Cooperative Communication and Cognitive Radio (3)

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Editor's Desk:
Cooperative communication and cognitive radio have become hot topics in recent research 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 a significant impact on the future wireless mobile communication system. This lecture comes in four parts. This part introduces the Cognitive Radio (CR)-related international standards, and three models combined of CR technology and cooperative communication technology.

2.5 CR-Related International Standards

Driven by some spectrum regulatory authorities, some standardization organizations, for instance IEEE and ITU, have admitted CR technology and have established a series of standards. The CR-related standards developed by IEEE are discussed in this chapter.

(1) IEEE 802.22

IEEE 802.22 is the first standard to fully incorporate the concept of CR as well as the first CR-related air interface standard. It has played an important role in evolution and development of CR technology. IEEE 802.22, also called standard for Wireless Regional Area Networks (WRANs), uses available Ultra High Frequency (UHF)/Very High Frequency (VHF) TV bands between 54 and 862 MHz (scalable to 41-910 MHz). It focuses on how to make effective use of these bands for wireless communications without interfering with existing TV bands and to develop a standard for physical/MAC layer air interface. To be compatible with various TV standards, its channel bandwidths include 6 MHz, 7 MHz and 8 MHz.

IEEE 802.22 system defines an air interface for fixed point-to-multipoint topology, which must consist of a Base Station (BS) and at least a RU. In addition to traditional BS functions, the BS in IEEE 802.22 system must have distributed cognition capability, guiding Customer Premises Equipment (CPE) to perform a distributed measurement of signals on different channels. Then, based on received feedback information and cognized information, the BS decides its next step, for instance, changing transmit frequency or transmit power, to avoid interference with licensed services in TV bands. Among IEEE 802 standards, IEEE 802.22, which is developed specifically for WRANs, has the largest coverage area because TV bands less than 900 MHz are of good propagation characteristics. If the BS's power is unlimited, its coverage can reach 100 km. Even with Effective Isotropic Radiated Power (EIRP) of 4 W, which is specified in the standard, the coverage range can reach 33 km. The spectral efficiency of 802.22 systems ranges from 0.5 to 5 bit/s/Hz. At an average value of 3 bit/s/Hz, the capacity of a 6 MHz channel can reach 18 Mbit/s.

In IEEE 802.22 standard, Orthogonal Frequency Division Multiple (OFDM) technology is adopted for both uplink and downlink at the physical layer. Taking into account the propagation delay latency of about 25-50 μs, the number of subcarriers is 2,048 and the length of cyclic prefixes is about 40 μs. OFDM Access (OFDMA) technology can easily realize subcarrier assignment and integrate spectrum holes that are not successive physically, enabling CR to efficiently utilize the spectrums. Combined with Adaptive Coded Modulation (ACM) technology, OFDM system can dynamically adjust its bandwidth and modulation scheme based on actual channel situations. As a result, it can meet different users' QoS requirements and offer flexible services. With such modulation technologies as Quadrature Phase Shift Keying (QPSK), 16-order Quadrature Amplitude Modulation (QAM) and 64QAM with convolutional code rates of 1/2, 3/4 and 2/3, the system can provide a wide range of rates: from several Kb/s of a subcarrier to 19 Mb/s of a TV channel. Initial link budget shows that one TV channel cannot meet data transmission requirements of IEEE 802.22 system. To solve the problem, channel combination solutions are proposed, where several TV channels are bound together. There are two kinds of channel combination: adjacent channel combination and

This work was supported by the National Natural Science Foundation of China under Grant No. 60872049, the National High-Tech Research and Development Plan of China ("863" Program) under Grant No. 2007AA10Z235, and the Teaching and Research Finances for the Returned Overseas Chinese Scholars.

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▼Table 2. IEEE 802.22 system parameters

Parameter	Specification
Channel Bandwidth (MHz)	6/7/8
Average Spectral Efficiency (b/s/Hz)	3 (0.5–5)
Average Channel Capacity (Mb/s)	18/21/24
Multiple Access	OFDMA
Duplex	TDD
WRAN BS's EIRP (W)	4
WRAN System's Coverage Radius (km)	33

EIRP: Effective Isotropic Radiated Power
OFDM: Orthogonal Frequency Division Multiplexing
WRAN: Wireless Regional Area Network
TDD: Time Division Duplex

non-adjacent channel combination, which are called channel bonding and channel aggregation respectively. Existing channel bonding schemes adopt fixed subcarrier spacing. That is to say, when two TV channels are bonded, the OFDMA system is configured with 2 × 2,048 subcarriers; while if three TV channels are bonded, 3 × 2,048 subcarriers are configured.

The system parameters and physical layer parameters of IEEE 802.22 standard are listed in Table 2 and Table 3 respectively.

