validate analytical results of outage probability and ergodic capacity as well as the achievable diversity. Given *i.i.d.* Rayleigh channels with a normalized gain, the performance comparison of OSTC, ORS and GSC in the absence and presence of outdated CSI is carried out. The numerical results are obtained by iterating 10^6 channel realizations in the simulation, and an end-to-end target rate of $R=1\text{bps/Hz}$ is applied for outage calculations. To guarantee the fairness of comparison, *the theoretical power mode* defined in (1) is applied. For brevity, the source's power is assumed to be $P_s=0.5P$, resulting in an average SNR $\bar{\gamma}_s=0.5P/\sigma^2$

for source-relay channels, while $\bar{\gamma}_{L}{=}0.5P/L\sigma^2$ and $\bar{\gamma}_{N}{=}0.5P/N\sigma^2$ for relay-destination channels. In all figures, the numerical results are marked by **markers**, while the analytical results derived from (27), (28) and (29) are plotted into **curves**. It can be seen that all markers strictly fall into their corresponding curves, which corroborate our theoretical analyses in this article.

We first investigate the impact of outdated CSI on a cooperative network with $K{=}8$ decode-and-forward relays, among which $N{=}2$ best relays are selected for OSTC. As shown in Fig.2a, OSTC suffers from a little bit performance loss compared to ORS when the knowledge of CSI is prefect, i.e., $\rho{=}1$. That is because a single relay with the strongest SNR transmits the regenerated signal in ORS, while a pair of relays with the strongest and second strongest SNR are utilized in OSTC. In the case of $\rho{=}1$, the curve of OSTC is in parallel with its counterpart in ORS that has a full diversity of $K{=}8$. It can be therefore concluded that OSTC also achieves a diversity of $d{=}8$ and its outage probability decays at a rate of $1/\bar{\gamma}^8$ in high SNR. As a benchmark, we set up another cooperative network with $K{=}1$ relay and draw its performance curve of $\rho{=}1$, which has a diversity of $d{=}1$ and is indicated by $K{=}1, \rho{=}1$ in the legend. Similarly, $K{=}2, \rho{=}1$ denotes the curve of ORS achieving a diversity of $d{=}2$. As we can see in high SNR, OSTC's curves in the cases of $\rho{=}0$ and $\rho{=}0.5$ are both parallel with $K{=}2, \rho{=}1$, while curves of ORS are parallel with $K{=}1, \rho{=}1$. That is to say, the diversity of ORS is 1 in the presence of outdated CSI, whereas an order of 2 is still kept by OSTC thanks to using $N{=}2$ selected relays.

As depicted in *Theorem* 2, the achievable diversity of OSTC equals to N in the presence of outdated CSI, even if the outdated CSI tends to the actual CSI ($\rho{\to}1$), whereas a full diversity of K is available when the knowledge of CSI is prefect. To prove this, OSTC's outage probability in high SNR (up to 50dB) is provided in Fig.2b. As a benchmark, the curves of $K{=}2, \rho{=}1$ and $K{=}8, \rho{=}1$ achieving $d{=}2$ and $d{=}8$, respectively, are given in this figure. As can be seen, OSTC's curves are all parallel with the curve of $K{=}2$ in high SNR no matter which correlation coefficient (e.g., $\rho{=}0.9$, 0.95 and 0.99) is used. Only the outage probability of $\rho{=}1$ decays at a different and faster rate. That is to say, the diversity of OSTC is $d{=}2$ when $\rho{<}1$ but a full diversity of $d{=}8$ when $\rho{=}1$. Hence, *Theorem* 2 is justified.

