Cooperative Communication and Cognitive Radio (2)

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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 key technologies for cooperative communications, and the basic concept and key technologies of Cognitive Radio (CR).

1.3 Key Technologies

Although a number of achievements have been made in the research of cooperative communication technology, there are still many issues to be addressed. Current researches on cooperative communication focus on the following aspects:

(1) Radio Resource Management

This mainly involves power allocation, partner selection and other issues. Early research on cooperative communication assumes that the power is evenly allocated between source and relay nodes. This assumption facilitates the research but obviously is not the optimal. Power allocation has always been a research hotspot in recent years. The power allocation schemes proposed in most references are centralized and do not match actual situations, so it is necessary to develop a distributed power allocation scheme. In a multi-user environment, selecting or assigning the best partners for each terminal is also very important because it has direct influence on system performance. As to partner selection algorithms, some issues need further study, for example, there may be some difference if "when to cooperation" is taken into account, and how they instantly adjust the cooperative partners when the locations of mobile terminals change.

(2) Mobility of Relay Node

In existing cooperative communication systems, relay nodes are often terminals with certain mobility, e.g. handsets in cellular networks, so the assumption that relay nodes are immobile does not conform to actual situations. However, few references discuss the mobility of relay nodes. On the other hand, the mobility of relay nodes has definite impact on many critical issues as partner selection. Therefore, an important research subject in cooperative communication is selecting a proper mobility model and considering the impact of mobility on system performance.

(3) When to Cooperation

Most of existing references are only focused on the benefits brought by cooperative communication, and few of them pay attention to the necessity of cooperative communications. It seems that cooperative communication technology is beneficial in any scenario. In fact, to improve resource utilization without decreasing system transmission performance, it is required to consider the transmission characteristics of source-relay, relay-destination and source-destination channels and select a proper time to cooperative.

(4) Synchronization and Channel Estimation Algorithm

Almost all researches assume that the system can implement precise synchronization and obtain accurate channel status information. In other words, the researches assume any two of source node, relay node and destination node are synchronous, which is actually hard to implement in practical scenarios. For distributed cooperative communication systems, accurate synchronization among several users and channel estimation are more difficult. As a result, research on synchronization and channel estimation algorithms is quite significant for developing a practical cooperative communication system.

(5) Combination with Other Communication Technologies

The above sections have briefly discussed the combination of cooperative communication technology with coding and space-time coding technologies. Currently, a hot topic is the combination of cooperative communication technology with OFDM, which aims at exploiting the advantages of both cooperative communication 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.

OFDM so as to obtain diversity gains as well as to combat frequency selective fading. Another hot topic is the combination of cooperative communication with Cognitive Radio (CR). Although these researches are just at the start stage, they offer new approaches for development and application of cooperative communication technology.

2 Cognitive Radio

With rapid development of wireless communication technologies, particularly those of WLAN, Wireless Personal Area Network (WPAN) and Wireless Metropolitan Area Network (WMAN), radio spectrums become increasingly scarce. Characterized by low transmission loss, long transmission distance and large coverage, the bands under 3GHz are extremely scarce. Radio spectrum resources have become a bottleneck that restrains the development of future wireless communication systems. But meanwhile, in existing wireless communication systems where the fixed spectrum allocation scheme is adopted, the allocated spectrums are far from full use, and most of them are more or less left unused in time or space. A survey conducted by the American Federal Communications Commission (FCC) at the end of 2003 showed that the utilizations of allocated spectrums ranged from 15 to 85%; some bands (e.g. the bands assigned to mobile networks) were overloaded, but a large number of bands, such as amateur radio, were not exploited. CR technology is introduced to solve the problem of low spectrum utilization in a fixed allocation scheme. With this technology, the user can be aware of the environment in a real–time way and make full use of the spectrum resources which are idle in either time or space, so the scarcity of spectrum resource is expected to be solved. This part discusses CR technology in terms of history, current research, basic concept, main functions, key technologies, and related standards.