(2) IEEE 802.16h

In December 2004, IEEE 802.16h Working Group was set up to improve coexistence mechanisms for license-exempt operation. The main idea of IEEE 802.16h standard is to use intelligent technology to let several systems share resources, thus enabling coexistence among license-exempt systems based on IEEE 802.16 to satisfy QoS requirements of IEEE 802.16 standard.

(3) IEEE SCC41/IEEE P1900

In 2005, IEEE P1900 Working Group was formed, focusing on Electromagnetic Compatibility (EMC) research related to the technologies and techniques for next generation radio and advanced spectrum management technologies. The working group has played a significant role in CR technology's development as well as coordination and coexistence with other wireless communication systems. This working group was further divided into four groups: IEEE 1900.1, IEEE 1900.2, IEEE 1900.3, and IEEE 1900.4. In 2007, IEEE P1900 working group was renamed as IEEE SCC41/DySPAN (IEEE Standards Coordinating Committee/Dynamic Spectrum Access Networks) working group, mainly dedicated to the research of advanced spectrum management technologies for next generation broadband wireless communication systems and commercial application of such technologies as CR and dynamic spectrum access. IEEE SCC41 expands its working groups into 6, namely 1900.1–6. IEEE 1900.1, 1900.2, 1900.3, 1900.4, 1900.5, 1900.6 Working Group focus on Terminology and Concepts for Next Generation Radio Systems and Spectrum Management, on Recommended Practice for Interference and Coexistence Analysis, on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules, on Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks, on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications, and on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems, respectively.

(4) IEEE 802.11h

IEEE 802.11h standard was originally designed to comply with European regulations on spectrum management and Transmit Power Control (TPC) protocol for 5 GHz band. In Europe, there are other devices (e.g. radar) operating in the 5 GHz band that is used in European High Performance Radio LAN (HIPERLAN) and IEEE 802.11a standards, and it is difficult to prevent WLAN from interference with such devices. To enable IEEE 802.11a radio system to detect the signals of these devices (e.g. radar) and avoid their interference, IEEE 802.11 Working Group developed and released IEEE 802.11h standard as an extension to IEEE802.11 MAC and physical layer specifications. Already applied in many countries, IEEE 802.11h modifies IEEE 802.11a physical layer standard, enhances network management, dynamical spectrum management and TPC of 5 GHz band, and improves such mechanisms as channel energy detection and report mechanism, channel coverage, Dynamic Frequency Selection (DFS) and TPC mechanisms in several regulatory domains.

(5) IEEE 802.11y

In July 2005, FCC opened 3.65–3.7 GHz band for public use, which was originally reserved for fixed satellite service networks. Developed for this band, IEEE 802.11y standard specifies the mechanism of WLAN communications in this band for the purpose of avoiding interference with other communication users. It defines such contents as transmission initialization process, channel status detection method and retransmission mechanism when a channel is found busy, and adopts several bandwidths and OFDM technology. With subcarrier assignment function of OFDM, IEEE 802.11y can achieve quick adjustment and flexible switch among several bandwidths, thus allowing CRs to avoid using LUs' working bands, reducing the interference with LUs and improving the system's robustness and flexibility.

3 Cooperative Cognitive Models and Their Effects on Wireless Communication Systems

As we all know, the two bottlenecks that hinder the development of wireless

▼Table 3. OFDM physical layer parameters of IEEE 802.22 standard

Channel Bandwidth (MHz)	Subcarrier Spacing (Hz)	FFT Period (μs)	Total Number of Subcarriers /Protection Interval	Number of Carriers (Data + Pilot)	Signal Bandwidth (MHz)
6	3,348	298.666	2,048/320	1,536+192	5.785
7	3,906	256.00	2,048/320	1,536+192	6.750
8	4,464	224.00	2,048/320	1,536+192	7.714

