Cooperative Communication and Cognitive Radio (1)

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Editor's Desk:
Cooperative communication and cognitive radio have become hot topics in recent researches of communication networks, attracting a widespread attention. Cooperative communication technique can enhance the transmission capacity of a communication system, while cognitive radio technique can improve the spectrum utilization ratio. As a result, the combination of the two techniques will have significant impact on the future wireless mobile communication system. This lecture comes in four parts. This part introduces the history of cooperative communication as well as several cooperation schemes.

1 Cooperative Communication

In multi-user communication environment, cooperative communication technique enables the neighboring mobile users with single antenna to share their antennas in some way for cooperative transmission, which is similar to a distributed virtual multi-antenna transmission environment and combines the advantages of both diversity technology and relay transmission technology. As a result, the spatial diversity gains can be achieved and the system's transmission performance can be improved in a cooperative communication system without adding any antennas. It can be applicable to such networks as cellular mobile communication systems, wireless Ad hoc networks, Wireless Local Area Networks (WLANs) and wireless sensor networks. Therefore, it is of significant value for research and will be one of hot topics that may have great impact on the development of future wireless communications, following multi-carrier modulation technology and multi-antenna technology. Moreover, being highly flexible, cooperative communication can be integrated with other technologies without sacrificing their respective advantages. For example, it can be integrated with Orthogonal Frequency Division Multiplexing (OFDM) technology, making full use of capability of combating frequency selective fading. It can be combined with coding or space-time coding scheme to obtain coding gain. Integrated with cognitive radio technology, it can improve the spectrum detection probability or get more spectrum access chances. This part discusses the cooperative communication techniques in terms of history, current research and cooperative schemes.

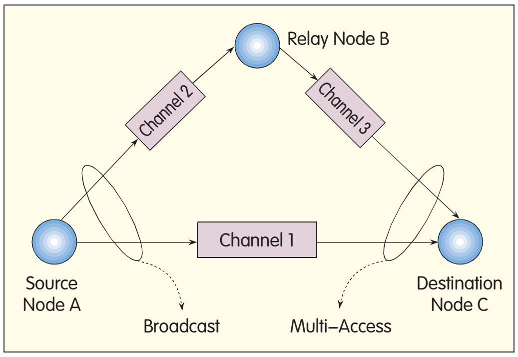
1.1 History and Current Status of Research

The origin of cooperative communication can be traced back to the work of Cover and El Gamal on the relay channel in 1979. Their relay channel model includes a source node, a relay node and a destination node, as shown in Figure 1. This model can be decomposed into a broadcast channel (where the source node A transmits the signals, the relay node B and the destination node C receive the signals) and a multiple access channel (where the source node A transmits the signals, the relay node B retransmits the signals received from node A, and the destination node C receives signals from node A and node B).

Cover and El Gamal' works demonstrates that the capacity of a discrete memoryless Additive White Gaussian Noise (AWGN) relay channel is better than that of the source-destination channel. They develop lower bounds on channel capacity via three structurally different random coding schemes:

• Facilitation, in which the relay does not actively help the source, but rather facilitates the source transmission by inducing as little interference as possible;

• Cooperation, in which the relay fully decodes the source message and retransmits, jointly with the source, a bin



▲Figure 1. Relay channel model.

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index (in the sense of Slepian-Wolf coding) of the previous source message;

- Observation, in which the relay encodes a quantized version of its received signal, using ideas from source coding with side information.

These random coding schemes are the basic methods for relay nodes of various cooperative communication systems to process information.

