Chapter 2
CSS Technology

In this chapter, the CSS technology is stated for detail, involving cooperative communication model and CSS model. Specifically, how to use the traditional cooperative communication technology to solve the problems existing in cognitive radio networks are illustrated clearly.

2.1 Introduction

Traditional wireless networks have predominantly used direct point-to-point or point-to-multipoint (e.g., cellular) topologies. In contrast to conventional point-to-point communications, cooperative communications allows different users or nodes in a wireless network to share resources and to create collaboration through distributed transmission/processing, in which each user's information is sent out not only by the user but also by the collaborating users [1, 2]. Cooperative communications is a new communication paradigm that promises significant capacity and multiplexing gain increase in wireless networks [3, 4]. It also realizes a new form of space diversity to combat the detrimental effects of severe fading [5]. It has been recently recognized as a powerful solution that can overcome the limitation of wireless systems [6]. The basic idea behind cooperative transmission rests on the observation that in a wireless environment, the signal transmitted or broadcast by a source to a destination node, each employing a single antenna, is also received by other terminals, which are often referred to as relays or partners. The relays process and retransmit the signals they have received. The destination node then combines the signals coming from the source and the partners, thereby creating spatial diversity and taking advantage of the multiple receptions of the same data at the various terminals and transmission paths. In addition, the interference among terminals can be dramatically suppressed by distributed spatial processing technology. By allowing multiple cognitive radios to cooperate in spectrum sensing, the hidden terminal problem can be addressed [7–9].

M. Li et al., *Cognitive Wireless Networks Using the CSS Technology*,
Lecture Notes in Electrical Engineering 384,
DOI 10.1007/978-3-319-31095-4_2

Cooperative techniques have already been considered for wireless and mobile broadband radio [10] and also have been under investigation in various IEEE 802 standards. The IEEE 802.11 standard is concerned with wireless local area networks (WLANs) in unlicensed bands in indoor environments. A recent evolution of IEEE 802.11 using mesh networking, i.e., 802.11s is considering the update of 802.11 MAC layer operations to self-configuration and multihop topologies [11]. The IEEE 802.16 standard utilize an orthogonal frequency-division multiplexing (OFDM), orthogonal frequency-division multiple access (OFDMA), and single-carrier based fixed wireless metropolitan-area network in licensed bands of 10–66 GHz. As an amendment of 802.16 networks, IEEE 802.16j is concerned with multihop relay to enhance coverage, throughput, and system capacity [1, 12].

However, the critical challenging issue in spectrum sensing is the hidden terminal problem, which occurs when the CR is shadowed or in severe multipath fading. Recent work has shown that cooperative spectrum sensing (CSS) can greatly increase the probability of detection in fading channels [12–23].

2.2 Cooperative Communication Model

2.2.1 Cooperative Diversity

In [24] and [25], Sendonaris et al. introduced and examined the concept of user cooperation diversity. The implemented strategy uses a pair of transmitting, full-duplex users who cooperate in sending independent data from both users to a common destination.

In cooperative wireless communication, we are concerned with a wireless network, being cellular or ad hoc variety, where the wireless agents, which we call users, may increase their effective quality of service (measured at the physical layer by bit error rates, block error rates, or outage probability) via cooperation. In a cooperative communication system, each wireless user is assumed to transmit data as well as act as a cooperative agent for another user (Fig. 2.1). Cooperation leads to interesting trade-offs in code rates and transmit power. In the case of power, one may argue on one hand that more power is needed because each user, when in cooperative mode, is transmitting for both users. On the other hand, the baseline

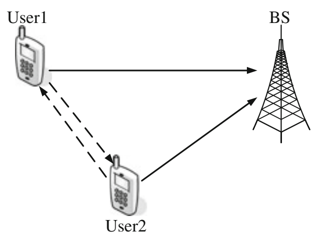

Fig. 2.1 Cooperative transmission model

transmit power for both users will be reduced because of diversity. In the face of this trade-off, one hopes for a net reduction of transmit power, given everything else being constant. Similar questions arise for the rate of the system. In cooperative communication each user transmits both his/her own bits as well as some information for his/her partner; one might think this causes loss of rate in the system. However, the spectral efficiency of each user improves, because, due to cooperation diversity the channel code rates can be increased [26].