FFT: Fast Fourier Transform

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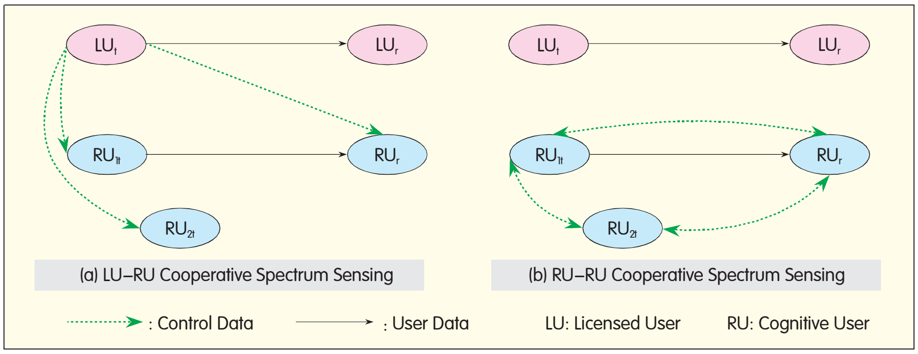
mobile communication systems are radio channel fading and limited spectrum resources. Although CR and cooperative communication technologies have made great progress: Cooperative communication technology can increase the system's anti-fading capability, and CR technology can improve spectral efficiency; neither of them can solve both the above two bottlenecks simultaneously. First, cooperative communication technology can improve channel capacity, but it does not help in making full use of spectrums. Second, in traditional CR system, RUs use idle channels of LUs for communication, which, from the perspective of information theory, is just time division multiplexing of spectrums among different users and does not increase channel capacity. In other words, transmission performance of each user is not improved. Hence, it is natural to consider the combination of CR and cooperative communication technologies in order to take their respective advantages. Essentially, the CR system can be regarded as a cooperative system between LUs and RUs: RUs use idle channels of LUs. In fact, the combination of CR and cooperative communication technologies has become a hot topic in recent research, and it may be a solution for improving the system's anti-fading performance, channel capacity, spectrum utilization and efficiency.

3.1 Cooperative Cognitive Models

Currently, researchers have started the analysis of integrating cooperative communication and CR technologies, and have made certain achievements. As most of existing CR systems are constructed on the basis of MCM technology, which associates multiple users' access with subcarrier allocation and adopts DFT for implementation, the cooperative cognitive model should take into account MCM and MIMO technologies. At present, three kinds of MCM-based cooperative cognitive models have been worked out of the existing combination models (e.g. Ghasemi and Devroye): Cooperative spectrum sensing model, cooperative communication model and hybrid model. In these models, the access of RUs is associated with subcarrier allocation, so they can be easily implemented. Moreover, RUs and LUs can not only contend for spectrums in time division multiplexing way and communicate independently to improve spectral efficiency, but also they can cooperate with each other to improve spectral efficiency and transmission performance by using cooperative communication technology. By participants, cooperation in CR systems can be divided into RU-RU cooperation and LU-RU cooperation; by implementation methods, it can be divided into cooperative spectrum sensing and cooperative communication.



▲Figure 10. Cooperative spectrum sensing model.

3.1.1 Cooperative Spectrum Sensing Model

Figure 10 illustrates two cooperative spectrum sensing models. Due to fading effect and noise interference, a RU may miss or falsely detect spectrums, leading to serious interference with LUs or low spectral efficiency. To solve this problem, two schemes are proposed. The first one is illustrated in Figure 10 (a), where LUs tell RUs about spectrum occupancy by ways of broadcast or via wired connection. This scheme can avoid interference between LUs and RUs and is simple to implement, however, it requires LUs' approval and a dedicated LU-RU control channel has to be added. In the second scheme shown in Figure 10 (b), when RU$_{1t}$ can correctly sense idle spectrums but RU$_{2t}$ cannot for some reasons (e.g. fading, or long distance from LU), RU$_{1t}$ and RU$_{2t}$ can cooperate with each other to increase RU$_{2t}$'s spectrum sensing probability. Such cooperation includes exchange of spectrum sensing information and data fusion decision.

3.1.2 Cooperative Communication Model

As to cooperative communication model (shown in Figure 11), where the prerequisite is that a RU has accurately sensed idle spectrum holes, there are also two schemes. Scheme 1 in Figure 11 (a) is based on interference channel sensing. In this scheme, the LU is the source and one or several RUs act as relays of the LU to assist its message forwarding. The scheme is designed to accelerate the transmission of LU's data and shorten LU's spectrum occupancy time, thus enabling RUs to get more spectrum access chances in terms of time domain. In scheme 2 in Figure 11 (b), RUs act as each other's relays, and they can be half duplex or full duplex. In case of half duplex mode, Time Division Multiple Access (TDMA) is often adopted, and the relay (e.g. RU$_{2t}$) has not any message to transmit but forwards the messages of the source (e.g. RU$_{1t}$). In case of full duplex mode, CDMA is often applied, where each RU, being a relay of other RUs, sends its own information as well as forwards the source node's messages.

3.1.3 Hybrid Model

Figure 12 is a hybrid model, which approximates actual situations the most. This model first senses the spectrum and then implements cooperative communication. Besides, different cooperative users can be selected in different phases.