Cooperative communication originates from the relay channel model but differs significantly from the model in many aspects. First, cooperative communication technology is applied in the fading channel for the purpose of reducing multipath fading, while Cover and El Gamal' relay channel model focuses on analyzing the capacity of AWGN channel. Second, the relay node in the relay model is only used to help the source node send information, while in cooperative communication, the entire system resources are fixed, each user can act as not only a relay node to help the source node but also a source node to transmit its own information. Therefore, they focus on different research fields. Combining the advantages of diversity technology and relay transmission technology, cooperative transmission enables a distributed virtual Multiple-Input Multiple-Output (MIMO) system (in cooperative communication, virtual MIMO refers to a transmission system where several relay nodes naturally form a virtual antenna array, and they simulate conventional MIMO application environment by coordinating and communicating with each other, thus achieving joint space-time coding), overcoming such limitations as coherence distance. Consequently, it can obtain a transmission gain approximating to that of multi-antenna and multi-hop transmission without adding antennas. Meanwhile, the destination node receives the signals not only directly from the source node, but also forwarded by the relay nodes. With sufficient valid information provided, e.g. the radio link status and the signal quality, the destination node can choose a proper method to combine these signals, thus achieving diversity gains and greatly improving data transmission rate.

Since Sendonaris et al. proposed the concept of cooperative communication in 1998, related research has been sparked and is flourishing worldwide.

Internationally, related subjects have been in progress. For example, Wireless World Research Forum (WWRF) has established a vision committee to specially study cooperative networks and has published several white papers. On January 1, 2004, European Union started a project named Wireless World Initiative New Radio (WINNER) under its Sixth Framework Programme (FP6), aiming to develop a ubiquitous wireless system which excels existing systems in terms of performance, efficiency, coverage and flexibility. In this project, relay-based concepts are involved. In addition, many well-known international periodicals and conferences have also opened special issues, technical symposia or workshop for reporting cooperative communication technology, including IEEE Communication Magazine, IEEE International Conference on Communications (ICC), IEEE Wireless Communications and Networking Conference (WCNC), and IEEE Global Telecommunications Conference (GlobleCom). In 2006, the academic journal Springer published a book on cooperative communication which was co-authored by many researchers.

The labs of many universities in the world have started the research, too. For example, the Wireless Communication Group of Communication Technology Lab of Swiss Royal Academy of Science has started the "Cooperative MIMO Wireless Network" project, and European Communication Council has launched the Information Society Technologies-Resource Management and Advanced Transceiver Algorithms for Multihop Networks (IST-ROMANTIK) project. Many professors and researchers also have made distinguished contributions to cooperative communication research, including Dr. J. N. Laneman of Massachusetts Institute of Technology, associate professor E. Erkip of US Polytechnic University, associate professor M. Dohler of King's College of the University of London, Dr. T. E. Hunter from the Media Communication Lag of University of Texas and Dr. M. O. Hasna of University of Minnesota.

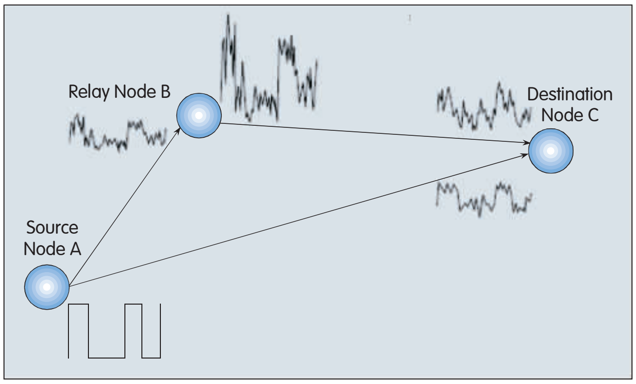
In China, cooperative communication technology has attracted widespread attentions recently. The National Natural Science Foundation of China (NSFC) and the Ministry of Education of China have sponsored many projects. Many Chinese universities also have started their research, including Beijing University of Posts and Telecommunications, Zhejiang University, and Xi Dian University.

1.2 Cooperative Scheme

By cooperative object, cooperative communication is classified into two kinds: cooperation among heterogeneous networks and cooperative communication within homogeneous network.

