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MULTICARRIER MODULATION AND COOPERATIVE COMMUNICATION IN MULTIHOP COGNITIVE RADIO NETWORKS

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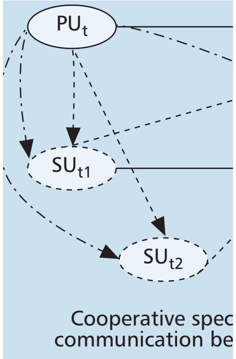

The authors combine CR with the cooperative diversity technique, and construct three cooperative diversity cognitive models: the collaborative spectrum sensing model, the cooperative communication cognitive model, and the hybrid model.

ABSTRACT

For high-data-rate wireless communication systems, two major issues are the underutilization of limited available radio spectrum and the effect of channel fading. Using dynamic spectrum access, cognitive radio can improve spectrum utilization. Almost all proposed CR systems are based on multicarrier modulation since multiple users can access the MCM systems by allocating subcarriers. Generally, MCM mainly includes two different schemes, orthogonal frequency-division multiplexing and filtered multitone modulation. Considering mutual interference elimination, synchronization, and transmission efficiency, we conclude that FMT is better than OFDM in MCM-based CR systems. Additionally, cooperative diversity can reduce the fading effect since the space diversity gain can be obtained through the distributed antennas of each user. Hence, in this article, we combine CR with the cooperative diversity technique, and then construct three cooperative diversity cognitive models: the collaborative spectrum sensing model, the cooperative communication cognitive model, and the hybrid model. Additionally, radio resources can be extended from time-frequency dimensions to space-time-frequency dimensions in the proposed models, which effectively improves both spectrum utilization and MCM-CR system performance. Finally, extensive simulations are conducted to show the validity and effectiveness of the proposed models.

INTRODUCTION

As we know, almost all existing wireless communication networks are allocated a fixed spectrum, resulting in a large portion of the assigned spectrum being used sporadically [1–3]. According to a report by the Federal Communications Commission (FCC), the percentage of the assigned spectrum that is occupied ranges only from 15 to 85 percent, varying widely in time and geographical position [2]. Hence, the limitation and underutilization of available spectrum resource accelerates new research. Ultra-wideband (UWB) and cognitive radio (CR) are candidate techniques to improve utilization of the assigned spectrum. Under the power spectral density emission limit of Part 15, which is –41.3 dBm/MHz or significantly lower (as low as –75 dBm/MHz), UWB can share wideband spectrum with other existing wireless systems. However, the application of UWB is limited because of its ultra-wideband frequency range, poor agility, and high complexity. The term *cognitive radio* was first introduced by Joseph Mitola. As a promising candidate, CR has the ability to share or reuse spectrum in an opportunistic manner by employing spectrum overlay and/or spectrum underlay approaches, which results in an increase of spectrum utilization [1–3]. In [1], the authors defined CR as an intelligent wireless communication technology that is aware of its surrounding environment, uses the methodology of understanding-by-building to learn from the environment, and then adapts its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters (e.g., transmit power, carrier frequency, and modulation strategy) in real time.

Moreover, high-data-rate wireless communication systems are limited not only by the limited spectrum, but often more significantly by the fading effects due to multipath propagation, the Doppler effect, and the angle spread of the wireless channel. Diversity is one of the most effectual methods to resist the fading effect. As we know, multiple-input multiple-output (MIMO), multicarrier modulation (MCM) and code-division multiple access (CDMA) are

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commonly considered as candidates. The MCM schemes, such as orthogonal frequency-division multiplexing (OFDM) and filtered multitone (FMT) modulation [4], are approaches to overcome the intersymbol interference (ISI) caused by multipath propagation. CDMA can suppress narrowband noise and interference by spreading the signal bandwidth to a wideband spectrum. Hence, MCM such as OFDM and multicarrier CDMA (MC-CDMA) are hailed as promising candidates for realizing spectrum overlay and spectrum underlay CR applications [2, 5], respectively. In MC-CDMA-based CR (MC-CDMA-CR) systems, it is possible to abandon distributed sensing in a way that the transmitting secondary user (SU) can spread its signal across the entire band, including that occupied by the primary user (PU), which results in a base station and/or signaling channel not being needed. Furthermore, MC-CDMA allows narrowband PU interferers to be excluded locally at the SU receiver, hence improving its performance. In other words, MC-CDMA technology is more suitable for spectrum underlay CR applications. However, we mainly focus on spectrum overlay CR systems in this article. Therefore, MC-CDMA-CR is not discussed below.