2.2.2 Relay Cooperation

In cooperative communications, independent paths between the user and the base station are generated via the introduction of a relay channel as illustrated in Fig. 2.2. The relay channel can be thought of as an auxiliary channel to the direct channel between the source and destination. A key aspect of the cooperative communication process is the processing of the signal received from the source node done by the relay. These different processing schemes result in different cooperative communications protocol. Cooperative communications protocols can be generally categorized into fixed relaying schemes and adaptive relaying schemes. In fixed relaying, the channel resources are divided between the source and the relay in a fixed (deterministic) manner. The processing at the relay differs according to the employed protocols. There are mainly three relaying protocols: amplify-and-forward (AF), decode-and-forward (DF), and coded cooperation (CF). In AF, the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low cost implementation. But the noise is also amplified at the relay. In DF, the relay attempts to decode the received signals. If successful, it re-encodes the information and retransmits it. In selective relaying,

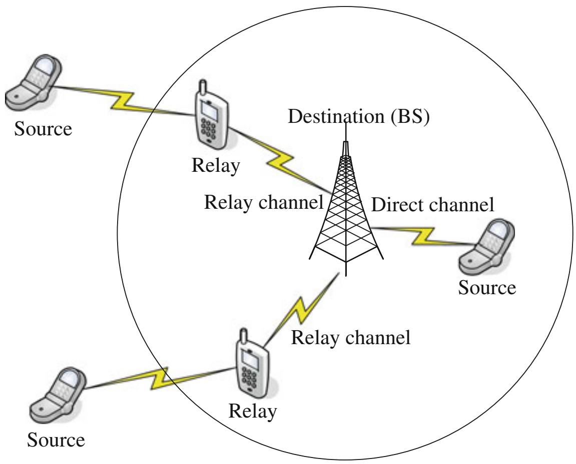

Fig. 2.2 The introduction of relay channel

if the signal-to-noise ratio of the signal received at the relay exceeds a certain threshold, the relay performs decode-and-forward operation on the message. On the other hand, if the channel between the source and the relay suffers from severe fading such that the signal-to-noise ratio is below the threshold, the relay idles. Moreover, if the source knows that the destination does not decode correctly, then the source may repeat to transmit the information to the destination or the relay may help forward information, which is termed as incremental relaying. In this case, a feedback channel from the destination to the source and the relay is necessary [27].

In this article, we only consider a single relay helping a user (source) in the network forwarding information. The basic steps of relay cooperation are as follows:

Step 1 A source sends information to its destination, and the information is also received by the relay at the same time.

Step 2 The relay can help the source by forwarding or retransmitting the information to the destination.

2.2.2.1 AF Relaying Protocol

In a fixed AF relaying protocol, the relay simply scales the received version and transmits an amplified version of it to the destination. Each user in this method receives a noisy version of the signal transmitted by its partner. As the name implies, the user then amplifies and retransmits this noisy version. The base station combines the information sent by the user and partner, and makes a final decision on the transmitted bit (Fig. 2.3). Although noise is amplified by cooperation, the base station receives two independently faded versions of the signal and can make better decisions on the detection of information [27].

The AF relay channel can be modeled as follows. The signal transmitted from the source x is received at both the relay and destination as

$$y_{s,r} = \sqrt{P}h_{s,r}x + n_{s,r} \tag{2.1}$$

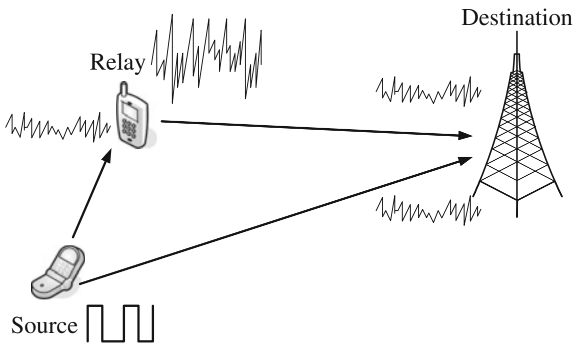

Fig. 2.3 Fixed amplify-and-forwarded relay protocol

$$y_{s,d} = \sqrt{P}h_{s,d}x + n_{s,d} \tag{2.2}$$

where, P is the transmitted power at the source, $h_{s,r}$ and $h_{s,d}$ are the channel fading coefficients between the source and the relay and destination, respectively. The terms $n_{s,r}$ and $n_{s,d}$ denote the additive white Gaussian noise with zero-mean and variance N_0.