For historical reasons, many access networks are now coexisting, such as WLAN, Worldwide Interoperability for Microwave Access (WiMAX), cellular network, and satellite communication network. Although these networks have their own advantages and meet the requirements of the users in one or several aspects regarding data transmission rate, coverage area and support for terminal mobility, so far, there is not yet a network that can meet all these requirements. In order to satisfy the demands of various users for different applications, future communication networks must have the capability of integrating existing networks onto one united information platform. The ITU, 3GPP and 3GPP2 from the perspective of telecom network, and IETF from the perspective of IP packet network describe the future communication networks. Despite their differences, these descriptions have one common point that their solutions are IP-based and adopt cooperation for different access networks so as to provide users with diversified circuit and packet switching services. Therefore, in the future telecom network development, one inevitable trend is to implement cooperation among different access networks, i.e. cooperation among heterogeneous networks. Obviously, the focus of cooperation is mobility management among heterogeneous networks, mainly including inter-network handover and roaming.

Cooperative communication within homogeneous network means all nodes work in the same kind of network. It can



▲Figure 2. AF scheme.

be realized with two cooperation schemes: fixed relaying and user cooperation. The fixed relaying scheme is very similar to the relay channel model shown in Figure 1. In this scheme, a fixed relay node is placed between the source node and the destination node in advance and it is wirelessly connected with the source node and the destination node. This relay node does not have any information to transmit, but forwards the information it receives. Unlike fixed relaying, user cooperation is more flexible. The source nodes can act as relay nodes to forward the information of cooperative partners in addition to sending their own information. As a result, these terminals should have such functions as signal forwarding and simple routing. By the ways the relay node processes the source node's information, user cooperation can be further divided into the following schemes: Amplify-and-Forward (AF), Decode-and-Forward (DF), Coded Cooperation (CC), Space-Time Coded Cooperation (STCC) and Network Coded Cooperation (NCC). In the following sections, we will discuss the basic principles of these schemes and compare them roughly. To simplify our description, we only discuss the case with single relay node here. The cases with multiple relay nodes are similar.

1.2.1 AF

AF scheme was first proposed by Laneman et al, as shown in Figure 2.

As shown in Figure 2, signal processing in AF scheme can be simplified into three phases: In Phase 1, the source node transmits the signals by way of broadcasting, while the destination node and the relay node receive the signals. In Phase 2, the relay node amplifies the powers of the signals received from the source node and forwards them to the destination node. In Phase 3, the destination node combines and decodes the signals received from the source node in Phase 1 and the relay node in Phase 2 so as to restore the original information. AF is also called non-regenerative relaying scheme and it is basically a processing method for analog signals. Compared with other schemes, AF is the simplest. Besides, as the destination node can receive independent fading signals from the source and relay nodes, full diversity gain and good performance can be achieved with this scheme. However, AF scheme is prone to noise propagation effect because the relay node amplifies the noise on the source-relay channel when the retransmitted signals are amplified.

1.2.2 DF

DF scheme was first presented by Sendonaris et al. Similarly to AF, signal processing in DF scheme can also be simplified into three phrases, as shown in Figure 3.

In Phase 1 and Phase 3, DF scheme processes the signals the same way as AF. In Phase 2, the relay node decodes and detects the signals received from the source node before it forwards the signals to the destination node. Hence, DF is also called regenerative relaying scheme. Obviously, DF is essentially a digital signal processing scheme. Although noise propagation problem will not take place, the signal processing in DF largely depends on transmission performance of source-relay channel. If Cyclic Redundancy Check (CRC) is not implemented in coding, full diversity orders can not be obtained. Moreover, the errors brought by the relay node during signal demodulation and decoding will accumulate with the increase of hops, thus affecting diversity advantage and relay performance. All these demonstrate that the transmission characteristics of source-relay channel have great impact on the performance of DF communication systems.

AF and DF aforementioned are often called fixed cooperation modes because the relay node always participates in cooperative communication no matter what the channel transmission characteristics are. As a matter of fact, cooperation does not always bring benefits. For example, in a half duplex mode, the data transmission rate and the utilization of the degrees of freedom will decrease. This indicates when to cooperate is a critical issue. To address the problem, selection modes and incremental modes are put forward based on AF and DF, which are listed in Table 1.