Additionally, MIMO can improve the channel capacity and performance of wireless communication systems by using space and time resources. However, it is not sufficient that only one antenna be built in the mobile station due to the limitations of its cost, size, and complexity. Moreover, the MIMO technique does not work well when the fading is large-scale. Consequently, cooperative diversity [6], also called virtual MIMO, has been proposed, in which users can transmit data by sharing antennas of other users surrounding them. Similarly, a cooperative communication system can obtain the space diversity gain and improve reliability. The basic ideas behind cooperative communication can be traced back to the groundbreaking work of Cover and El Gamal on the information theoretic properties of the relay channel with additive white Gaussian noise (AWGN). However, the aim of relays is only to help the source transmit information, whereas the users in cooperative communication systems can act as both information sources and relays. Nosratinia *et al*. have proven that even though the interuser channel is noisy, cooperation can still lead not only to an increase in capacity for both users, but also to a more robust system [6]. In this case, the achievable rates of users are less susceptible to channel variations. There are three main cooperative signaling protocols: amplify-and-forward (AF), detect-and-forward (DF), and coded cooperation (CC) methods [6]. In this field, the key techniques mainly include power allocation, cooperative partner selection, performance evaluation, and so forth.

In fact, CR and cooperative communication have developed rapidly in their own fields. However, there is little advantage in improving spectrum utilization when only cooperative communication is used, whereas CR is not good for improving the symbol error rate performance of each user. Consequently, combining CR with cooperative communication may be a good solution to both problems. Ghasemi [7] and Ganesan [8] first proposed the collaborative (exchanging spectrum hole vectors with each other) and cooperative communication scheme to improve the detection probability of spectrum sensing in CR systems. Nevertheless, both of them are only based on AF and do not take the locations of SUs into consideration. After that, Devroye introduced cooperative communication to data transmission, and obtained fundamental limits of achievable rates in CR systems. Obviously, this model is ideal and needs cooperative communications among SUs. Finally, Simeone *et al*. studied the cognitive relaying scheme between PUs and SUs [9], which is of course a simple and elementary discussion. Consequently, in this article we expand the models of Ghasemi and Devroye, and give an overview of the cooperative diversity cognitive models, which combine MCM, cooperative diversity, and CR techniques together.

This article is organized as follows. In the next section we discuss MCM techniques in the multihop CR system. Then three cooperative diversity cognitive models are proposed. Simulation results show the effectiveness of the proposed models in the following section. Conclusions are drawn in the final section.

MULTICARRIER MODULATION TECHNIQUES IN MULTIHOP CR NETWORKS

Recently, some work has been reported on multihop CR networks [10], in which each node has a list of available frequency bands and must work adaptively among these frequency bands because of dynamic spectrum access. It is well known that two nodes cannot communicate if they work on different frequency bands. Hence, routing in multihop CR networks becomes a critical and challenging issue. In general, solutions of this problem mainly focus on the methods in the network layer, whose processing delay is on the order of milliseconds. However, the high-speed wireless channel in multihop CR networks varies on the order of microseconds due to multipath fading, the Doppler effect, and dynamic occupancy of the subchannel by PUs. Therefore, the solutions proposed in the network layer may cause heavy interference to PUs. To this end, adopting MCM to intersection nodes (i.e., RUs) of multihop CR networks may be a good solution in the physical layer. Because of the usage of MCM, the intersection node can allocate some unused subcarriers to different information flows; thus, all flows can be transmitted simultaneously.

In fact, considering that the access of multiple users can be implemented by the allocation of subcarriers in an MCM system, almost all of the proposed spectrum overlay CR systems are based on MCM technology, specifically the MCM-CR system. Moreover, almost all proposed MCM-CR systems are based on OFDM [2], such as IEEE 802.22, the spectrum pooling system proposed by Timo A. Weiss, and the Next Generation (xG) communication networks proposed by the Defense Advanced Research

The longer the delay spread of the channel is, the longer the length of the CP is, and thus the less the efficiency is. Obviously, these methods conflict with the concept of improving the spectrum utilization of the CR technique.