In this protocol, the relay amplifies the signal from the source and forwards it to the destination ideally to equalize the effect of the channel fade between the source and the relay. The relay does that by simply scaling the received signal by a factor that is inversely proportional to the received power, which is denoted by [27]

$$\beta_r = \frac{\sqrt{P}}{\sqrt{P|h_{s,r}|^2 + N_0}} \tag{2.3}$$

The signal transmitted from the relay is thus given by $\beta_r y_{s,r}$ and has power P equal to the power of the signal transmitted from the source. To calculate the mutual information between the source and the destination, we need to calculate the total instantaneous SNR at the destination. The SNR received at the destination is the sum of the SNRs from the source and relay links. The SNR from the source link is given by [27]

$$SNR_{s,d} = \Gamma|h_{s,d}|^2 \tag{2.4}$$

where, $\Gamma = P/N_0$.

In the following we calculate the received SNR from the relay link. In step 2 the relay amplifies the received signal and forwards it to the destination with transmitted power P. The received signal at the destination in phase 2 can be described as:

$$y_{r,d} = \frac{\sqrt{P}}{\sqrt{P|h_{s,r}|^2 + N_0}} h_{r,d} y_{s,r} + n_{r,d} \tag{2.5}$$

where $h_{r,d}$ is the channel fading coefficient from the relay to the destination and $n_{r,d}$ is an additive noise. More specifically, the received signal $y_{r,d}$ in this case is

$$y_{r,d} = \frac{\sqrt{P}}{\sqrt{P|h_{s,r}|^2 + N_0}} h_{r,d} h_{s,r} x + n'_{r,d} \tag{2.6}$$

where,

$$n'_{r,d} = \frac{\sqrt{P}}{\sqrt{P|h_{s,r}|^2 + N_0}} h_{r,d} n_{s,r} + n_{r,d} \quad (2.7)$$

Assume that the noise terms $n_{s,r}$ and $n_{r,d}$ are independent, then the equivalent noise $n'_{r,d}$ is a zero-mean, complex Gaussian random variable with variance

$$N'_0 = \left(\frac{P|h_{r,d}|^2}{P|h_{s,r}|^2 + N_0} + 1 \right) N_0 \quad (2.8)$$

The destination receives two copies from the signal x through the source link and relay link. There are different technologies to combine the two signals. The optimal technology that maximizes the overall signal-to-noise ratio is the maximal ratio combiner (MRC). Note that MRC combining requires a coherent detector that has knowledge of all channel coefficients. The SNR at the output of the MRC is equal to the sum of the received signal-to-noise ratios from both branches [27].

With knowledge of the channel coefficients $h_{s,d}$, $h_{s,r}$ and $h_{r,d}$, the output of the MRC detector at the destination can be written as

$$y = a_1 y_{s,d} + a_2 y_{r,d} \quad (2.9)$$

It is needed to note that the combining factors a_1 and a_2 should be designed to maximize the combined SNR.

2.2.2.2 DF Relaying Protocol

After the relay has received the signal from the destination, it also can process the received signal by decoding it, re-encode it and then retransmit it to the receiver. This kind of relaying is termed a DF relaying protocol, which is often simply called a DF scheme without the confusion from the selective DF relaying scheme.

In this method a user attempts to detect the partner's bits and then retransmits the detected bits (Fig. 2.4). The partners may be assigned mutually by the destination. If the decoded signal at the relay is denoted by $\hat{x}$, the transmitted signal from the relay can be denoted by $\sqrt{P}\hat{x}$, given that $\hat{x}$ has unit variance. Note that the decoded signal at the relay may be incorrect. If an incorrect signal is forwarded to the destination, the decoding at the destination is meaningless. It is clear that for such a scheme the diversity achieved is only one, because the performance of the system is limited by the worst link from the source-relay and source-destination. Although fixed DF relaying has the advantage over AF relaying in reducing the effects of additive noise

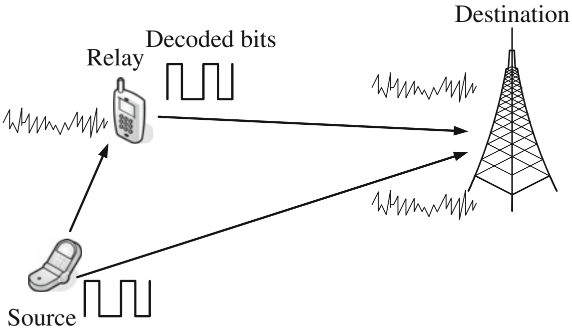

Fig. 2.4 Fixed decode-and-forwarded relay protocol

at the relay, it entails the possibility of forwarding erroneously detected signals to the destination, causing error propagation that can diminish the performance of the system. The mutual information between the source and the destination is limited by the mutual information of the weakest link between the source-relay and the combined channel from the source–destination and relay–destination [27].