Selection modes compare transmission characteristics of the source-relay channel against a predefined threshold. Only when the characteristic value is greater than the threshold, cooperative communication is implemented; otherwise, the source node direct transmission again. Hence, the key in selection modes is the conditions of source-relay channel. In incremental modes, the feedback of the destination

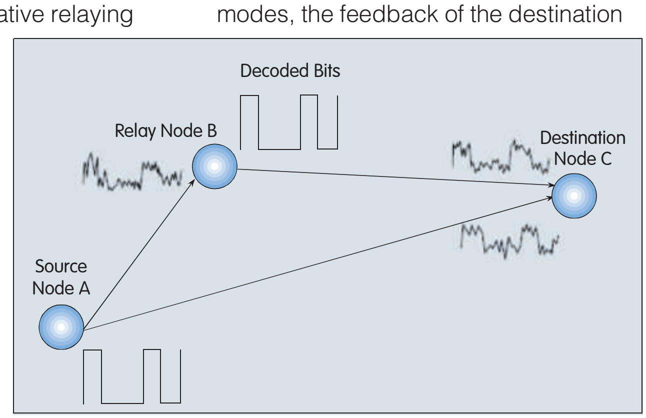


Figure 3.▶ DF scheme.

▼Table 1. Three cooperation modes

Forward Mode	Cooperation Mode		
	Fixed Mode	Selection Mode	Incremental Mode
AF	Fixed AF	Selection AF	Incremental AF
DF	Fixed DF	Selection DF	Incremental DF

AF: Amplify–and–Forward DF: Decode–and–Forward

node is used to determine whether the direct transmission is successful. If the data are correctly detected, source node will send new data; otherwise, the relay node will participate in the cooperative communication process. This process is equivalent to adding redundancy mechanism or automatic detection and retransmission mechanism in the relay transmission. Obviously, the key issue involved in incremental modes is the conditions of source–destination channel. In fixed or selection modes, the relay node has to repeatedly send the information received from the source node, which may lead to decreased usage of the degrees of freedom; while in incremental modes, cooperative communication is used only when it is needed, avoiding repeated transmission, but a feedback channel is required.

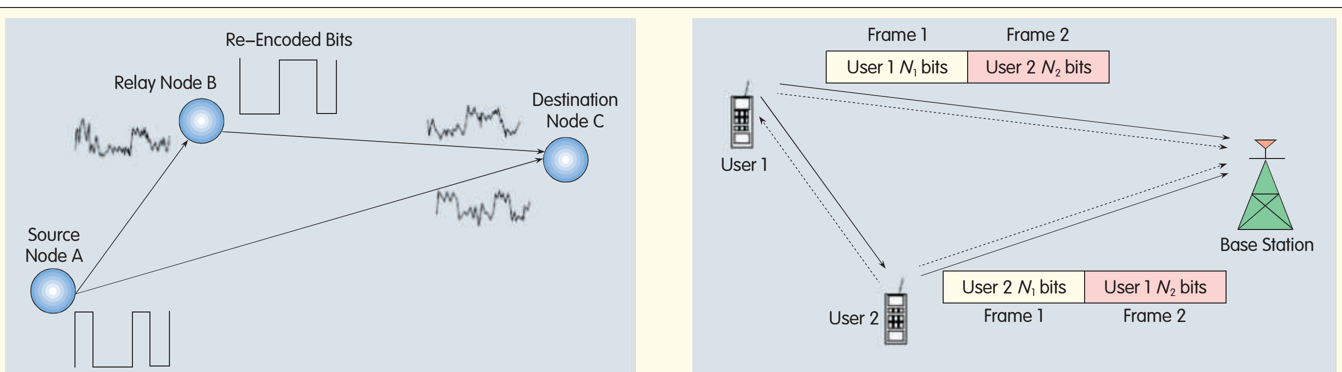
From the perspectives of reliability and effectiveness, Incremental AF (IAF) performs best. In terms of the complexity of algorithm, AF is simplest and can achieve full diversity gain; DF performs poor and cannot obtain full diversity gain; Selection DF (SDF) can achieve full diversity gain but it is more complicated than AF. Analyses show that both Selection AF (SAF) and Incremental DF (IDF) can not achieve good performance: Selective mode pays much attention to the transmission characteristics of the source–relay channel, but in AF, the source–relay channel and the relay–destination channel are of the same importance because the relay node only amplifies, not decodes, the information received from the source node; the incremental mode focuses on the source–destination channel, but in DF scheme, errors will accumulate and broadcast with information forwarding if serious fading takes place on the source–relay channel and lots of errors are resulted from decoding. Therefore, selection mode is more suitable for DF scheme, while incremental mode is more suitable for AF scheme.

