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Device-to-Device Based Cooperative Relaying for 5G Network: A Comparative Review

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Abstract

Due to the proliferation of mobile internet access, the cellular traffic is envisaged to experience a 1000-fold growth in the second decade of the 21st century. To meet such a huge traffic demand, the Fifth Generation (5G) network have to adopt new techniques to substantially increase spectral efficiency and reliability. At the base station side, available resources (power supply, equipment size, processing capability, etc.) are far more sufficient than that of the terminal side, which imposes a high challenge on the uplink transmission. The concept of cooperative communications opens a possibility of using multiple terminals to cooperatively achieve spatial diversity that is typically obtained by means of multiple antennas in the base station. The application of Device-to-Device (D2D) communications in the 3GPP LTE system further pushes the collaboration of terminals from the theory to the practice. The utilization of D2D-based cooperative relaying is promising in the era of 5G. In this paper, we comparatively study several cooperative multi-relay schemes, including the proposed opportunistic space-time coding, in the presence of imperfect channel state information. The numerical results reveal that the proposed scheme is the best cooperative solution until now from the perspective of multiplexing-diversity tradeoff.

Keywords

cooperative communications; Device-to-Device (D2D); Distributed Space-Time Coding (DSTC); outdated chanel state information; opportunistic relaying

1 Introduction

Due to the proliferation of mobile internet access, the cellular traffic experienced an exponential growth in the past years, which imposes a high pressure on the current networks and urges the industry to develop a new generation wireless system [1]. A consensus for the 5G system is that mobile traffic will increase 1000 times in the second decade of the 21th century [2], [3]. In addition to other cutting-edge paradigms, protocols and architectures (Licensed-Assisted Access [4], Device-to-Device (D2D) communications [5], software-defined networking [6], network function virtualization [7], etc.), the 5G system has to adopt New Radio (NR) transmission techniques to substantially increase spectral efficiency and reliability so as to meet such a huge capacity demand. However, a multi-path channel suffers from a severe fading due to constructive and destructive interferences of received signals in wireless communications [8]. At a high data transmission rate, it is challenging for a receiver to correctly detect a signal without some form of diversity. Since the time and frequency resources in a wireless system are tightly limited, the exploitation of spatial resource is of great importance. A particularly appealing approach is the utilization of antenna array, such as Multiple-Input Multiple-Output (MIMO) [9] and massive MIMO [10], which can achieve higher diversity by means of simply installing additional antennas.

Until now, the technical discussions on the application of antenna array in a wireless system are mainly focused on the base station side. Due to the limitations of power supply, cost and hardware size, a mobile terminal is traditionally hard to be equipped with multiple antennas. Recently, the millimeter wave (mmWave) band [11] has been intensively investigated and the size of antenna at this band is small enough to be massively integrated in a mobile terminal. However, due to the severe propagation characteristics of radio signals at the higher frequencies, an mmWave-based system cannot independently form a wide-area-covered network in a cellular manner. Complementary to macro-cell coverage, it suits to provide ultra-high data access at hot spots [12]. Taking into account the requirement of ubiquitous signal coverage, especially the provision of control signaling and system information broadcasting [13], the carrier frequencies below 6 GHz is still the mainstream for macro-cell transmission and plays a vital role from the perspective of a holistic wireless system. In a nutshell, the working assumption of a signal antenna at the mobile terminal for macro-cell transmission is practically meaningful.

With a single antenna, it is infeasible to exploit multi-antenna diversity for mobile terminals in a cellular system. In this context, the concept of cooperative communications [14] has been proposed to solve this problem by means of making full use of the broadcast nature of wireless signals in a relay channel [15], where multiple single-antenna terminals can form a virtual antenna array to collaboratively transmit their signals. Once a terminal sends a signal to its destination (a base station), its neighboring terminals that overhear this signal are capable of decoding and retransmitting. By means of combining multiple copied versions of the original signal at the receiver, an inherent spatial diversity referred to as cooperative diversity [16] can be achieved.