2.2.2.3 CF Relaying Protocol

Coded cooperation differs from the previous schemes. Coded cooperation is a method that integrates cooperation into channel coding. Coded cooperation works by sending different portions of each user's code word via two independent fading paths. The basic idea is that each user tries to transmit incremental redundancy to its partner. When it is not in possible, the users automatically revert to a noncooperative mode. The key to the efficiency of coded cooperation is that all of this is managed automatically through code design, without feedback between the users (Fig. 2.5) [26, 28, 29].

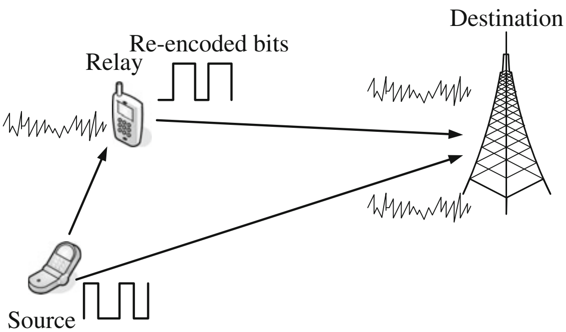

Fig. 2.5 Coded cooperation relay protocal

2.3 CSS Model

In CRN, the cooperative technologies can be used by SUs to achieve CSS so as to improve the signal detection efficiency. According to the analysis above, the CSS model can be divided into the following two categories: (1) cooperative relay transmission (named as relay based CSS thereafter) (2) cooperative transmission between secondary nodes to improve spatial diversity, which further include centralized based CSS and distributed based CSS.

2.3.1 Cooperative Diversity for CSS

Multiple antennas technology has been shown as an efficient way to provide superior reception performance due to the potential high-space diversity [30]. In CRN, it is not practical to implement multiple antennas at each SU because of the increasing cost and hardware complexity. However, a virtual antenna array can be formed by allowing multiple SUs to cooperate. Consequently, the classical space-time coding approaches [31] which have been widely used in multiple-input multiple-output (MIMO) systems can be used in CRN so as to achieve a high cooperative diversity [9].

According to the cooperative method, there are centralized based CSS and distributed based CSS to achieve cooperative diversity. In centralized based CSS, a CR BS called FC controls the three-step process of CSS. First, the FC selects a channel or a frequency band of interest for sensing and instructs all cooperating SUs to individually perform local sensing. Second, all cooperating SUs report their sensing results via the control channel. Then the FC combines the received local sensing information, determines the presence of PUs, and diffuses the decision back to cooperating SUs. While in distributed based CSS, the SUs do not rely on a FC for making the cooperative decision and each SU act as a FC. In this case, SUs communicate among themselves and converge to a unified decision on the presence or absence of PUs by iterations. In this article, we only consider the centralized based CSS as example to study the CSS performance.

Consider the case when two-located SUs cooperate on spectrum sensing, as illustrated in Fig. 2.6. Since the two users are close, the channels between two users

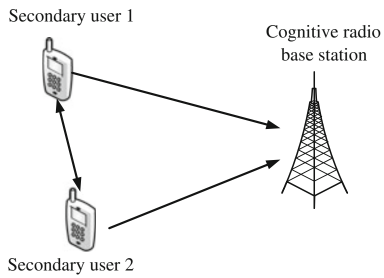

Fig. 2.6 Cooperative diversity technique for centralized based CSS. The two co-located SUs exchange their local decisions and form a distributed antenna array over the reporting channels

can be assumed to be ideal. Firstly, the two users perform local spectrum sensing independently and obtain the sensing results D_1 and D_2 for user 1 and user 2, respectively. Then, they may exchange their decisions and send them alternatively in two time slots, with user 1 transmitting $\{D_1, D_2\}$ and user 2 transmitting $\{-D_2, D_1\}$. By doing so, each decision is reported to the common receiver through two independent fading channels. This gives rise to a space diversity gain of 2. When the number of SUs in cooperative spectrum sensing is K, it can be expected that a diversity gain of K will be achieved [9].