The capacity comparison of OSTC, ORS and GSC as a function of the number of selected relays is given in Fig.3a, where $K{=}16$ and $\bar{\gamma}{=}20\text{dB}$ are applied. When $N{=}1$, all schemes achieve the same performance since both OSTC and GSC are transformed to ORS if a single relay is selected. If the number of selected relays is more than $N{=}5$, the capacity of OSTC become nearly constant and are around 1.9bps/Hz, accounting for approximate 75% of ORS's capacity. GSC's capacity continuously decreases with the increased number of N. Using $N{=}16$ as an example, its capacity is 0.4bps/Hz, accounting for only 16% of ORS and 21% of OSTC. That is to say, OSTC achieves 5-times higher capacity over GSC, although they obtain the same diversity in the presence of outdated CSI. On the other hand, ORS is vulnerable to the outdated CSI since its capacity reduces from 3.6 to 2.5bps/Hz when $\rho{=}1$ is changed to $\rho{=}0$, equivalent to a loss of 1.1bps/Hz. In contrast, the capacity loss of OSTC and GSC are far smaller, e.g., less than 0.2bps/Hz in the case of $N{=}8$, implying their effectiveness of combatting the outdated CSI and their '*robustness*' feature we pursued.

In addition to the fair comparison under the same end-to-end power constraint, the simulation taking advantage of *the practical power mode* depicted in (2) has also been carried out. Outage probabilities of OSTC and ORS as a function of the average SNR P_u/σ^2 in the case of $K{=}10$ are illustrated in Fig.3b. Contrary to the performance loss shown in Fig.2a, OSTC achieves a better performance than ORS in the case of $\rho{=}1$. That is because the transmit power of relay is fixed to P_u and the number of selected relays for OSTC are $N{=}2$ and $N{=}4$, resulting in double and four-times power consumptions than ORS. Interestingly, the outage probability of $N{=}4$ is worse than that of $N{=}2$, although the former consumes more power. That is because the Alamouti scheme for $N{=}2$ is the unique full-rate full-diversity coding, while 4-dimensional OSTBC supports a maximal rate of only $3/4$. In the presence of outdated CSI, it can be seen that OSTC remarkably outperforms ORS with a SNR gain of more than 10dB. We can conclude that the proposed scheme outperforms ORS and GSC *in the practical power mode*, and the achieved performance gain is more remarkably than *in the theoretical power mode*.

VII. Conclusions

In this article, we proposed a robust opportunistic relaying scheme to combat the outdated CSI for decode-and-forward cooperative systems. The proposed scheme opportunistically selects a predefined number of relays, rather than a single relay in the conventional ORS, to decode and simultaneously retransmit the original signal. When the knowledge of CSI is prefect, the full diversity of K, i.e., the number of cooperating relays, is achieved. In the presence of outdated CSI, where the outage probability of ORS drastically deteriorates and its diversity degrades to one, i.e., no diversity, the diversity of N can still be kept by this scheme. Compared to GSC, the capacity loss of this scheme is negligible thanks to the simultaneous transmission by means of space-time coding. In contrast to DSTC, the relay selection process is introduced so that the number of selected relays is fixed and known beforehand by the whole cooperative system, which makes sense for the practical systems. From the perspective of both achieved performance and implementation complexity, the proposed scheme is the best solution until now. Next, the following works are worth being explored: 1) making clear the optimal number of selected relays from the viewpoint of multiplexing-diversity trade-off, 2) designing a robust scheme for amplify-and-forward opportunistic relaying, and 3) evaluating the performance by utilizing realistic channel models to capture as many as possible their behaviors in real-world.

Appendix A
Derivation of Lemma 1

To investigate the performance of such an *NchooseK* problem, we take advantage of a *probability space partition* approach proposed in [10] [41]. For the sake of mathematical tractability, the outdated SNRs of relays belonging to the decoding subset, i.e., $\hat{\gamma}_{k,d}$, $k{\in}\mathcal{DS}$, are rewritten as a new set of $\{\hat{\gamma}_1,\hat{\gamma}_2,...,\hat{\gamma}_L\}$. To construct *partitions*, a group of sets $\mathcal{A}_i, i{\in}\{1,...,L\}$ are defined as

$$\mathcal{A}_i := \left\{ \{\hat{\gamma}_1,...,\hat{\gamma}_L\} \,\middle|\, \exists\, |I|{=}N{-}1,\ s.t.\ l{\in}I : \hat{\gamma}_l{>}\hat{\gamma}_i \right\},$$