Currently, it is still impossible to commercially implement a full-duplex [17] mobile terminal to simultaneously transmit and receive signals at the same frequency. A terminal has to operate in a half-duplex mode where Time- or Frequency-Division Multiplexing (TDD/FDD) is applied. Without loss of generality, we are allowed to use TDD as an example to analyze the cooperative relaying. Basically, an end-to-end signal transmission happens in two phases [18]. In the broadcast phase, a terminal (the source) transmits its signal in the source-relay channels while all neighboring terminals listen. Those neighboring terminals who have overheard and successfully decoded this signal can act as the relays. In the relaying phase, all or a subset of the relays retransmit this signal in the relay-destination channels. However, a scheduling problem occurs in the scenario of multi-relay cooperative transmission. That is which relays should be selected and how the regenerated signals should be transmitted by the selected relays. In the literature, several cooperative multi-relay schemes have been proposed. Generalized Selection Combining (GSC) [19] choosing multiple relays to orthogonally retransmit suffers from a substantial loss of spectral efficiency. To avoid this penalty, the distributed BeamForming (BF) [20] based on simultaneous transmission has been taken into account. Given a perfect channel knowledge, the relays adjust the phases of their transmit signals for coherently combining at the receiver. As we know, BF is very sensitive to phase noise [21]. That is why co-located antennas in an MIMO system must apply an antenna calibration scheme to align phase distortions on different radio-frequency (RF) chains. However, the RF-chain calibration schemes designed for co-located antennas cannot be applied among spatially-distributed terminals. In practice, the performance degradation from the phase distortions overwhelms the expected BF gain. In [22], an approach called Distributed Space-Time Coding (DSTC) has been proposed to transmit space-time-coded signals by multiple relays. 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, the synchronization among simultaneously transmitting relays becomes challenging when the number of relays is large. In a nutshell, the aforementioned multi-relay transmission methods are hard to be applied for practical systems.

In [23], Bletsas et al. revealed that the multi-relay synchronization problem can be avoided while keeping full cooperative diversity by opportunistically selecting the best relay to retransmit. They proposed an approach referred to as Opportunistic Relaying System (ORS), which has been extensively verified as a simple but efficient cooperative relaying scheme. Although only a single terminal with the best channel (in accordance to a given selection criterion) is selected to serve as a relay, a full spatial diversity with the number of all cooperative relays can be available. Its achieved performance is about the same as that of the DSTC scheme, which uses an all-participating strategy [24]. From the perspective of multiplexing-diversity tradeoff, the ORS scheme provides no performance loss in comparison with the DSTC scheme, while avoiding the complicated implementation.

From the practical point of view, the channel state information (CSI) at the time instant of relay selection may substantially differ from the CSI at the instant of using the selected relay to retransmit owing to the channel fading and feedback delay. The imperfect CSI imposes a possibility of wrongly selecting the best relay in the ORS scheme, which drastically deteriorates its performance. The impact of the outdated CSI on the performance of opportunistic relaying has been extensively analyzed in the previous works. In [25], a closed-form expression of outage probability for Decode-and-Forward (DF) ORS has been derived. Seyfi et al. [26] investigated the impact of feedback delay and channel estimation error on the relaying selection. Kim et al. evaluated the performance degradation in terms of symbol error probabilities in [27]. Regarding Amplify-and-Forward (AF) ORS, Torabi et al. presented a lot of results through [28]–[30]. The impact of the outdated CSI on partial relay selection has also been reported in [31] and [32]. The error probabilities of ORS considering channel estimation errors have been derived in [33]. Based on the outcomes presented in the literature, the following conclusions can be drawn:

1) The relay selection is very vulnerable to the imperfect channel quality, where its achieved diversity is limited to one (no diversity).
2) Regardless of the number of relays participating in a cooperation, there is no diversity, even if correlation coefficient of the actual and outdated CSI tends to one $(\rho \rightarrow 1)$.
3) From a practical point of view, it is worth designing a robust cooperative strategy to combat the outdated CSI.