For high data rate wireless communications, channel frequency selectivity becomes a critical challenging issue that can significantly affect the system performance. Orthogonal frequency division multiplexing (OFDM) is a powerful tool that can deal with the detrimental effects of multipath fading [32] and has been adopted in many wireless standards such as DTV and wireless LAN. In particular, an OFDM-based cognitive radio system structure is considered by the IEEE 802.22 working group for wireless regional area networks (WRAN). For OFDM-based cognitive radios, cooperative diversity technique can be performed as follows. The two users exchange their local spectrum sensing decisions. Then, the decisions will be sent through two separated sub-channels from each user to the common receiver. By doing so, a frequency diversity gain of 2 can be achieved over frequency-selective fading channels. Therefore, by exploiting a cooperative diversity among co-located secondary users, we can reduce the reporting error probability and then enhance the CSS performance. However, when there are multiple SUs to detect one PU's presence, their local spectrum sensing results have the same information about the detected PU, in this case, the local spectrum sensing results can be directly transmitted to the FC to achieve diversity gain without the information's exchange by the two SUs, which have been widely studied. In this book, we also consider this occasion of the CSS by diversity cooperation, which is also called as CSS based on nodes' cooperation (CSS for short in the following) [9].

The CSS model with N nodes is shown in Fig. 2.7. The whole process is divided into two steps. Step (1): Each SU perform the local spectrum sensing independently to detect the PU signal. Step (2): Each SU send the detected PU information to the FC, and the FC combines all of the information to make a final decision.

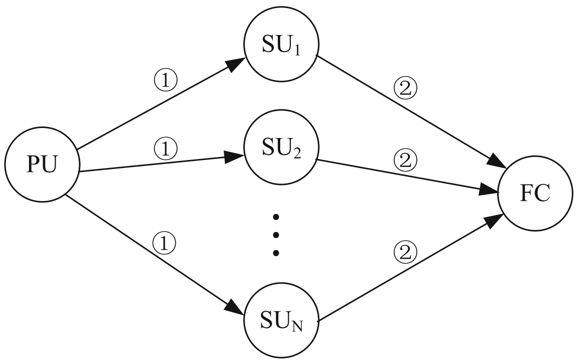

Fig. 2.7 Cooperative spectrum sensing model with *N* nodes

2.3.2 Relay Diversity for CSS

CR has been suggested to improve the spectrum utilization by allowing secondary unlicensed users to opportunistically share the spectrum that is not used by the primary licensed users. Cooperative relay technology is regarded widely as a key technology for increasing transmission diversity gain in various types of wireless networks, including CRNs, which can combat signal fading due to multipath propagation in a wireless medium. The original idea of cooperative relay transmission comes from the basic relay model that consists of three terminals: a source S, a relay R, and a destination D. By enabling a set of cooperating relays to forward received information, the spatial diversity can be achieved through cooperation by multiple terminals [2, 33]. In this article we investigate a simple wireless network, where a spectrum-rich node is selected as the relay node to improve the performance between the source and the destination.

In the context of CRN, cooperative relay transmission can give rise to the following two different but basic scenarios.

1. Cooperative relay transmission between PUs and SUs.

In this case, SUs can relay the traffic of a primary transmitter toward the intended destination. The rationale behind such a decision is that helping PUs finish their transmissions as quickly as possible will, in turn, lead to more transmission opportunities for SUs [33, 34].

2. Cooperative relay transmission between SUs.

In this scenario, a SU acts as a relay from the transmission of another (source) secondary node. When the reporting channels of some SUs experience heavy shadowing, the local decisions in these SUs cannot be forwarded to the FC. Then, the maximum cooperative diversity gain of CSS will be reduced. Assume that SU i fails to send its decision to the FC due to heavy shadowing in its reporting channel. This is the case when the received signal power is so weak that it is merged into the noise. In this case, FC has to make a random decision if it incorporates such an unreliable SU into the cooperative decision. Hence, using some unreliable cognitive radios cannot improve the CSS performance. To address this issue, FC could censor the SNR of the received signal to check whether this cognitive radio is reliable enough before counting it into the cooperative decision. If the SNR of the received signal from SU_i is lower than a predefined threshold, then the SU i will be labeled as an unreliable one. Under the supervision of the FC, the unreliable one can relay its local spectrum sensing result to other cognitive radios which are in enough good channel state, as shown in Fig. 2.8 [33].