where the mathematical symbol $\exists$ stands for *there exists*, and I is an index set with $N-1$ elements. That is to mean the set $\mathcal{A}_i$ is a set of L elements $\{\hat{\gamma}_1, ..., \hat{\gamma}_L\}$ where $\hat{\gamma}_i$ is N^{th} largest SNR[3] denoted by $\hat{\gamma}^{(N)}=\hat{\gamma}_i$. For instance, $\mathcal{A}_1$ is an L-tuples set, in which $\hat{\gamma}_1$ is exactly N^{th} largest SNR, and there exists $N-1$ relays whose SNRs are larger than $\hat{\gamma}_1$.

Using OSTC, the total SNR at the receiver could be written as $\gamma_{tot}=\sum_{l=1}^{L} T(\hat{\gamma}_l)$, where $T(\hat{\gamma}_l)$ is a testing function:

$$T(\hat{\gamma}_l) = \begin{cases} \gamma_l, & \hat{\gamma}_l > \hat{\gamma}^{(N)} \\ 0, & \hat{\gamma}_l \leqslant \hat{\gamma}^{(N)}, \end{cases} \tag{39}$$

where γ_l denotes the actual SNR corresponding to its outdated version of $\hat{\gamma}_l$. According to the mathematical method depicted in [10] and [36], the moment generating function of the total SNR γ_{tot} can be calculated by

$$\begin{aligned}\mathcal{M}_\gamma(s)=&\sum_{i=1}^{L}\int_0^\infty \sum_I \underbrace{\int_0^\infty\cdots\int_0^\infty}_{L}\underbrace{\int_0^{\hat{\gamma}_i}\cdots\int_0^{\hat{\gamma}_i}}_{L-N}\\ &\times\underbrace{\int_{\hat{\gamma}_i}^\infty\cdots\int_{\hat{\gamma}_i}^\infty}_{N-1}\prod_{l=1}^{L}\left[e^{-sT(\hat{\gamma}_l)}f_{\gamma_l|\hat{\gamma}_l}(\gamma|\hat{\gamma})f_{\hat{\gamma}_l}(\hat{\gamma})\right]\\ &\underbrace{d\hat{\gamma}_{l_1}\cdots d\hat{\gamma}_{l_{N-1}}}_{N-1}\underbrace{d\hat{\gamma}_{l'_1}\cdots d\hat{\gamma}_{l'_{L-N}}}_{L-N}\underbrace{d\gamma_1\cdots d\gamma_L}_{L}d\hat{\gamma}_i,\end{aligned} \tag{40}$$

where $\{\hat{\gamma}_{l_1}, \ldots, \hat{\gamma}_{l_{N-1}}\}$ denotes a set of outdated SNRs larger than $\hat{\gamma}_i$, the index set in this case is $I=\{l_1, \ldots, l_{N-1}\}$, while $\{\hat{\gamma}_{l'_1}, \ldots, \hat{\gamma}_{l'_{L-N}}\}$ is a set of outdated SNRs less than $\hat{\gamma}_i$. Due to the assumption of *i.i.d.* Rayleigh channels, the outdated SNR is exponentially distributed, whose PDF is given by

$$f_{\hat{\gamma}_l}(\hat{\gamma}) = \begin{cases} \dfrac{1}{\bar{\gamma}_N}e^{-\frac{\hat{\gamma}}{\bar{\gamma}_N}}, & \hat{\gamma}\geqslant 0 \\ 0, & \hat{\gamma}<0, \end{cases} \tag{41}$$

where $\bar{\gamma}_N$ is the average SNR of relay-destination channels as defined in (1) and (2). According to [10], substituting (3), (39) and (41) into (40), yielding

$$\begin{aligned}\mathcal{M}_\gamma(s)=&L\binom{L-1}{N-1}\sum_{l=0}^{L-N}\sum_{t=0}^{L-N-l}\sum_{m=0}^{l}\left(\frac{1}{1+s\bar{\gamma}_N}\right)^{L-l-1}\\ &\times\frac{(-1)^{t+m}(L-N)!}{(L-N-l-t)!m!t!(l-m)!}\cdot\frac{1}{\eta(s)},\end{aligned} \tag{42}$$

where

$$\eta(s)=(1+s\bar{\gamma}_N)(L-l)+m[1+s\bar{\gamma}_N(1-\rho^2)].$$

[3]We assume that the occurrence probability for two or more relays have an identical SNR, i.e., $\hat{\gamma}_l=\hat{\gamma}_i$, is very low and can be neglected.