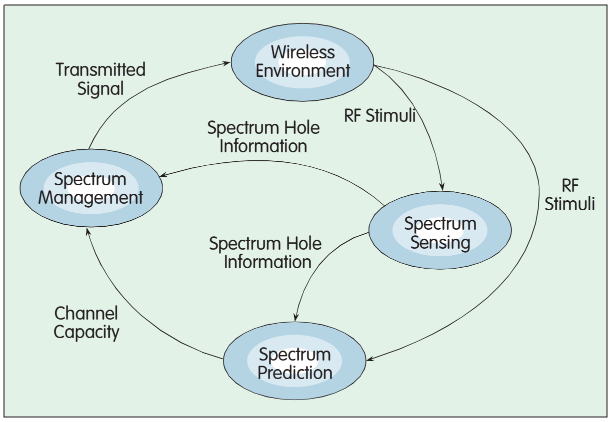
2.1 History and Current Research

The concept of CR was first proposed by Dr. Joseph Mitola in 1999. As challenges existing in fixed spectrum allocation scheme, CR has been attracted widespread attention since its introduction and has been successively supported from the spectrum regulatory bodies in many countries, such as FCC. In December 2002, FCC pointed out that unlicensed devices should have the capability of identifying idle bands. In November 2003, FCC proposed a new performance index, i.e. interference temperature, for quantifying and managing interference to expand unlicensed operations into mobile and satellite bands. In December 2003, FCC set up CR working group, clearly expressing its support for CR and amending the Telecommunications Act of the US. In May 2004, FCC proposed to allow unlicensed radio systems to operate in TV broadcast bands.

CR technology has also aroused concern from the academic society and the communications industry. Many famous researchers and research institutes have invested in the CR research or started CR–related projects, including Spectrum Pooling system proposed by Professor Timo A Weiss et al from Karlsruhe University (Germany), OFDM–based Cognitive Radio (OCRA) system suggested by professor Ian F Akyildiz et al from the Georgia Institute of Technology of USA, CORVUS and Nautilus systems of University of California, CR system of Virginia Polytechnic Institute, Cosine Modulated Multitone (CMT) CR system developed by Peiman et al, Filtered MultiTone (FMT) CR system proposed by W Xiang et al, Next Generation (XG) program sponsored by Defense Advanced Research Products Agency (DARPA) of the United States Department of Defense and End–to–end Reconfigurability (E2R) project of European Union. Driven by these CR projects, it has made certain achievements in the respect of basic theory, key technology and coexistence with existing networks. To timely share research achievements, IEEE specially sponsored two important international conferences on Cognitive Radio Oriented Wireless Networks and Communications, and on Dynamic Spectrum Access Networks respectively, namely CrownCom and DySPAN, respectively. Moreover, many leading international academic journals have also published special issue on CR. In China, the National Natural Science Foundation of China (NSFC) and the Ministry of Science and Technology have successively approved and invested in several CR–related foundation projects and "863" projects in recent years, respectively; some universities have also started their CR research.

2.2 Basic Concept

In his dissertation, Dr. Mitola introduced the term CR and described it as follows: it identifies the point at which wireless Personal Digital Assistants (PDAs) and the related networks are sufficiently computationally intelligent regarding radio resources and related computer–to–computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs. He also depicted a cognition cycle model for application layer based on communication environment detection. Figure 8 illustrates a basic cognition cycle model, which focuses on spectrum processing. After Mitola, many organizations and scholars have given definitions of CR from different perspectives. Among them, the typical ones are definitions made by FCC and Simon Haykin. FCC defines CR as "a radio that can change its transmitter parameters based on the environment in