With the relay technique, we see that CSS achieves the full cooperation among SUs by avoiding transmission of local sensing results over bad reporting channels. Suppose that M out of K SUs experience heavy shadowing. Without any relay, the diversity gain of the CSS is only (K-M). However, with the help of other relay

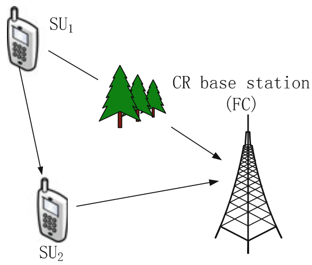

Fig. 2.8 Cooperative relay sensing

cognitive radios, it is demonstrated that the maximum cooperative diversity gain K can be achieved [1, 35].

We can see that cooperation transmission between SUs aims to increase the secondary throughput for a given spectral hole, whereas cooperation transmission between PUs and SUs aims to increase the probability of transmission opportunities. In summary, both of the cooperation transmission schemes described above try to improve spatial diversity for the same spectrum frequency band.

In this book, we only consider the latter and do deep research on how to improve the sensing performance by SUs' cooperation. CSS is based on cognitive relay, which is also called the relay based CSS in the following, as shown in Fig. 2.9. The whole process is divided into three steps. Step (1): The SU detect the PU signals by performs the local spectrum sensing. The secondary relay (SR) can choice whether to detect the PU signals. Step (2): The SU send the detected information to the FC and the SR. Step (3): If the SR has successfully received the information from the SU, the SR will forward the received information to the FC. Further more, if the PU signal has also been detected by the SR in step (1), then the SR will combine the information received from the SU and the PU's information detected in the above step, and then transmit the combined information to the FC. The SR can also feedback to the SU whether it has received the correct information. This kind of collaborative approach is actually a typical application in CR of cooperative transmission mode. In this approach, the FC can achieve diversity gain by receiving the two signals from the SR (including the SU's information) and the SU.

In the two CSS model described above, there exist multiple methods when the SR and the SU forward the information to the FC, such as AF, DF and CC [2, 23]. In the CRN, the SU and the SR play not only as destination node, but also as source node. When they are played as source nodes, they have already received the PU signal or the SU signal and therefore they are also acted as the forwarding nodes,

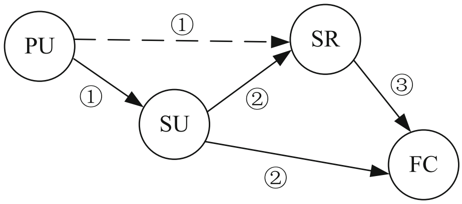

Fig. 2.9 Cooperative spectrum sensing model based on cognitive relay

which are different between the cognitive relay cooperation communication and the traditional relay cooperation communication. In order to describe the three data forwarding modes described above, the nodes acted as transmission source nodes in both models are called the source nodes and the nodes in the receive side are called the destination nodes. For example, in the relay-based CSS, the SU is the source node and the SR is the destination node in step (2); while in step (3), the SR is the source node and the FC is the destination node. In the second CSS method, the SU is the source node and the FC is the destination node. In the AF mode, the source node simply amplifies and forwards the received signals to the destination node without any decoding or encoding operations. In the DF mode, the signal received by the source node will be demodulated, decoded and estimated at first, and then transmitted to the destination node. In the CC mode, the cooperation and the channel coding are combined, in which, the source node will decode and recode the received signals and then transmit the recoded signal to the destination node. The above three relay cooperative approaches have their values in different scenarios to realize respective advantages. In this article, we mainly consider the DF mode when doing research on the relay based CSS; while during the CSS study, we mainly consider the AF and the DF mode.