To the best knowledge of the author, a few cooperative schemes to tackle the outdated CSI problem have been proposed until now. Taking advantage of Geo-location information, a scheme has been proposed in [34]. However, it makes sense only in a fixed wireless system, where the relays' locations do not change, rather than a mobile network. Another scheme taking into account the statistical knowledge of channel has been given in [35]. In spite of a remarkable increase of the implementation complexity, this scheme achieves merely a marginal performance gain and its diversity is always limited to one. Generalized selection combining [19] and its enhanced version called N plus Normalized Threshold Opportunistic Relay Selection (N+NT-ORS) [36] have also been applied. However, they require at least N orthogonal channels to retransmit, resulting in a large loss of spectral efficiency.

In this context, we proposed a simple but effective scheme called Opportunistic Space-Time Coding (OSTC) [37] to alleviate the effect of the outdated CSI while avoiding an unnecessary loss of spectral efficiency. A predefined number N of relays, rather than a single relay in the conventional ORS, are opportunistically selected from K cooperating relays according to instantaneous CSIs of the relay-destination channels. At these selected relays, N-dimensional orthogonal space-time block coding (OSTBC) [38] is employed to encode the regenerated signals. N branches space-time coded signals are simultaneously transmitted from the selected relays to the destination, followed by a simple maximum-likelihood decoding based only on linear processing at the receiver. In contrast to DSTC where all relays participate in the signal's retransmission without a process of relay selection, only a subset of relays are opportunistically activated. Therefore, opportunistic space-time coding can be regarded as a combination of opportunistic relay selection and distributed space-time coding. Our research outcomes [39], [40] further recommend that the optimal number of relays to be selected is $N=2$. A pair of relays with the strongest and second strongest CSI at the relay-destination channels are selected, and the Alamouti scheme [41] is applied to encode the original signal. Since the Alamouti scheme is a unique space-time code achieving both full-rate and full-diversity with complex signal constellations, there is no spectral efficiency loss in comparison with the case of $N>2$. Another consideration of using $N=2$ is that the less number of relays can simplify the distributed synchronization. The practical timing and frequency synchronization schemes [42], [43] proposed for cooperative systems can help two relays to achieve a satisfied level of synchronization, whereas the time and frequency offsets become unacceptable with the increased number of relays.

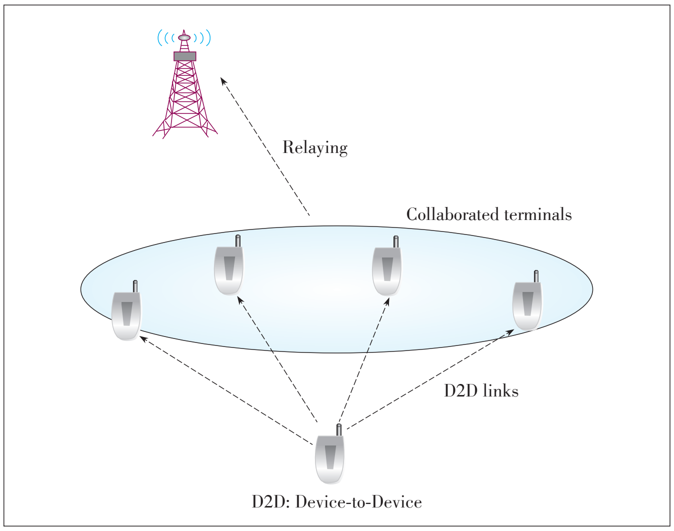
This paper gives a comparative review of the cooperative multi-relay transmission schemes. The rationale of different schemes, as well as their performance in terms of outage probability and channel capacity, are presented. The rest of this paper is organized into the following four sections. Section 2 introduces the system model of DF cooperative system. Section 3 illustrates the aforementioned cooperative schemes. In Section 4, simulation results are given. Finally, Section 5 concludes this paper.

2 Sytem Model

2.1 Multi-Relay Cooperative Network

A dual-hop decode-and-forward cooperative network is considered, where a terminal (the source) communicates with a base station (the destination) with the help of neighboring terminals (relays). Due to the line-of-sight blockage, a direct link between the source and the destination is assumed to be neglected. 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. Currently, it is impractical to commercially implement a full-duplex mobile terminal. Hence, the relays have to operate in a half-duplex mode and the TDD scheme can be applied. It is generally assumed that the relays are equipped with a single antenna due to the limitations of cost, power supply and hardware size on mobile terminals. Although the spatially-distributed terminals with independent oscillators give rise to multiple timing offset and multiple carrier frequency offset, this multi-relay synchronization problem has been well-addressed and reported in the literature [42]–[45]. For simplicity, as most of papers in this field, we assume perfect synchronization throughout the rest of this paper.