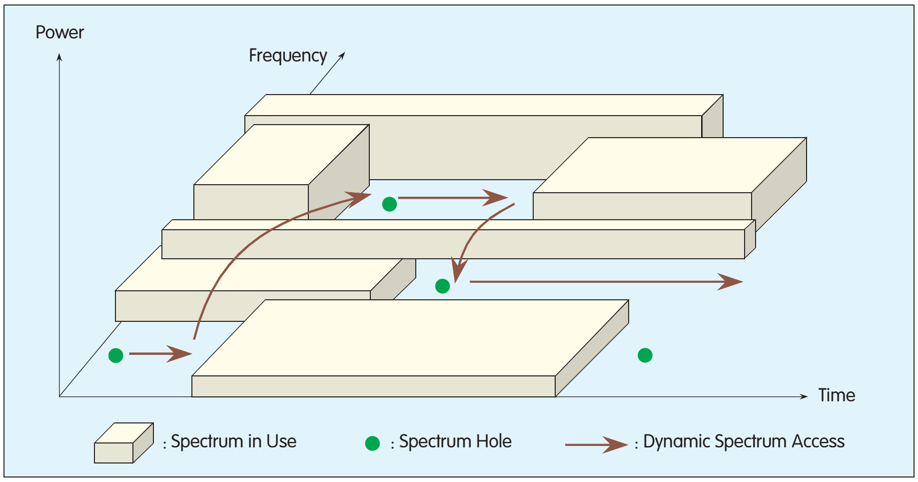
▲Figure 8. Cognition cycle model.

which it operates". Simon Haykin, from the perspective of signal processing, gives another definition: "CR is an intelligent wireless communication system that is aware of its surrounding environment (i.e. outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: highly reliable communications whenever and wherever needed; efficient utilization of the radio spectrum".

Seen from the above definitions, CR should at least have two basic capabilities: The capability of cognizing ambient environment in real time and the capability of reconfiguring communication system parameters. The cognitive capability allows the system to interact with ambient environment, thus selecting proper communication parameters for specific environment. The reconfiguration capability enables the system to adaptively modify such communication parameters as transmit carrier frequency, power and modulation scheme without changing any hardware. From the perspective of cognition, CR is a signal processing and learning process; while in terms of reconfiguration, CR is more likely to use Software Defined Radio (SDR) technology to execute the tasks that are obtained with cognitive capability.

2.3 Main Functions

According to CR's definitions, its ultimate objective is to find out the optimal available spectrums with cognitive capability and use them through reconfiguration capability, thus improving radio spectrum utilization. As most spectrums have already been allocated licensedly, the greatest challenge for CR technology is how to enable Cognitive Users (CUs) to share those allocated spectrums with Licensed Users (LUs) without interfering with them. Figure 9 depicts how CUs dynamically use spectrum holes or white spaces, which are temporarily not used in space, time and/or frequency. If a band is then used by a LU, the CU which is occupying this band goes to another spectrum hole or continues to use the band but changes its transmit power and modulation scheme so as to avoid interference with the LU. In this way, Dynamic Spectrum Access (DSA) is achieved. In Figure 9, the solid arrows illustrate a possible DSA scheme.



▲Figure 9. Spectrum hole.

The main functions of CR can be generalized as follows:

(1) Spectrum Sensing

This function detects spectrum holes and senses the presence of the LU when the CU operates on a licensed band.

(2) Spectrum Management

This function is used to select the best available channel based on the QoS requirements of a CU.

(3) Spectrum Sharing

It is used to coordinate channel access with other users, which involves multi-user multi-address and resource allocation.

(4) Parameter Adjustment

This function changes communication parameters to adaptively react to environmental change.

2.3.1 Spectrum Sensing

An essential capability of CR is spectrum sensing, that is, the capability of timely sensing spectrum holes. This is also the basis and precondition for CR application. In order not to interfere with the LU, when a CU uses a spectrum hole to communicate, it has to quickly detect the presence of the LU, and timely exit from related band or continues to use the band for communication if the interference threshold is not exceeded. As a result, CUs should be equipped with highly reliable spectrum sensing function and be able to detect spectrums in a continuous and real-time way. Existing spectrum sensing technologies can be categorized into two kinds: single node and cooperative spectrum sensing algorithm. Single node sensing means a single CR node independently identifies spectrum characteristics based on local radio frequency environment. The algorithms in this category mainly include matched filter detection, energy sensing and cyclostationary characteristic detection. In fact, neither of the above single node spectrum sensing algorithms performs quite well. Especially when the system suffers serious fading or when the LU sends signals with small power, the CU can hardly achieve accurate spectrum detection, thus severely interfering to LU. To solve this problem, cooperative spectrum sensing algorithms are proposed, which make decisions based on detection results of several nodes and by way of data convergence. The cooperative sensing algorithms not only lower the requirements for each single detection node and reduce its load, but also improve the accuracy in weak signal detection, which is equivalent to enlarging geographical range of spectrum sensing. As a result, spectrum utilization is likely to be further improved. However, cooperative sensing algorithms require participation of cooperative partners and are much more complicated to implement than

non-cooperative ones.