2.4 The Process of CSS

According to the description in Sect. 2.3.2, the relay-based CSS actually can be seen as the case that the FC combines the information of two nodes. In the relay-based CSS, the information transmitted from the SR to the FC may contain not only the PU information but also the SU information. The overall sensing process can be described by two consecutive processes of centralized-based CSS: sensing process and reporting process. As shown in Fig. 2.10, the whole process consists of three steps: local spectrum sensing, the local spectrum sensing results' transmitting and information fusion. In the following, we will take a brief

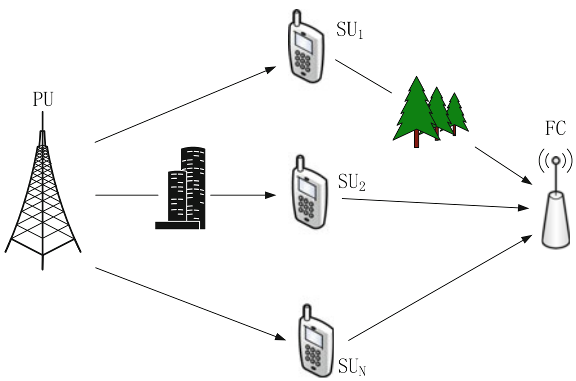

Fig. 2.10 The centralized based CSS in CRN

introduction to the three steps of the CSS and point out the problem we considered in this article.

Step 1: Local spectrum sensing

Each SU performs local single spectrum sensing utilizing certain detection algorithms, such as energy detection algorithm, matched filter detection algorithm and cyclostationary detection method etc. In the energy detection method, the SU determines whether the channel is idle or not by measuring the energy of radio frequency signal or the received signal strength indicator. Its process is simple: firstly, the input signal is filtered with a band-pass filter to select the interesting bandwidth. The output signal is then squared and integrated over the observation interval. Finally, the integrator output signal is compared to a predefined threshold to infer whether the PU signal is present or not. Since the energy detection method is simple and easy to operate, a lot of literatures have studied the local spectrum sensing performance by using energy detection method [17, 36–39]. When energy detection method is used in the local spectrum sensing, each SU will transmit the detected energy signal or decision results to the destination node.

Step 2: Local spectrum sensing results' transmitting

In the centralized based CSS, each SU send the detected signals to the FC through the reporting channel. Many researchers have studied the cooperative spectrum sensing performance when the reporting channels (the channels from SUs to the FC) are Additive White Gaussian Noise (AWGN) [13–15, 20, 21, 40, 41]. As shown in Fig. 2.10, the hidden terminal problem also exist in the reporting channels, for example, there exists shadowing between SU_1 and the FC, therefore, the data transmitted from SU_1 to the FC will be impacted by the channel fading, which may result the error transmission. We can learn from literature [1, 35] that the fading of the reporting channel will also affect the performance of CSS. At present, the research of CSS performance under both imperfect sensing channels and reporting channels still at an initial stage, and we will study it deeply in this paper.

Step 3: Information fusion at the FC

In the centralized based CSS, the FC combines all of the information from each SU and makes a final decision to infer the presence or absence of the PU in the observed channels. There are different ways for information fusion. The performance of a variety of fusion methods have been studied in literature [42–46]. We can conclude that the main fusion methods including soft combination and hard combination. In the method of soft combination, the SU will be weighted before sending information to the FC so that the channel state information can be used to improve the accuracy of information combination; while in method of hard combination, the SU sends the information to the FC directly without any preprocessing. In the other hand, fusion method can be divided into data fusion and decision fusion in the point of the data format having been transmitted by the SU.

From Step 1 to Step 2, when each SU performs the local spectrum sensing, it can either directly send the detected PU information to the FC or can make a judgment firstly and then send the result to the FC, where, the former belongs to data fusion, and the latter belongs to decision fusion.

In this paper, the SU performs local spectrum sensing using energy detection method. If the SU directly sends its detected PU energy to the FC, we regard it as a kind of AF method from the point of cooperative method. On the other hand, we call it as the energy fusion (belongs to the data fusion) from the point of fusion, if the received energy signal at the SU is directly forwarded to the FC without any decoding or encoding operations. Each SU transmits the detected PU energy signal to the FC, and the FC makes a final decision by combing all of the received data from each SU utilizing equal gain combing (EGC), maximum ratio combining (MRC) and selection diversity combining (SDC) etc. From [43, 47–50], we can see that the better detection performance can be achieved by data fusion, however, because the CR system is a band-limited system, if there are more SUs the more control channel bandwidth will be occupied for sending the local sensing results, which may result in the lower spectrum utilization.