As illustrated in **Fig. 1**, a base station provides cell coverage to a number of mobile terminals. A terminal may suffer from an out-of-coverage problem due to the blocking of buildings or a weak received signal when it locates at the cell edge. Besides, in the scenarios of disaster relief or emergency events as investigated in Aerial Base Stations with Opportunistic Links for Unexpected & Temporary Events (ABSOLUTE) project [46], this base station might be rapidly deployed without any network planning and optimization. In this case, the coverage is not good enough while the requirement of link reliability and system robustness is quite high. To improve the spectral efficiency at the cell edge, extend the signal coverage and improve the link reliability, cooperative communications can be applied by exploiting the broadcast nature of wireless signals. The mobile terminals cooperate with one another to communicate using the cooperative relaying. As shown in Fig. 1, the signals are first transmitted from the source terminal outside the coverage area of base station to its neighboring terminals through D2D communications. Those neighboring terminals that overheard this signal are capable of decoding and retransmitting. The distributed antennas at the terminals form a virtu-



▲Figure 1. Principle of cooperative communications.

al antenna array. By means of combining multiple copied versions of the original signal at the receiver, an inherent spatial diversity referred to as cooperative diversity can be achieved without any need of physical antenna array.

2.2 Outdated CSI

From a practical point of view, the channel information is imperfect due to the feedback delay and channel estimation error. In a traditional system such as the MIMO system, this imperfect CSI has a neglect effect mainly on the performance of signal detection. However, the relay selection scheme is far more vulnerable since the CSI is applied to not only detect a received signals but also select the best relay(s). The CSI at the time instant of relay selection denoted by h may substantially differ from the actual CSI $\hat{h}$ at the instant of data retransmission. Using the relays selected according to the outdated version of CSI rather than the actual CSI may make the wrong selection decision. To quantify the impact of imperfect CSI on the system, the envelop of correlation coefficient is defined as

$$\rho = \frac{\left|\mathrm{cov}(h,\hat{h})\right|}{\mu_h \mu_{\hat{h}}}, \qquad (1)$$

where $\mathrm{cov}(\cdot)$ and μ stand for the covariance of two random variables and the standard deviation, respectively. The detail modeling of the outdated CSI and its statistics can be found in [47] and [48].

3 Cooperative Multi-Relaying Schemes

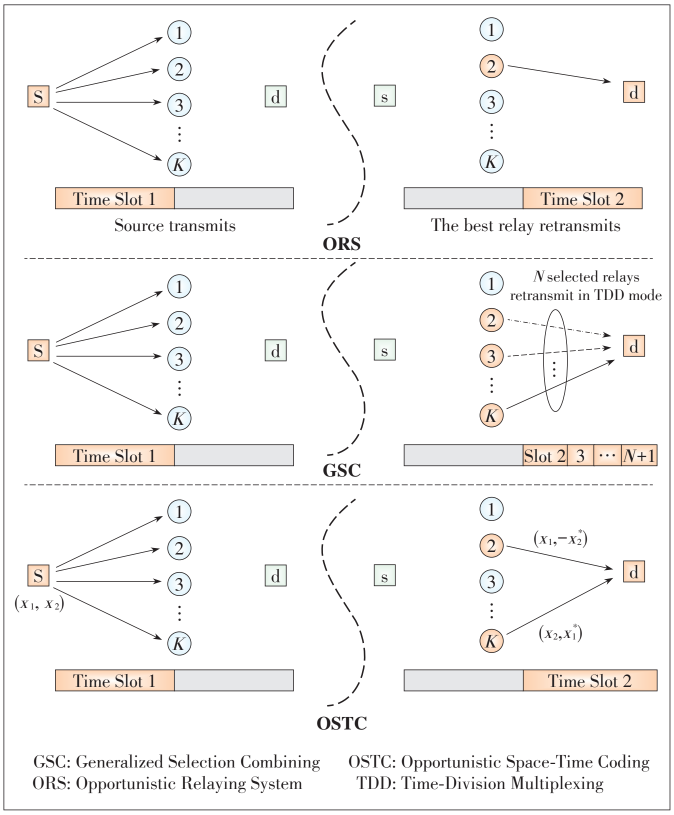
This section introduces mechanisms of different cooperative schemes, including ORS, GSC and OSTC. Because of the severe attenuation of radio signals, a single-antenna relay has to operate in a half-duplex mode to avoid harmful self-interference between the transmitter and receiver. Without loss of generality, the end-to-end signal transmission can be divided into two time slots: the broadcast and relaying phases. In the broadcast phase (Time Slot 1 indicated in **Fig. 2**), the source transmits and those relays that can correctly decode the original signal constitute a decoding subset:

$$DS \triangleq \left\{k: \frac{1}{2}\log_2(1+\hat{\gamma}_{SK}) \geqslant R\right\}, \qquad (2)$$

where $\hat{\gamma}_{SK}$ is the Signal-to-Noise Ratio (SNR) of source-relay channel, and R stands for an end-to-end target data rate for the dual-hop relaying. Note that the required rate for each hop doubles to $2R$ owing to the half-duplex mode.

In the ORS scheme, the relay having the strongest SNR (interchangeable with CSI if the given transmit power for each relay is equal) in the relay-destination channels is selected from the decoding subset to serve as the best relay, i.e.,

$$\dot{k} = \arg\max_{k\in DS} \gamma_{kd}, \qquad (3)$$



▲**Figure 2. Schematic diagrams of ORS, GSC and OSTC.**

where γ_{kd} denotes the instantaneous SNR of relay-destination channel at the instant of selecting relay, which may be outdated in comparison with the actual SNR $\hat{\gamma}_{kd}$ at the instant of using the selected relay to retransmit.

Instead of only a single relay, the GSC scheme selects N relays with the largest SNRs to retransmit the original signal in the second phase. In the relaying phase, as shown in Fig. 2, the time resource is divided into N sub-slots. Following the time-division multiplexing, each selected relay occupies one different slot to orthogonally retransmit the original signal. Equivalently, the frequency-division multiplexing can be applied to orthogonally retransmit the signal over relay-destination links, i.e., N subcarriers or sub-channels are used by N selected relays at the same time. Its enhanced version, the N+NT-ORS scheme, introduces a normalized threshold to further select qualified relays from the remaining $K-N$ relays. Although the number of selected relays may be different, the N+NT-ORS scheme still relays the signal in an orthogonal manner. These two schemes require at least N orthogonal channels to retransmit, resulting in a large loss of spectral efficiency.

In the DSTC scheme, no relay selection process is performed, but all relays within the current decoding subset are used to simultaneously retransmit by means of space-time coding. In this case, the number of participating relays is unknown and randomly varying since the decoding subset dynamically changes with the fluctuation of radio channels. Neither selecting a single relay in ORS nor all-participating in DSTC, the OSTC scheme chooses a predefined number N of relays. In the relaying phase, an N-dimensional orthogonal space-time block code is applied to encode the regenerated signals at the selected relays in a distributed manner. N branches 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. If the number of relays in the current decoding subset is denoted by L, we have $0 \leqslant L \leqslant K$. It is possible that $L < N$. In this case, all of L relays participate in the signal retransmission directly in combination with an L-dimensional orthogonal space-time block code.