As given in [42], we have the following equality:

$$\sum_{t=0}^{T} \frac{(-1)^t}{(T-t)!t!} = \begin{cases} 1, & T=0 \\ 0, & T>0 \end{cases}. \tag{43}$$

It can be known that the second and third sum of (42) denoted by $\phi(l,\rho)$ and $\psi(l)$ in the following equation, respectively, are independent with each other. Hence, we can rewrite (42) as

$$\begin{aligned} \mathcal{M}_\gamma(s) =& L(L-N)! \binom{L-1}{N-1} \sum_{l=0}^{L-N} \left(\frac{1}{1+s\bar{\gamma}_{N}}\right)^{L-1-l} \\ & \times \underbrace{\sum_{m=0}^{l} \frac{(-1)^m}{m!(l-m)!} \cdot \frac{1}{\eta(s)}}_{\phi(l,\rho)} \\ & \times \underbrace{\sum_{t=0}^{L-N-l} \frac{(-1)^t}{(L-N-l-t)!t!}}_{\psi(l)}. \end{aligned} \tag{44}$$

Replacing T in the equality of (43) by $L-N-l$, we know that $\psi(l)$ is nonzero only when $L-N-l=0$, that is

$$\psi(l) = \sum_{t=0}^{L-N-l} \frac{(-1)^t}{(L-N-l-t)!t!} = \begin{cases} 1, & l = L-N \\ 0, & l \neq L-N \end{cases}.$$

That is to say, only the item in the case of $l=L-N$ is nonzero, while others are all equal to zero. Therefore, we expand (44) and remove the items of $l\neq L-N$, yielding (23) and (24).

Appendix B
Asymptotic analysis of Theorem 2

In high SNR regime, the average SNRs of source-relay and relay-destination channels, i.e., $\bar{\gamma}_s$, $\bar{\gamma}_{L}$ and $\bar{\gamma}_{N}$, all satisfy an assumption of $1/\bar{\gamma}_x \to 0$. For simplicity, their subscripts are neglected and denoted hereinafter by a unified notation of $\bar{\gamma}$. As we can see in (27), OSTC's outage probability behaves in a different way with respect to the value of ρ, so our asymptotic analysis needs to be carried out upon three extreme cases:

1) $\rho=1$: When the knowledge of CSI is prefect, the function given in (24) can be simplified into $\eta(s)=N(1+s\bar{\gamma})+m$. Then, the MGF given in (23) is rewritten as

$$\begin{aligned} \mathcal{M}_\gamma(s) =& L(L-N)! \binom{L-1}{N-1} \left(\frac{1}{1+s\bar{\gamma}}\right)^{N-1} \\ & \times \underbrace{\sum_{m=0}^{L-N} \frac{(-1)^m}{m!(L-N-m)!} \cdot \frac{1}{N(1+s\bar{\gamma})+m}}_{\omega(s)}. \end{aligned} \tag{45}$$

Referring to [42], we have the following equality:

$$\sum_{m=0}^{M} \frac{(-1)^m}{m!(M-m)!} \cdot \frac{1}{\alpha+m} = \prod_{m=0}^{M} \frac{1}{\alpha+m}.$$

It is obvious that $\omega(s)$ in (45) is exactly a sample of this equality in the case of $M{=}L{-}N$ and $\alpha{=}N(1{+}s\bar{\gamma})$. Accordingly, $\omega(s)$ can be transformed to

$$\omega(s){=}\sum_{m=0}^{L-N}\frac{(-1)^m}{m!(L-N-m)!}\cdot\frac{1}{N(1+s\bar{\gamma})+m}$$
$$=\prod_{m=0}^{L-N}\left(\frac{1}{N(1+s\bar{\gamma})+m}\right).$$