2.3.2 Spectrum Management

In CR systems, spectrum holes detected may disseminate in a wide frequency range that may include both licensed bands and unlicensed bands and differ in time, space and/or frequency domains. For example, they may have different central frequencies, different bandwidths, or they are available in different times. In order to find the optimal out of all available bands for the users so as to meet users' various QoS requirements, CR technology should have spectrum management function. Spectrum management is to conduct spectrum analysis and judgment based on spectrum sensing results, that is, to select the optimal channel from all detected spectrum holes based on QoS requirements of CUs and interference thresholds of LUs. The purpose of spectrum analysis is to summarize spectrum characteristics of spectrum holes so as to make a spectrum decision that best meets the user's requirements; while the goal of spectrum judgment is to select the most suitable band for current transmission based on the user's transmission rate, acceptable error rate, maximum delay, transmission mode and transmission bandwidth.

CR users adopt DSA rather than fixed spectrum allocation scheme. When channel status changes or a user with higher priority accesses current band, the CU should timely stop using the band or go to another idle band to continue its communication. This is called spectrum's mobility management, i.e. the capability of link maintenance and spectrum switching. In the list of available channels of a CU, there may be several available spectrums, so quick spectrum selection algorithms and switching algorithms are necessary for mobility processing. Spectrum selection algorithms select spectrums for users based on available spectrums' channel characteristics and service requirements, thus it can optimize spectrum utilization of the entire system; while spectrum switching algorithms ensure upper layer services not to be affected during spectrum switching. Spectrum switching can proceed in three stages: initialization, judgment and switch.

2.3.3 Spectrum Sharing

In CR systems, one great challenge for the open wireless spectrum is spectrum sharing. Unlike spectrum sensing, which is mainly involved in physical layer, and spectrum management, which is closely associated with upper layer services, spectrum sharing functions similar to multi-user multi-access and resource allocation technologies in the MAC layer of existing communication systems. The main issues covered in spectrum sharing include coexistence of CUs and LUs and management of available non-continual bandwidths.

Depending on different criteria, spectrum sharing technologies can be classified in several ways. By network structure, spectrum sharing technologies can be divided into centralized and non-centralized (i.e. distributed). The centralized spectrum sharing means all nodes (i.e. users) in the network send their spectrum sensing information to the central control unit, and the control unit draws spectrum allocation mapping. The distributed spectrum sharing means all nodes decide their spectrum access by themselves. Depending on spectrum allocation behaviors, spectrum sharing technologies can be categorized into cooperative and non-cooperative. In cooperative spectrum sharing, each node shares its sensing results of ambient environment with other nodes and spectrum allocation algorithm makes decisions based on all these information; while in non-cooperative spectrum sharing, each node only considers its own behaviors, that is to say, each node is selfish. By access technology, spectrum sharing technologies can be divided into overlay and underlay. Overlay means a CU accesses the network via unused spectrum hole. It actually realizes time division multiplexing of a spectrum between LUs and CUs, so the interference with LUs is the least. Underlay means a CU can use such spectrum spreading technologies as Code Division Multiple Access (CDMA) and Ultra Mobile Broadband (UWB) to share the same band with a LU. In case of underlay, the LU treats all CU signals as noises (which involves the concept of interference temperature). Obviously, when a CU knows all information of a licensed system, overlay performs better than underlay; but when the CU cannot obtain the information of a licensed system, underlay is better than overlay.

Spectrum sharing in CR system should not affect reliable and smooth communication of LUs. In other words, the interference of CUs to LUs must be always controlled under the interference temperature limit. In distributed network architecture, improper power allocation of CU is the main reason for interference. As a result, it is quite important to develop distributed power control schemes that are suitable for CR technologies.