For illustration purposes, we select N=2 and use the Alamouti scheme to clarify the OSTC scheme. In the broadcast phase, as illustrated in Fig. 2, the source sends a pair of symbols (x_1,x_2) to all relays within two consecutive symbol periods. Those relays that correctly decode the original signal constitute a decoding subset. In accordance to instantaneous SNRs of the relay-destination channels, a pair of best relays are opportunistically selected. In the relaying phase, the regenerated symbols are space-time encoded as:

$$(x_1,x_2) \rightarrow \begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{pmatrix}, \tag{4}$$

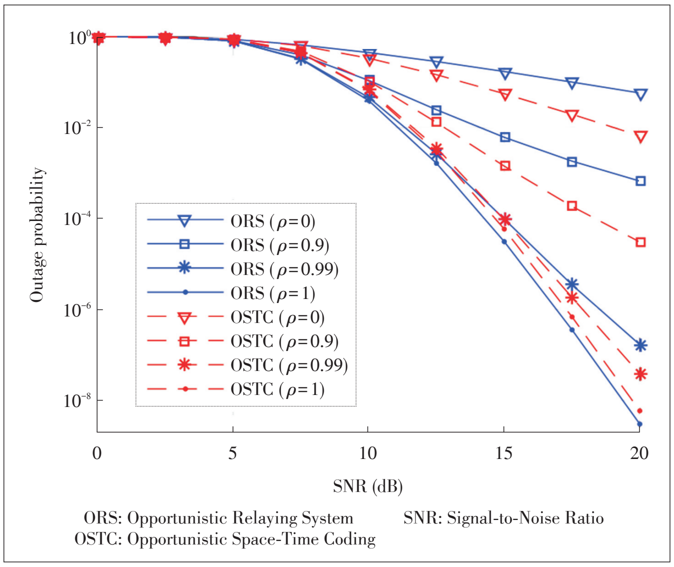
where the superscript * denotes the complex conjugate. Then, a relay transmits the first branch of coded symbols $(x_1,-x_2^*)$, while another relay sends (x_2,x_1^*) simultaneously at the same frequency, analogous to the Alamouti scheme applying for two co-located antennas in the MIMO system.

4 Performance Comparisons

The Monte-Carlo simulations are setup in order to comparatively get the performance results in terms of outage probability and ergodic capacity. Given i.i.d. Rayleigh channels with a normalized gain, performance comparisons of ORS, GSC and OSTC in the absence and presence of imperfect channel quality are carried out. The numerical results are obtained by iterating 10^6 channel realizations into Monte-Carlo simulations, and the target rate is set to R=1 bps/Hz.

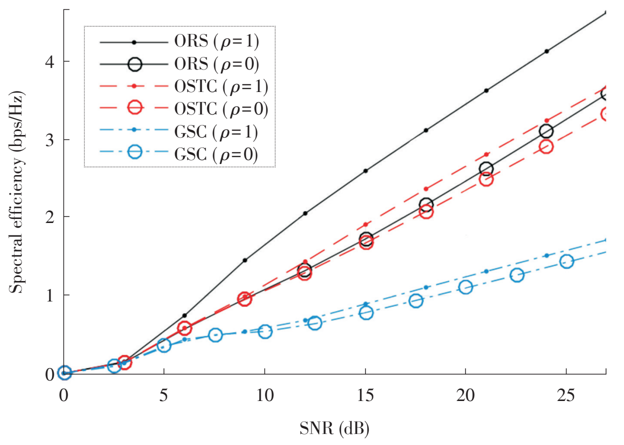
We first investigate the impact of the outdated CSI on a cooperative network with K=9 decode-and-forward relays. A single relay is selected for ORS, whereas N=2 relays are selected for OSTC in combination with the Alamouti scheme. During the simulation, it can be observed that GSC and OSTC achieve the same outage probability in any value of ρ. It is also theoretically proved in the literature that GSC and OSTC have the same performance in terms of outage probability. Hence, only the curves of OSTC is given in **Fig. 3** for simplicity. As shown in the figure, OSTC suffers from a little bit performance loss compared to ORS at the perfect channel quality. This 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. The relay with the second strongest SNR causes this performance gap. In the case of $\rho=1$, the curve of OSTC is in parallel with its counterpart in ORS that has a full diversity. It can be therefore concluded that OSTC also achieves the diversity of $d=9$, namely its outage probability decays at a rate of $1\sqrt{\bar{\gamma}^9}$ in the high SNR. In addition, OSTC´s curves in the cases of $\rho=0$, $\rho=0.9$, and $\rho=0.99$ are also provided. These curves are parallel among others in the high SNR with the diversity of 2, while the curves of ORS have the diversity of 1. That is to say, the diversity of ORS is one in the presence of outdated CSI, whereas an order of 2 is still kept by OSTC thanks to using N=2 selected relays. It can be observed that even in the case of 0.99, the outdated CSI brings an obvious performance degradation compared to the case of perfect CSI. When the correlation coefficient is reduced to 0.9, at the SNR of 20 dB, the outage probability is increased from 10^{-8} to 10^{-3}, which proves that vulnerability of the relay selection.