Neglecting m due to $\bar{\gamma}\gg m$ in high SNR, then

$$\omega(s)\approx\left(\frac{1}{N(1+s\bar{\gamma})}\right)^{L-N+1}. \tag{46}$$

Substituting (46) into (45), yields

$$\mathcal{M}_\gamma(s)\approx\frac{L(L-N)!}{N^{L-N+1}}\binom{L-1}{N-1}\left(\frac{1}{1+s\bar{\gamma}}\right)^L. \tag{47}$$

According to *proposition 3* of [43], the diversity order equals to the pole of MGF. Letting $s{\to}\infty$, (47) can be rewritten as

$$\mathcal{M}_\gamma(s)\approx\left(\frac{1}{s}\right)^L, \tag{48}$$

We get that the pole of (48) equals to L and therefore its corresponding diversity is L. In terms of *proposition 5* of [43], the asymptotic form of $\Pr(outage|L{>}N)$ is expressed as

$$\Pr(outage|L{>}N)=\left(\frac{1}{\bar{\gamma}}\right)^L+o\left(\left(\frac{1}{\bar{\gamma}}\right)^L\right), \tag{49}$$

where $o(x)$ is the *little-o notation* standing for a quantity that is ultimately smaller than x.

On the other hand, we can know that the diversity order of $\Pr(outage|L{\leqslant}N)$ is also L from its closed-form expression given in (20). Similar to (49), its asymptotic form is given by

$$\Pr(outage|L{\leqslant}N)=\left(\frac{1}{\bar{\gamma}}\right)^L+o\left(\left(\frac{1}{\bar{\gamma}}\right)^L\right). \tag{50}$$

Applying the Taylor series expansion centered at 0, we have

$$e^x=1+x+x^2/2!+...$$

Therefore, the occurrence probability in (17) can be expanded to the following asymptotic form:

$$\Pr(|\mathcal{DS}|{=}L)=\left(\frac{1}{\bar{\gamma}}\right)^{K-L}+o\left(\left(\frac{1}{\bar{\gamma}}\right)^{K-L}\right). \tag{51}$$

Substituting (49), (50) and (51) into (26), we can get the asymptotic form of the overall outage probability as

$$P'_{ostc}{=}\left(\frac{1}{\bar{\gamma}}\right)^K+\sum_{L=1}^{N}\left(\left(\frac{1}{\bar{\gamma}}\right)^K+o\left(\left(\frac{1}{\bar{\gamma}}\right)^K\right)\right)$$
$$+\sum_{L=N+1}^{K}\left(\left(\frac{1}{\bar{\gamma}}\right)^K+o\left(\left(\frac{1}{\bar{\gamma}}\right)^K\right)\right)$$
$$=\left(\frac{1}{\bar{\gamma}}\right)^K+o\left(\left(\frac{1}{\bar{\gamma}}\right)^K\right).$$

According to the definition of diversity order [17], we have

$$d{=}-\lim_{\bar{\gamma}\to\infty}\frac{\log(P'_{ostc})}{\log(\bar{\gamma})}$$
$$={-}\lim_{\bar{\gamma}\to\infty}\frac{-\log\bar{\gamma}^{K}}{\log\bar{\gamma}}=K. \tag{52}$$

2) ρ=0: If the actual CSI and its outdated version are independent of each other, (24) changes to $\eta(s){=}(1{+}s\bar{\gamma})(N{+}m)$. Then, the MGF in (23) can be rewritten as

$$\mathcal{M}_{\gamma}(s){=}L(L-N)!\binom{L-1}{N-1}\left(\frac{1}{1+s\bar{\gamma}}\right)^{N}$$
$$\times\sum_{m=0}^{L-N}\frac{(-1)^{m}}{m!(L-N-m)!}\cdot\frac{1}{(N+m)}.$$

Letting $s\to\infty$, it is further transformed to

$$\mathcal{M}_{\gamma}(s)=\left(\frac{1}{s}\right)^{N}+o\left(\left(\frac{1}{s}\right)^{N}\right).$$