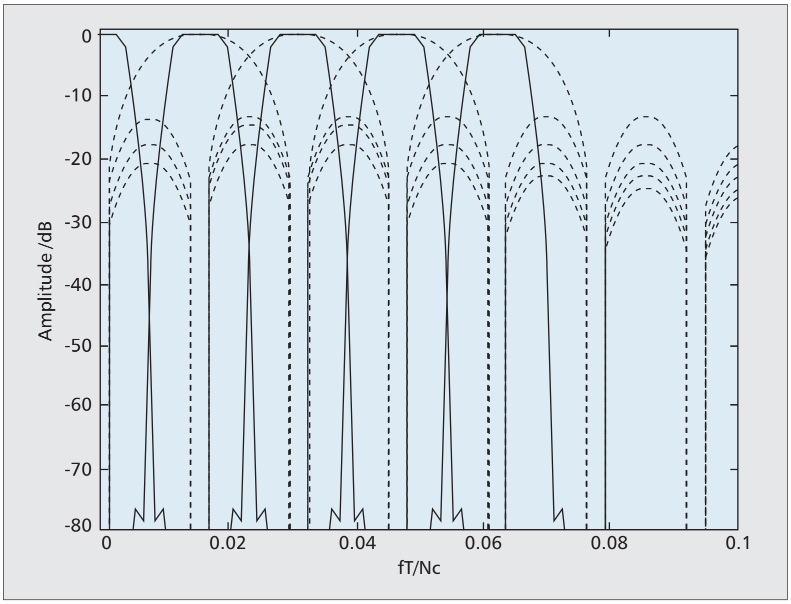

Figure 1. *Frequency response of the first five subcarriers in MCM system with* N_c *= 64 (solid: FMT, dashed: OFDM).*

Projects Agency (DARPA) [2]. Recently, cosine modulated multitone (CMT)-based CR (CMT-CR) and FMT-based CR (FMT-CR) systems have also been proposed [3].

In an MCM-CR system, a maximum likelihood detection (MLD) model is deduced under the constraint of the interference temperature [3]. Moreover, the optimal detection region, and the probability of detection and false alarm are obtained in [3]. Spectrum allocation and access algorithms are well studied in [2, 3]. Based on the MLD scheme and Markovian chain prediction (MCP) model, an efficient SU access algorithm based on spectrum hole vector (SHV) is proposed to meet the quality of service (QoS) requirements of the SUs in a centralized MCM-CR system in [3]. However, one issue of the MCM-CR system is that it requires a large size inverse discrete Fourier transform (IDFT)/DFT operation due to the varying locations of each subcarrier in a wide spectrum, resulting in a heavy implementation complexity and serious delay. To this end, a scheme combining Cooley-Tukey's recursive algorithm with pruning algorithm can be adopted. Now, the main issue becomes: which technique is better in an MCM-CR system, OFDM or FMT? We discuss more detail in the following.

Recently, some challenges in the physical layer of OFDM-CR systems have been analyzed (e.g., mutual interference and synchronization) [2]. In OFDM-CR systems, spectrum partitioning is realized in the form of overlapping subbands, in which adjacent subcarriers are at the nulls of the *sinc*(*f*) function. Therefore, spectrum efficiency is high. However, the requirement of synchronization is also very strict, especially for frequency synchronization. If the subcarriers are not orthogonal, the sidelobes of the sinc-shaped spectrum on each subcarrier may fully interfere with PUs even if the parameter of the OFDM system used by PUs and SUs is the same. Moreover, the worse case is that OFDM is not adopted by PUs, or the parameters of OFDM for both PUs and SUs are different even though OFDM is used by PUs. To decrease the interference, the received OFDM signal is windowed in the time domain before it is fed into the operation of Fourier. Another method is to leave some virtual subcarriers (VCs) free. Furthermore, in an OFDM-CR system, the cyclic prefix (CP) or so-called guard interval is added to each transmitted symbol to avoid ISI, which occurs in multipath channels and destroys orthogonality. Unfortunately, like VCs, CP leads to a loss of transmission efficiency. The longer the delay spread of the channel, the longer the length of the CP, and thus the lesser the efficiency . Obviously, these methods conflict with the concept of improving the spectrum utilization of the CR technique.

Compared with OFDM-CR systems, an FMT-CR system does not require CP between several continuous transmitted symbols [4]. Instead, the bandwidth of each subcarrier is chosen to be quasi-orthogonal in the frequency domain, which is also called subcarrier spectral containment, and it can be achieved by the use of steep rolloff bandpass filters (i.e., filter bank). As a result, the time domain response of these filters may overlap in several successive transmitted symbol periods. Therefore, it is necessary for equalization per subchannel to reduce any remaining ISI, even if the channel is in an ideal state. A high level of subcarrier spectral containment is good for CR systems because the leakage of signal energy between adjacent subchannels may be neglected since it is as low as –70 dB where the subcarriers are closely spaced, as shown in Fig. 1. Figure 1 illustrates the frequency response of the first five subcarriers in an MCM system, where the solid and dashed lines denote FMT and OFDM, respectively. Due to the tight spectral containment achieved by the prototype filter in FMT, negligible power leaks into adjacent banks. Hence, fewer VCs are needed to comply with the regulatory power spectral mask than in an OFDM system.