2.3.4 Parameter Adjustment

To adapt the changing ambient wireless environment, a CU's communication parameters have to be timely adjusted based on the results of spectrum sensing, management and allocation rather than preset at first. Hence, the self-configuration capability is quite important for a CR system. In this sense, CR is an intelligent communication system. Generally, the following parameters are adjustable in the CR system:

(1) Frequency band: An optimal frequency band should be selected based on ambient wireless environment, and it should be adaptively switched among spectrum holes by CU.

(2) Transmit power: The transmit power should be dynamically adjusted within the allowed range so as to minimize the interference between CUs and LUs as well as between CUs and ensure smooth communication.

(3) Coding/modulation scheme: The coding and modulation scheme should be adjusted in real time to suit the transmission characteristics of current spectrum hole and meet the users' QoS requirements. For example, in real-time voice services, data transmission rate is more important than error rate, so an efficient channel coding and an M-ary modulation scheme should be selected.

(4) Communication system: If the communication environment changes, CR may be even required to be switched between different communication systems.

In reality, the above functions of CR system are difficult to be strictly defined. They often blend with each other and act as a whole.

2.4 CR Key Technologies

So far, CR research has achieved a great deal, but there are still many issues to be further studied. Currently, the research on CR focuses on the following key technologies or aspects:

(1) Spectrum Sensing and Allocation Technologies

Spectrum sensing is the basis for CR implementation, while adaptive spectrum allocation technologies exploit those detected, idle spectrums and improve radio spectrum utilization. As to spectrum sensing, current research focuses on accurate spectrum sensing algorithms, especially the algorithms for low Signal-to-Noise Ratio (SNR), such as cooperative spectrum sensing algorithm and cyclostationary spectrum detection algorithm. For adaptive spectrum allocation/user access algorithms, the following are specially studied: Prediction-based spectrum allocation algorithm, graph theory-based spectrum allocation algorithm, pricing auction-based spectrum algorithm, game theory-based spectrum sharing algorithm and common channel establishing for transmitting spectrum hole information and control information.

(2) Interference Cancellation Technologies

In CR systems, interference mainly falls into three kinds: CUs' interference with LUs, inter-CUs interference and LUs' interference to CUs. To ensure service quality of LUs, it is required to control CUs' interference to LUs at a level lower than the interference temperature. Currently, the approaches used in interference cancellation include: To reduce out-band leakage of OFDM spectrums by selecting a suitable pulse and window, to adopt accurate spectrum sensing algorithms and to use conflict-avoidance spectrum allocation algorithms.

(3) Multi-Carrier Modulation (MCM) Technologies

MCM technologies associate multi-user access with sub-carriers allocation. As they are easy to implement using Discrete Fourier Transform (DFT), most of current CR systems are constructed on the basis of MCM. MCM technologies mainly include OFDM and FMT modulation schemes. In CR systems, OFDM is easier to implement than FMT, but it requires strict frequency synchronization and has large sidelobe leakage, so it brings severe interference to LUs. With filter bank being used, FMT is more complicated than OFDM but brings less interference. Therefore, taking into account cancellation of mutual interference, sensitivity to synchronization and transmission efficiency, FMT is more advantageous than OFDM.

(4) Network Topology

In a CR network, there are two systems: The licensed system made up of LUs and the cognitive system composed of CUs. The two systems are independent but they associate with each other. Usually, the topology of the licensed system is fixed, while the cognitive system can use a topology with a central node or an Ad hoc system without any central node. Currently, research mainly focuses on the system with a central node rather than Ad hoc system because the later is much more complex.

(5) Combination with Other Technologies

CR technology can work with many other technologies to improve system capacity with their respective advantages. For example, its combination with cooperative communication technology, as mentioned above, can improve both transmission performance and spectrum utilization; the integration of CR with channel coding technologies can further improve the system's capability of overcoming wireless channel fading; and combination of CR with multi-carrier technologies can not only resist frequency selectivity and achieve flexible CR user access, but also simplify the algorithms.

(to be continued)

Biographies

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