1.2.3 CC

In AF and DF, the relay node always repeatedly forwards the information received from the source node, which often leads to decreased usage of the degrees of freedom. To solve the problem, Hunter et al. integrated channel coding into cooperative communication and proposed CC scheme. Signal processing in CC scheme is shown in Figure 4(a).

In CC scheme, different segments of each user's code words can be sent via two different fading paths. Each user correctly decodes the information received from cooperative partners and then re–encodes them before forwarding them. With redundant information bits being repeatedly transmitted through different spaces, the system performance is improved. In CC scheme, each mobile terminal achieves diversity and coding gains by re–encoding and transmitting different redundant bits, thus the system performance is greatly enhanced. Moreover, this scheme does not require information feedback between cooperative nodes. When a relay node cannot correctly decode the information bits, it automatically reverts back to non–cooperative mode, ensuring the system efficiency.

Figure 4(b) gives an example of CC scheme. The mobile terminal first encodes the information bits to be sent by blocks and then adds the CRC codes. During cooperative transmission, the encoded information is divided into two segments, containing the information bit N_1 and the additional punctured bit N_2 (the length of original code word is $N_1 + N_2$ bits) respectively. Apparently, two time slots (i.e. frames) are needed to send N_1 and N_2, respectively. In the first frame, each mobile terminal sends its own N_1 information, and at the same time it tries to decode the information bits transmitted in the first frame of its partner. If the partner is correctly decoded, which is verified with CRC check, the terminal then sends N_2 bits of its partner in the second frame. If the terminal cannot correctly decode the partner's information, it transmits its own N_2 information. In this way, each mobile terminal always sends the information block of N_1+N_2 bits in two time slots.



(a) CC scheme (b) Example of CC scheme

▲Figure 4. CC scheme.

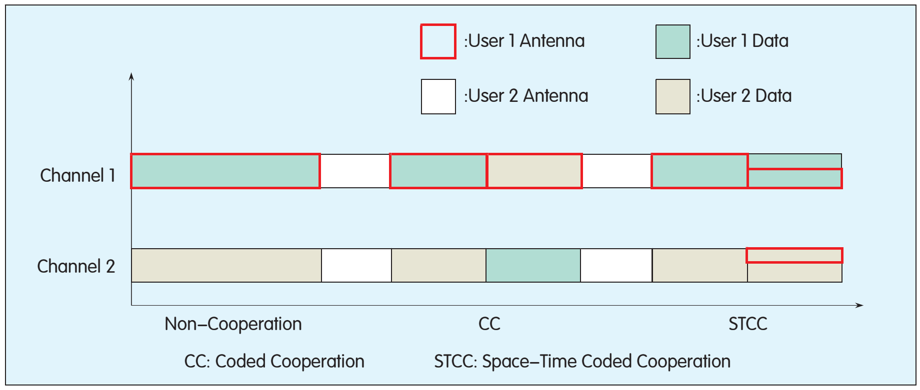
Finally, the destination node decodes the information blocks it receives. Unlike SDF, CC scheme manages to automatically switch between cooperative and non-cooperative modes through code design, regardless of transmission characteristics of the source-relay channel directly.