Therefore, it is obvious that only a few VCs are needed since the CP is not necessary for FMT systems; thus, the transmission efficiency of FMT systems is better than that of OFDM systems. Without loss of generality, we define the transmission efficiency as

$$\eta = \frac{N_c}{N_c + L_{CP}} \frac{N_c - N_{vc}}{N_c} = \frac{N_c - N_{vc}}{N_c + L_{CP}} \times 100\%, \qquad (1)$$

where N_c, N_{vc}, and L_{CP} denote the number of subcarriers, the number of VCs, and the length of the CP, respectively. For example, when the bandwidth of occupied spectrum equals 20 MHz, $N_c = 64$, $L_{CP} = 16$, and $N_{vc} = 12$ in an OFDM system based on the standard of HIPERLAN/2 or IEEE 802.11a, while $L_{CP} = 0$ and $N_{vc} = 2 \sim 4$ in an FMT system. Accordingly, the efficiency of OFDM and FMT is $\eta_{OFDM} = 65$ percent and $\eta_{FMT} \approx 94$ percent, respectively.

Moreover, synchronization among different users is not serious in an FMT system because of its tight spectral containment. The disadvantage of the FMT is its complexity due to the filter bank and equalization per subchannel. However,

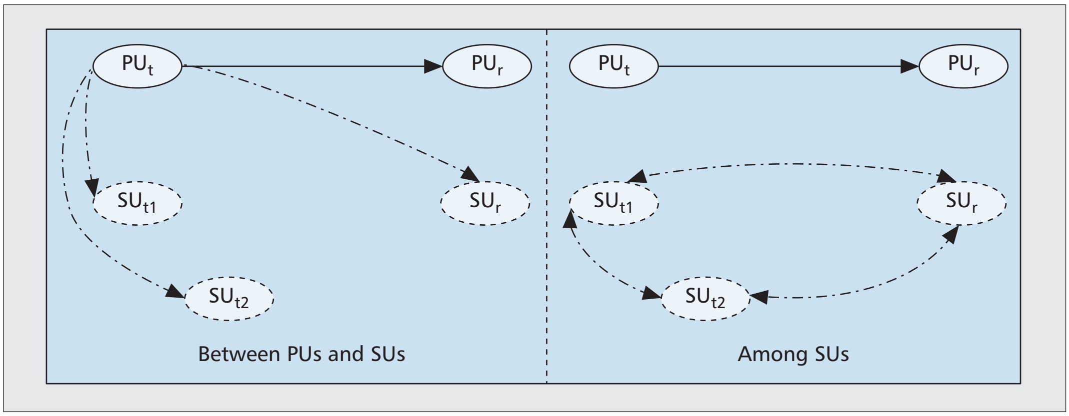

Figure 2. *Proposed collaborative spectrum sensing model.*

The disadvantage of FMT is its complexity due to the filter bank and equalization per subchannel. However, it may not be a serious issue in the future due to the fast development of digital signal processing techniques.

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In summary, taking mutual interference suppression, synchronization, and transmission efficiency into consideration, it is much better to adopt FMT than OFDM in MCM-CR systems.

Proposed Cooperative Diversity Cognitive Models in an MCM-CR System

When the idea of CR is taken into account in the cooperative communication system, the cooperative communication system with cognitive relay can be proposed to further improve the spectrum efficiency. On the other hand, cooperative diversity CR systems can also be proposed when the idea of cooperative diversity is considered in a CR system. Thus, based on Chasemi and Devroye's model, combining MCM, cooperative diversity, and CR techniques, we propose three cooperative diversity cognitive models, including the collaborative spectrum sensing model, the cooperative communication cognitive model, and the hybrid model, as shown in Figs. 2, 3, and 4, respectively. Solid and dashed ellipses denote PUs in the primary network and SUs in the secondary network, respectively. Furthermore, dash-dotted lines denote the link to transmit the control data, including signaling and spectrum hole vector information. The solid and dashed lines denote the transmissions of the users' self data and the partners' data for cooperative retransmission, respectively.

Collaborative Spectrum Sensing Model

In the process of spectrum sensing, the fading effect, noise, and interference may cause some errors (result in false alarm detection and false dismissal detection), which are very harmful because they may introduce serious interference to PUs, resulting in a decrease of the spectrum utilization ratio. The left model in Fig. 2, which is one of the proposed collaborative spectrum sensing models between PUs and SUs, means that a PU leaves or broadcasts the spectrum hole information to SUs over the air or through a wired channel. Obviously, the PU is the licensed user, who would not do this. However, if a PU would like to allow SUs access to his/her licensed spectrum when he/she was not using them, he/she should offer the spectrum hole information to help SUs. Certainly, this proposed collaborative spectrum sensing model is simple and introduces no any interferences to PU because spectrum hole information is very accurate in this case. Nevertheless, the disadvantage of this model is that it needs an additional specialized channel to transmit the spectrum hole information from PU to SUs, as well as the permission and authorization of the PU. The proposed collaborative spectrum sensing model among SUs is shown in the right part of Fig. 2. *Collaborative* means that SUs can exchange or cooperatively retransmit their SHV information with each other. For some reasons, such as deep fading or distance from PUs, some SUs (e.g., SU$_{t2}$) may not detect the used spectrum successfully, which will cause a false dismissal detection. However, their neighbors (e.g., SU$_{t1}$) can do them a favor. Therefore, the detection probability of SU$_{t2}$ can be improved by cooperatively communicating with its adjacent SUs (e.g., SU$_{t1}$) or exchanging SHV information with each other. SHV exchange and cooperative communication were first proposed by Chasemi [7] and Ganesan [8], respectively. However, only AF was considered in [8]. Obviously, there are still many key techniques of the proposed collaborative spectrum sensing model that need to be further studied, such as the spectrum sensing algorithm, the influence of the detection probability and locations of SUs, the choice of cooperative partner, and so forth.