To shed light on the channel capacity of different schemes in the absence and presence of outdated CSI, their capacities as a function of the average SNR in the cases of $\rho=0$ and $\rho=1$ are shown in **Fig. 4**. The number of cooperating relays is assumed to be K=8 and the number of selected relays for OSTC and GSC is N=4. At the perfect CSI, OSTC suffers from a small capacity loss since the applied 4-dimensional OSTBC supports a maximal rate of only 3/4 in relay-destination link. The capacity loss of GSC is more severe due to the use of 4 orthogonal channels, equivalent to a rate of 1/4 in comparison with that of the ORS scheme. For example, ORS, OSTC and GSC achieve the spectral efficiencies of 4.3 bps/Hz, 3.4 bps/



ORS: Opportunistic Relaying System SNR: Signal-to-Noise Ratio
OSTC: Opportunistic Space-Time Coding

▲Figure 3. Outage probabilities of ORS and OSTC as a function of the average SNR. GSC and OSTC have the same performance in terms of outage probability.



GSC: Generalized Selection Combining
ORS: Opportunistic Relaying System
OSTC: Opportunistic Space-Time Coding
SNR: Signal-to-Noise Ratio

▲**Figure 4. Spectral efficiencies of ORS, GSC and OSTC as a function of the average SNR.**

Hz and 1.6 bps/Hz, respectively, at a given SNR of 25 dB. In the case of $\rho=0$, the spectral efficiency of OSTC closes to that of ORS with a loss of less than 0.2 bps/Hz. That is to say, despite a diversity gain of $d=4$ achieved by OSTC in the presence of outdated CSI, the price on the spectral efficiency loss is negligible. In comparison, GSC's spectral efficiency is around 1.5 bps/Hz at a given SNR of 25 dB, less than a half of ORS and OSTC. On the other hand, ORS is vulnerable to the outdated CSI because its spectral efficiency is reduced from 4.3 bps/Hz to 3.3 bps/Hz when the correlation coefficient is decreased to 0 from 1, equivalent to a loss of 1.0 bps/Hz. In contrast, the spectral efficiency loss is less than 0.3 bps/Hz for OSTC and GSC, implying their effectiveness of combatting the outdated CSI and their robustness feature.

5 Conclusions

The exponential growth of mobile traffic imposed a high pressure on the 5G system, where NR technologies have to be applied to substantially improve transmission performance, especially in the uplink. Taking advantage of D2D links, the cooperative communication can provide a remarkable performance gain in terms of spectral efficiency and reliability by means of collaborating the neighboring terminals. In this paper, we comparatively reviewed several cooperative multi-relay schemes in the presence of imperfect channel state information. The ORS scheme is easy to implement, and can achieve the full diversity, i.e., the number of all cooperating relays, at the perfect CSI. But in the presence of outdated CSI, the outage probability of ORS drastically deteriorates and its diversity degrades to one, i.e., no diversity. The GSC scheme is robust to the outdated CSI, while its capacity loss is large due to the orthogonal transmission. The proposed OSTC scheme opportunistically selects multiple relays, rather than a single relay, to decode and simultaneously retransmit the original signal by means of space-time coding. When the knowledge of CSI is perfect, it can achieve the full diversity. In the presence of outdated CSI, the diversity of N can still be kept. Besides, OSTC has a negligible capacity loss in comparison with that of ORS. Compared to DSTC, a fixed number of relays is used, instead of a random number, which makes sense for the practical systems. From the perspective of both performance and complexity, the OSTC scheme has been considered as the best solution until now.

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