Currently, there are already many channel coding schemes that are integrated with cooperative communication, for instance, convolutional code, Turbo code, and Low Density Parity Check (LDPC) code. In case of slow fading, the CC scheme can improve the bit error rates of two communication mobile terminals even if the transmission characteristics of the channel between two mobile terminals are very poor. Besides, if the two cooperative partners can correctly decode each other's information, the system can achieve full diversity gain. But in case of fast fading, the CC scheme sacrifices the performance of the terminal whose uplink channel is of good transmission characteristics. To solve this problem, STCC is brought forward.

1.2.4 STCC

STCC is to apply space-time coding into coded cooperation scheme. The main difference between STCC and CC is that STCC allows each mobile terminal to simultaneously send data over multi-access channels of its own and of its cooperative partner; while in CC, each mobile terminal can only send information over its own multi-access channel. Many researchers have successively suggested their own STCC implementation methods but their solutions are almost the same. Figure 5 compares signal processing of STCC, CC and non-cooperation schemes.

In Figure 5, axis-X and axis-Y represent time and frequency, respectively, and Frequency Division Multiple Access (FDMA) method is adopted. In STCC and CC schemes, the time originally taken in non-cooperation scheme is divided into two time slots, i.e. Phase 1 and Phase 2. As shown in Figure 5, STCC and CC work in the same way in Phase 1, and their difference lies in Phase 2. For the sake of description, let's take the example for User 2 to explain the work process of STCC. In



▲Figure 5. Comparison of signal processing in STCC, CC and non-cooperation scheme.

phase 1 of STCC scheme, User 1 and User 2 use Channel 1 and Channel 2 respectively to send their source node information to their cooperative partners and the destination node in a broadcasting way. In phase 2, if User 2 decodes the information sent by User 1 correctly, it sends its partner's (i.e. User 1) information and its own information over Channel 1 and Channel 2 respectively to the destination node; otherwise, it uses both channels to send its own information. Comparatively, if the information of the cooperative partner is successfully decoded in Phase 2, each user only sends the decoded information over its own channel in CC scheme, but in STCC scheme, each user sends its own information as well as the information of its partner. Studies show that STCC scheme can achieve full diversity gain even in a fast fading environment without sacrificing the performance of the mobile terminal with better channel quality.

Currently, many space-time cooperation schemes have been developed by integrating different space-time coding with cooperative communication technology, including Space Time Block Coding (STBC) and Space Time Trellis Coding (STTC). Among them, STBC has attracted special attentions due to its simple design.

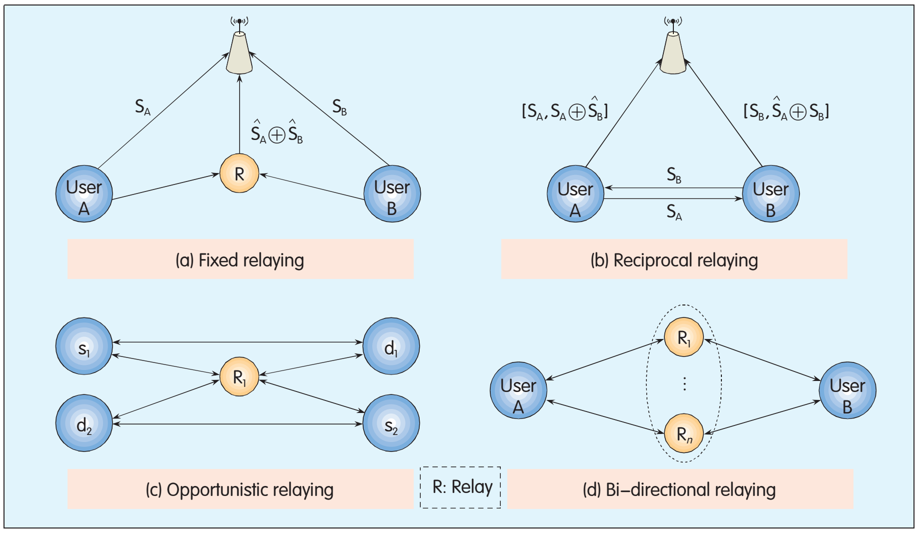
1.2.5 NCC

NCC is formed by incorporating network coding into CC scheme.