Cooperative Communication Cognitive Model

In this proposed model, we assume that the SHV has been detected successfully by SUs. The top part of Fig. 3 shows the cooperative communication between PUs and SUs. PUs (e.g., PU$_t$ and PU$_r$) are source/receiver, and SUs (e.g., SU$_{t1}$ or SU$_{t2}$) act as relays to retransmit PUs' data. The rationale of this choice is that helping the PU to increase its throughput entails (for a fixed demand of rate by the PU) a diminished transmission time for the PU, which leads to more transmission opportunities for the SUs. That is to say, the PUs' data can be transmitted

In the proposed hybrid model, which may be close to the systems easily to carry out, there are two steps needed: collaborative spectrum sensing and cooperative communication. Certainly, they can also be implemented simultaneously.

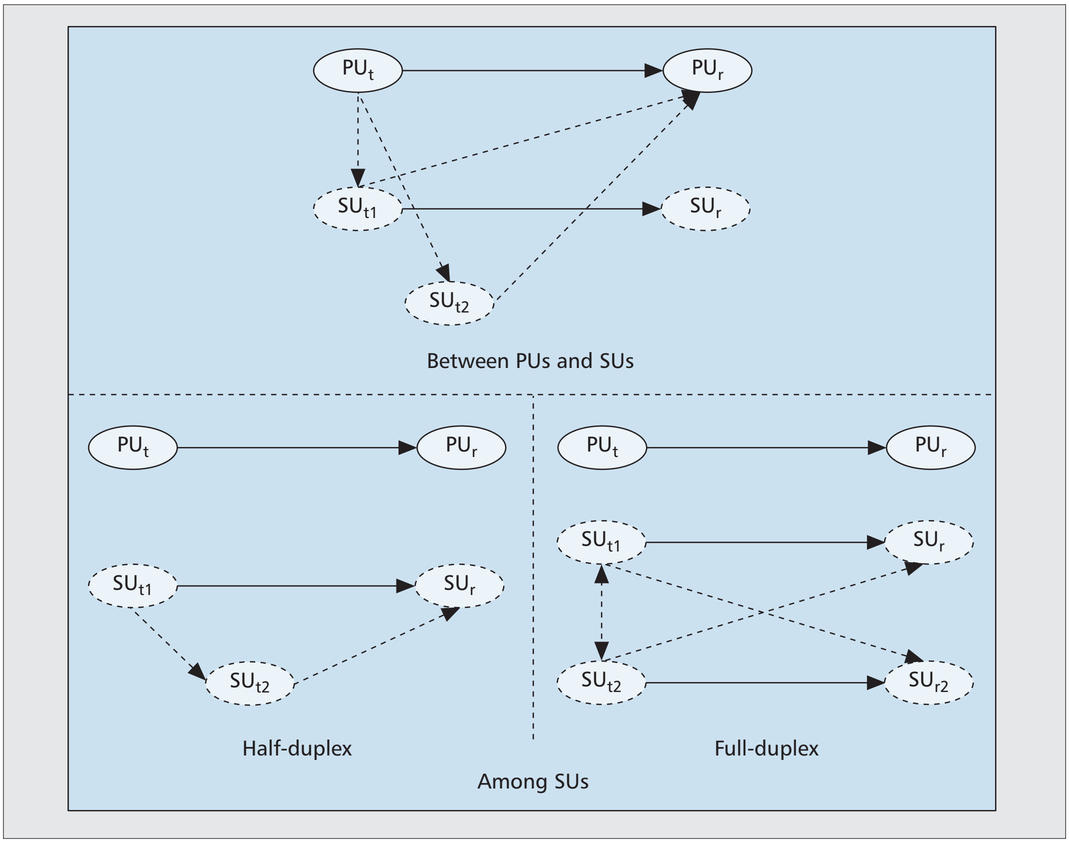

Figure 3. *Proposed cooperative communication cognitive model.*

quickly, and some seconds are then saved for SUs to access the idle spectrum. The bottom part of Fig. 3 shows the cooperative cognitive model among SUs, where the SUs act as cooperative partners with each other. In such a case, SUs can work in either half-duplex (left bottom) or full-duplex (right bottom) mode. When it is in half-duplex mode, time-division multiple access (TDMA) is often adopted by SUs, and SUs as relays (e.g., SU$_{t2}$ in the left bottom of Fig. 3) do not transmit data themselves. For full-duplex mode, CDMA is always selected by SUs, and SUs act as both source and relay (e.g., SU$_{t1}$ and SU$_{t2}$ in the right bottom of Fig. 3). Similar to the proposed collaborative spectrum sensing, there are also many key techniques that need to be studied, such as the transmitter scheme of cooperative communication, capacity and diversity gain analysis, power allocation algorithm, receiver designing, partner selection algorithm, and so on.

HYBRID MODEL

As aforementioned, the proposed model of collaborative spectrum sensing is helpful for spectrum detection, while the proposed model of cooperative cognitive communication is mainly for data communication. However, spectrum detection and data communication will be as a whole in future practical CR systems. Therefore, the combination of the aforementioned two models (i.e., a hybrid model) is proposed in this subsection, which is shown in Fig. 4. Obviously, in the proposed hybrid model, there are two steps needed: collaborative spectrum sensing and cooperative communication. Certainly, they can also be implemented simultaneously. Both collaborative spectrum sensing and cooperative communication are between PUs and SUs on the left of Fig. 4, while they are both among SUs on the right . Apparently, the same collaborative partners are not needed during the different steps. For example, collaborative spectrum sensing occurs between PUs and SUs during the first step, while cooperative communication is among SUs during the second step. Therefore, the probability of spectrum detection is very important. In the future, further research is needed on the hybrid model, including spectrum sensing, the influence of probability of spectrum detection, the selection of cooperative users, the synchronization and channel estimation algorithm, and so forth.

Note that we need to point out that the MCM technology can be used in any of the three proposed models. Moreover, the space diversity gain can be obtained by adopting cooperative communication technology. Therefore, the introduction of cooperative diversity expands CR research from two dimensions (time-frequency) to three dimensions (space-time-frequency). In summary, all resources can be fully and effectively utilized to improve the performance of MCM-CR systems.

Finally, it is necessary to point out that the PU's model to occupy the channel is no limitation in this article. This is because we mainly focus on the model description and performance

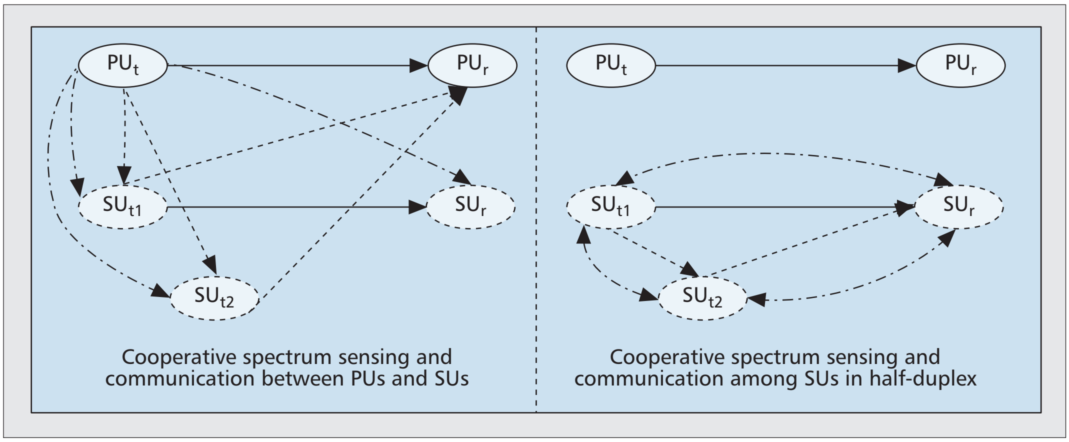

Figure 4. *Proposed hybrid model.*

analysis, which results in the detection probability of the spectrum being the chief factor considered in the three proposed models, regardless of the PU's model to occupy the channel.

SIMULATION RESULTS

To get insight into the effectiveness of the proposed models and validate some related analytical results, extensive computer simulations have been conducted in which M-phase shift keying (MPSK) modulation is used, and channel coefficients $h_{i,j}(i \in \{s, r\}, j \in \{r, d\})$ are independent samples of zero mean complex Gaussian random variables with variance $\sigma^2_{i,j}$, where s, r, and d denote the source, relay, and destination, respectively. Moreover, we assume $\sigma^2_{s,d} = 1$, $\sigma^2_{s,r} = 1$, $\sigma^2_{r,d} = 10$, and the total transmitted power $P = P_s + P_r$, where P_s and P_r represent the power allocated to source and relay, respectively.