In accordance of *proposition 3* and *proposition 5* of [43], we know that the diversity order of $\Pr(outage|L{>}N)$ is N and its asymptotic form can be given by

$$\Pr(outage|L{>}N)=\left(\frac{1}{\bar{\gamma}}\right)^{N}+o\left(\left(\frac{1}{\bar{\gamma}}\right)^{N}\right). \tag{53}$$

Since (17) and (20) are independent of the correlation coefficient, their asymptotic forms are unchangeable for different values of ρ. Hence, (50) and (51) can be reused in this case. Substituting (50), (51) and (53) into (26), yields

$$P'_{ostc}{=}\left(\frac{1}{\bar{\gamma}}\right)^{K}+\sum_{L=1}^{N}\left(\left(\frac{1}{\bar{\gamma}}\right)^{K}+o\left(\left(\frac{1}{\bar{\gamma}}\right)^{K}\right)\right)$$
$$+\sum_{L=N+1}^{K}\left(\left(\frac{1}{\bar{\gamma}}\right)^{K-L+N}+o\left(\left(\frac{1}{\bar{\gamma}}\right)^{N}\right)\right)$$
$$=\left(\frac{1}{\bar{\gamma}}\right)^{N}+o\left(\left(\frac{1}{\bar{\gamma}}\right)^{N}\right). \tag{54}$$

Similar to (52), the achievable diversity for ρ=0 is

$$d=-\lim_{\bar{\gamma}\to\infty}\frac{-\log\bar{\gamma}^{N}}{\log\bar{\gamma}}=N.$$

3) $\rho\to1$: As we know, one of the Taylor series expansion centered at 0 is

$$\frac{1}{1-x}=\sum_{n=0}^{\infty}x^{n}.$$

The item $1/\eta(s)$ in (23) can be expanded with respect to $1-\rho^2\to 0$, we have

$$\begin{aligned}\frac{1}{\eta(s)}=&\frac{1}{N(1+s\bar{\gamma})+m[1+s\bar{\gamma}(1-\rho^2)]}\\=&\frac{1}{N(1+s\bar{\gamma})+m}\cdot\frac{1}{1+\frac{ms\bar{\gamma}(1-\rho^2)}{N(1+s\bar{\gamma})+m}}\\=&\frac{1}{N(1+s\bar{\gamma})+m}\sum_{n=0}^{\infty}\left(\frac{-ms\bar{\gamma}(1-\rho^2)}{N(1+s\bar{\gamma})+m}\right)^n\\=&\frac{1}{N(1+s\bar{\gamma})+m}\\&\times\left(1-\frac{ms\bar{\gamma}(1-\rho^2)}{N(1+s\bar{\gamma})+m}+o(1-\rho^2)\right).\end{aligned}\tag{55}$$

If $s\to\infty$, substituting (55) into (23), we can get

$$\mathcal{M}_{\gamma}(s)=\left(\frac{1}{s}\right)^N+o\left(\left(\frac{1}{s}\right)^N\right).$$

In accordance to *proposition 3* and *proposition 5* of [43], it is obtained that the diversity order of $\Pr(outage|L>N)$ is N. Hence, the asymptotic form of $\Pr(outage|L>N)$ for $\rho\to 1$ is identical to (53). Similarly, we can get a diversity order of $d=N$ in the case of $\rho\to 1$.

According to [17], the outage probability is a decreasing function as ρ and applying the definition of diversity order, we can get

$$d_{\rho=0}\leqslant d_{\rho'}\leqslant d_{\rho\to 1},$$

where ρ' stands for an arbitrary value of $\rho\in(0,1)$. Since both the low and high end of d is equal to N, i.e., $d_{\rho=0}=d_{\rho\to 1}=N$, it can be concluded that the diversity order of the proposed scheme is always $d=N$ when $\rho<1$.

In summary, we can make the conclusion that the proposed scheme achieves a full diversity of $d=K$ when the knowledge of CSI is perfect and an order of $d=N$ in the presence of outdated CSI.

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