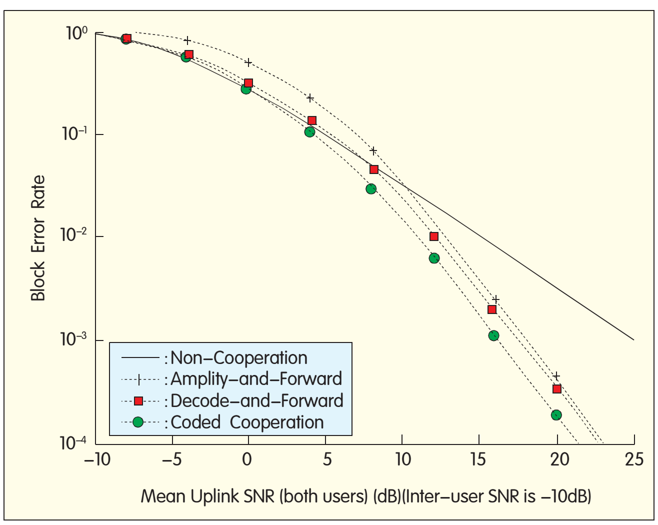
Network coding is a multi-cast technology. The core idea of network coding is that an intermediate node no longer performs simple store-and-forward function but encodes and forwards the received information, thus improving the capacity and robustness of the whole network. The network coding concept was originally used for wired networks, so is most of current related work. But the broadcast characteristics of radio channels are suitable for application of network coding in wireless networks, and the information interaction between wireless nodes can be fully achieved via network coding. As a result, the combination of network coding and cooperative communication can effectively improve the performance of wireless communication systems.

Current NCC research focuses on the relay node's network coding schemes and basic communication methods. By the network coding schemes used by the relay node, NCC can be divided into two categories: linear and non-linear; by basic communication methods adopted, NCC can be divided into fixed relaying, opportunistic relaying, reciprocal relaying, and bi-directional relaying. The signal processing in NCC are illustrated in Figure 6.

Figure 6(a) illustrates the fixed relaying scheme, where R acts as a fixed relay node of User A and User B. The relay node itself has no data to transmit but performs network coding on the data it receives from User A and User B. Figure 6(b) shows reciprocal relaying scheme, which is also called user cooperation mode. In this scheme, User A and User B act as cooperative partners of each other. Hence, in addition to transmitting their own data, they perform network coding on their own data and their partner's data. Figure 6(c) illustrates opportunistic relaying, where s_1 sends data to d_1, and s_2 sends data to d_2. The relay node R_1 does not participate in



▲Figure 6. NCC scheme.



◀Figure 7. BER performances of different cooperation schemes.

relay transmission only when an error occurs in the direct s_1–d_1 or s_2–d_2 transmission link. During its participation, R_1 performs network coding. Figure 6(d) is bi-directional relaying, where User A and User B communicate with each other and there are many relay nodes between them. The relay nodes perform network coding on the data exchanged between User A and User B to improve the system throughput.

Figure 7 compares the Block Error Rate (BER) of several cooperative schemes. For the sake of comparison, the case of no cooperative is also illustrated. It can be easily seen from Figure 7 that the BER performances of cooperative communication systems are better than that of non-cooperative system. Among the above-discussed cooperative schemes, performance of CC, NCC and STCC are often better than that of AF and DF, but they involve complicated algorithms as well as diverse coding technologies. As a result, the signal processing time and delay at the relay node is increasing, which is not good for the development of modern wireless communication systems. Therefore, with all factors being considered, AF and DF are regarded more practical than the other schemes.

(To be continued)

Biographies

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Luo Tao, PhD, is an associate professor at Beijing University of Posts and Telecommunications (BUPT). His research interests include cognitive radio, cooperative communications, MIMO, OFDM, and high-speed wireless network architecture. He has participated in several "863" Program of China and National Natural Science Foundation of China projects and has published more than 30 papers.

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