PERFORMANCE LOSS WITH PROBABILITY OF SPECTRUM DETECTION

Here, we adopt the half-duplex model seen in the right part of Fig. 4, in which SHV information is exchanged for collaborative spectrum sensing and cooperative communication among SUs. We assume that there is only one communication link between PU_t and PU_r, and several links among SUs. Obviously, the collaborative probability of spectrum detection $P_d = 1 - (1 - P_{ds})^n$, where P_{ds} (we have assumed that it is the same for all SUs) is the probability of spectrum detection by each SU without any help, and n is the number of SUs selected to join in SHV exchange for collaborative spectrum sensing. Then we further assume that only one SU (e.g., SU_{t2}) is randomly selected to be a relay partner for cooperative communication after collaborative spectrum sensing. Based on these assumptions, the unconditional symbol error rate (SER) performance in an AF cooperation communication system is illustrated in Fig. 5, in which $P_{ds} = 0.9$, and equal power allocation (EPA) is used. In Fig. 5, for comparison, the curve with perfect spectrum sensing ($P_d = 1$) is also plotted. Obviously, it can be concluded from Fig. 5 that there is about 4.0 dB loss without cooperation ($n = 1$ and $P_d = P_{ds} = 0.9$) when SER is 10^{-3}, and the SER performance is very close to the results with perfect sensing information when the number of collaborative SUs equals 3 ($n = 3$ and $P_d = 0.99$). That is to say, there is about 4.0 dB gain when two more SUs join for collaborative spectrum sensing. Obviously, the complexity of the system increases because of the cooperative partners' joining.

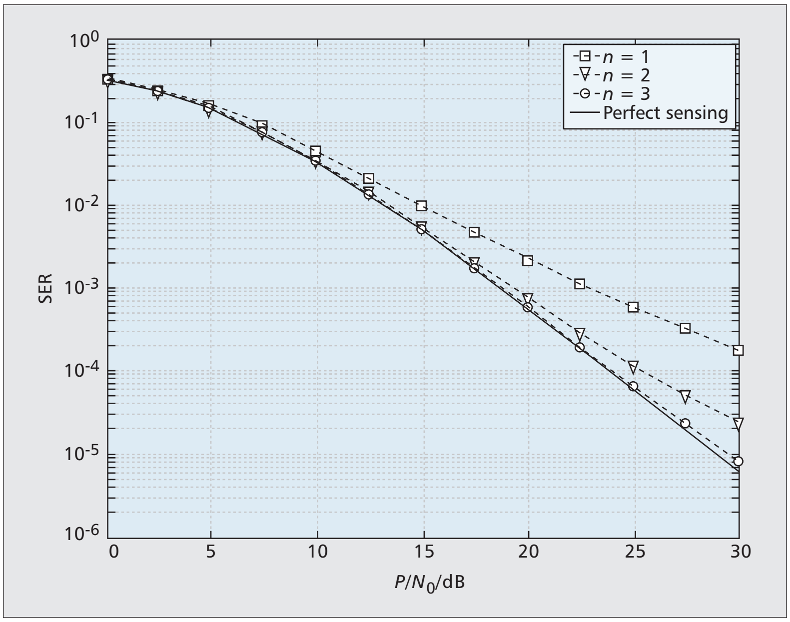

Figure 5. *SER performance using the half-duplex model in Fig. 4 with* $P_{ds} = 0.9$.

POWER CONTROL SCHEME OF SUs UNDER THE CONSTRAINT OF INTERFERENCE TEMPERATURE

In this subsection, under the constraint of the interference temperature, we discuss a CR system based on the cooperative cognitive half-duplex model on the bottom left of Fig. 3 in which SU_{t1}, SU_{t2}, and SU_r are source, relay, and destination, respectively, and PU_t is the PU. Without loss of generality, Q denotes the interference temperature level. Hence, the problem becomes how to obtain the optimal performance