In sum, with cooperative diversity being introduced, CR systems are expanded from two dimensions (i.e. time and frequency) to three dimensions (i.e. space, time and frequency); hence, they

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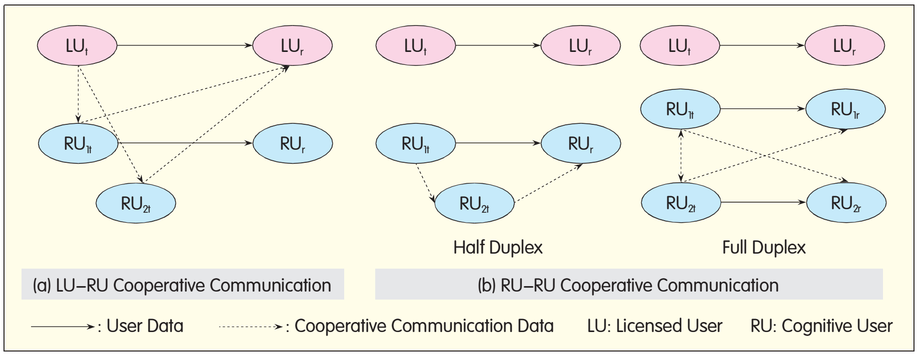
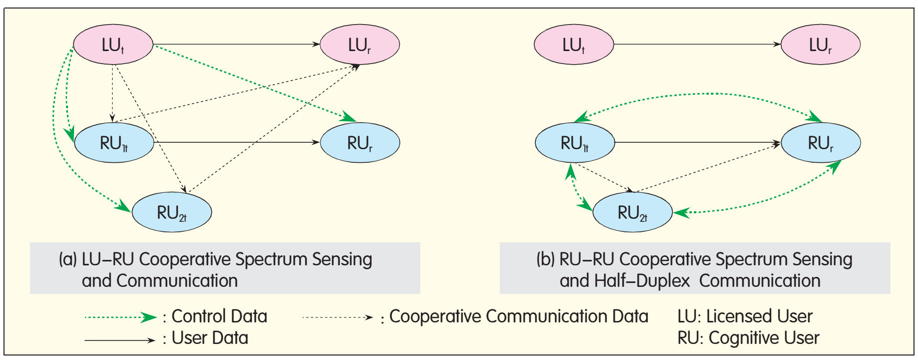
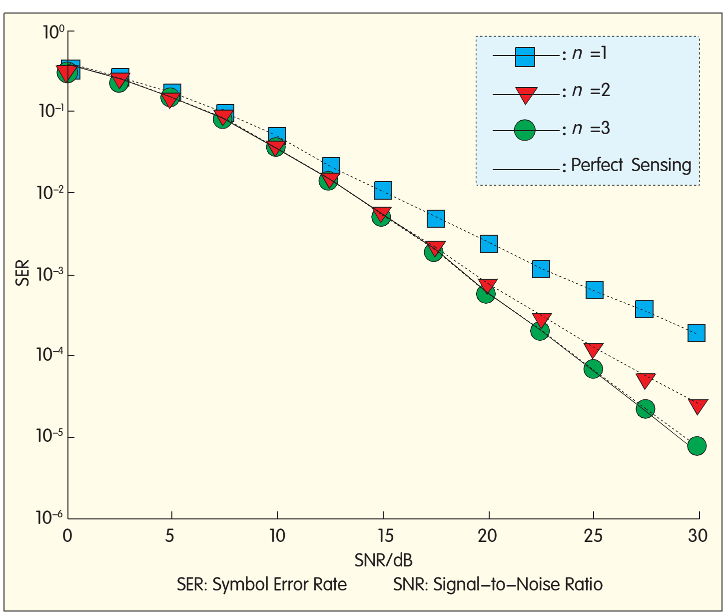


▲Figure 11. Cooperative communication model.



▲Figure 12.Hybrid cooperative cognitive model.



▲Figure 13. Performance of a cooperative cognitive model.

can make full use of various resources and improve system performance.

Currently, the following two aspects are studied with respect to the above cooperative cognitive models:

- Cognitive radio system based cooperative communication: It introduces the concept of multi–user cooperative diversity into cognitive system, and the research focuses on effect and contribution of cooperative communication technology to CR system performance.
- Cognitive relay system: It introduces spectrum sensing technology into cooperative communication system, allowing each relay or cooperative user to have spectrum sensing capability, and the research focuses on effect and contribution of spectrum sensing technology to cooperative communication system performance.

Figure 13 gives Symbol Error Rate (SER) vs SNR results by simulating the hybrid model shown in Figure 12 (b) over the Rayleish fading environment. In the simulation, it is assumed that the probability of spectrum sensing for all RUs is the same, i.e., 0.9, and equal power allocation algorithm is used in cooperative communications. It is further assumed that there are all n RUs in the simulated system, but only one of them is randomly selected as the cooperative partner for cooperative communication. The performance curve of perfect spectrum sensing is also illustrated in Figure 13 for comparison. It can be easily seen from Figure 13 that the performance of the hybrid model with n =3 approximates to that of perfect spectrum sensing. When SER is 10^{-3}, the hybrid model with n = 3 can produce about 4 dB gain compared with its non–cooperation case (i.e., n = 1).

(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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