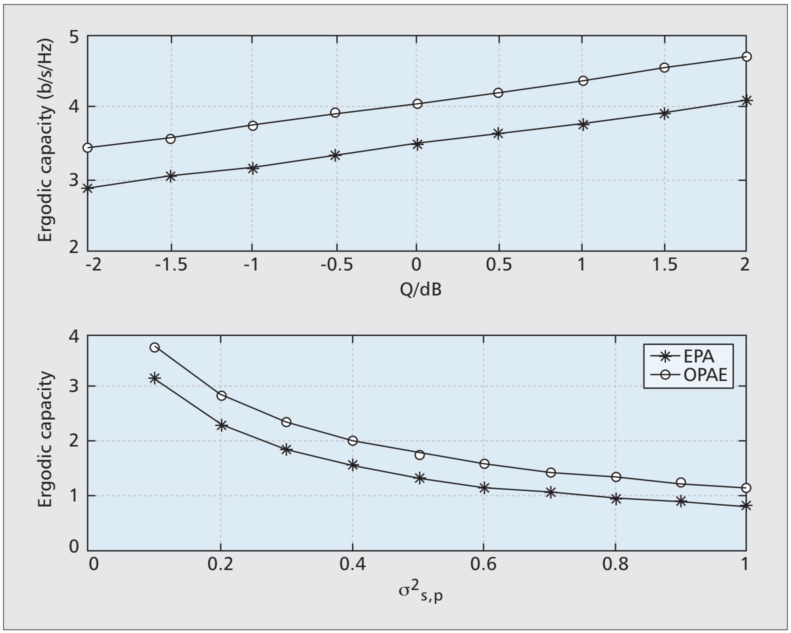

Figure 6. *Ergodic capacity with different* Q *(top) and* $\sigma^2_{s,p}$ *(bottom), respectively.*

of the SUs' network under constraint Q. It is well known that power control is one simple solutions. In order to obtain the maximal ergodic capacity, the approximate optimal power allocation scheme (OPAE) is proposed in the conducted simulations, and an AF cooperative communication protocol is selected among SUs. Furthermore, cooperative communication is obviously not adopted when the source-to-destination channel is better than the relay-to-destination one. Figure 6 illustrates the ergodic capacity with the changing of Q and the channel variances of the source-to-PU ($\sigma^2_{s,p}$), respectively, where $\sigma^2_{s,p} = 0.1$ in the upper part and $Q = -1$ dB in the lower part. Obviously, it can be seen from Fig. 6 that the capacity performance of the proposed OPAE scheme outperforms that of the existing EPA, and the capacity performance monotonically increases with increasing Q and monotonically decreases with increasing $\sigma^2_{s,p}$.

CONCLUSIONS

In this article, we have first studied the MCM techniques in a multihop MCM-CR system. Considering mutual interference elimination, synchronization, and transmission efficiency, we conclude that FMT is better than OFDM in an MCM-CR system. Second, we propose three cooperative diversity cognitive models: the collaborative spectrum sensing model, the cooperative communication cognitive model, and the hybrid model. The introduction of cooperative diversity expands CR research from time-frequency dimensions to space-time-frequency dimensions. Therefore, all resources can be fully and effectively utilized to improve the performance of an MCM-CR system. Finally, some simulations have been conducted to verify that the collaborative spectrum sensing can improve the probability of spectrum detection, resulting in enhancement of the performance of the MCM-CR system.

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REFERENCES

[1] S. Haykin, "Cognitive Radio: Brain-empowered Wireless Communications," *IEEE JSAC*, vol. 23, no. 2. Feb. 2003, pp. 201–20.

[2] I. F. Akyildiz *et al*. "Next Generation Dynamic Spectrum Access Cognitive Radio Wireless Networks: A Survey," *Comp. Net*., Sept. 2006, pp. 2127–59.

[3] T. Luo *et al*., "A Subcarriers Allocation Scheme for Multi-carrier Modulation Based Cognitive Radio Systems," *IEEE Trans. Wireless Commun*., vol. 7, no. 9, Sept. 2008, pp. 3335–40.

[4] I. Berenguer, *Filtered Multitone (FMT) Modulation for Broadband Fixed Wireless Systems*, Master's thesis, Univ. of Cambridge, 2002.

[5] V. Chakravarthy *et al*., "Novel Overlay/Underlay Cognitive Radio Waveforms Using SD-SMSE Framework to Enhance Spectrum Efficiency — Part I: Theoretical Framework and Analysis in AWGN Channel," *IEEE Trans. Commun*., vol. 57, no. 12, Dec. 2009, pp. 3794–3804.

[6] A. Nosratinia *et al*., "Cooperative Communication in Wireless Networks," *IEEE Commun. Mag*., vol. 42, no. 10, Oct. 2004, pp. 74–80.

[7] A. Ghasemi *et al*., "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments," *Proc. IEEE DySPAN '05*, 2005.

[8] G. Ganesan and Y. Le, "Cooperative Spectrum Sensing in Cognitive Radio, Part I: Two User and Part II: Multiuser Networks," *IEEE Trans. Wireless Commun*., vol. 6, no. 6, June 2007, pp. 2204–22.

[9] O. Simeone and U. Spagnolini, "Cooperation and Cognitive Radio," *IEEE ICC '07*, 2007, pp. 6511–15.

[10] Y. Shi and Y. T. Hou, "A Distributed Optimization Algorithm for Multi-Hop Cognitive Radio Networks," *IEEE INFOCOM*, 2008, pp. 1292–1300.

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