Usually, in the CSS, a simple decision fusion method is usually used in order to save the control channel bandwidth. Each SU will make a binary decision based on its local observation. It indicates the presence of the PU if the local decision result is 1, and the absence of the PU is 0. Actually, this method is a kind of simple DF method, in which the PU's signal is firstly demodulated, decoded and re-estimated and then transmitted to the FU by the SU. In the decision fusion mode, the SU will make a 1 bit quantization judgment according to the detected signal firstly and then makes a final decision according to multiple 1 bit result utilizing 'k out of N' criterion. Researchers have made a detailed study to the performance of 'k out of N' in the literature [21, 42, 51]. The 'or' rule corresponds to the case of $k = 1$, in which the FC infers the presence of the PU as long as one of the SUs assume the presence of the PU. It can be seen that the 'or' rule is very conservative for the SUs to access the licensed band, which is to ensure that the interference to the PU is minimized and to reduce the probability of miss detection. The 'and' rule corresponds to the case of $k = n$, in which the FC makes judgment that the PU is exist only when all of the SUs infer the presence of the PU. It can be seen that the 'and' rule is an aggressive strategy, i.e., the SU can access the licensed spectrum as long as one of the SUs infer the absence of the PU. Compared with the 'or' rule the higher spectrum efficiency can be achieved in the 'and' rule, while the probability of miss detection also increased at the same time. The 'or' rule gives better performance than other rules in the point of protecting the PU. In the actual occasions of spectrum sharing, the SU access the idle spectrum opportunistically. The PU may return to the occupied spectrum at any time, so we must make sure that the PU is protected sufficiently. Therefore, in the research of CSS, when the decision fusion is considered, the FC often combine the information by the 'or' rule.

2.5 Research Status

In CRN, the PU should be protected sufficiently when the SUs access the spectrum. Therefore, how to accurately sense the idle channels and detect the presence of the PU so as to ensure the PU un-disturbed when the SUs access the channels are our primary research objects. The hidden terminal problem is a difficult problem in spectrum sensing [1, 20], i.e. the channel multipath fading and shadowing effects often make the single-user spectrum sensing performance very poor, so it is very difficult to accurately detect whether the PU signal is present or not in single-user spectrum sensing. The detection performance under fading sensing channels can be effectively improved by multiple SUs' cooperative spectrum sensing, which has been studied widely.

The system performance gain caused by user's collaboration has been investigated in [20, 21] when the sensing channels are AWGN, in which, the two user's cooperation method and multiple-users' cooperation method are given based on the periodic spectrum sensing. Researchers have studied the affect of sensing diversity order to the CSS performance when the sensing channel experiences AWGN channel and fading channel respectively [13–15]. The results show that the performance of CSS improves with the increase of sensing diversity. Furthermore, it has been proved theoretically that compared with the single user spectrum sensing, the CSS can reduce the demand of the average signal-to-noise of sensing channels. The researches above are all based on periodic spectrum sensing, in which, the sensing time and sensing performance are contradictory, i.e. a longer sensing duration can produce a better sensing performance but results in a longer waiting time for the SUs to access the channel, which will cause serious interference to the PU [1]. Optimal sensing duration has been studied to improve the system performance in [51–56]. However, the researches described above did't consider the occasion that the reporting channels suffer from fading. In [1, 7, 35], the authors pointed out that the reporting channel's fading would deteriorate the CSS performance. In addition, in CSS, the total sensing time include two parts: the local detection time and the reporting time for sending the SUs' local information. In the existing studies, the Time Division Multiple Access (TDMA) mode has been considered for sending local sensing results. Obviously the fewer SUs involved in CSS, the shorter the whole sensing duration. However, a small number of SUs in CSS results in a small sensing diversity order which will lead to the lower probability of detection. This problem can be addressed by allowing the SUs to send the decisions on orthogonal frequency bands, i.e. Orthogonal Frequency Division Multiple Access (OFDMA) mode, but this requires a large portion of the available bandwidth [1], consequently the lower frequency utilization, which should be studied further.

In CSS, more SUs participated in cooperation will make the higher sensing diversity order and the better sensing performance. In the decision based CSS, the control bandwidth can be greatly reduced by one bit quantization compared with data fusion and multiple bits quantization method. However, when the number of sensing users is very large, the total number of sensing bits transmitted to the FC is still very huge and the larger control bandwidth will be occupied. Consequently, how to save the control bandwidth as soon as possible and improve the spectrum utilization at the same time deserved further research. In addition, in [35], it has been shown that the influence of reporting channels' fading to the sensing performance is also related to the sensing diversity order. Under certain reporting channels' fading, the higher sensing diversity order will result the worse sensing performance. Therefore, how to make a tradeoff between the reporting channels' fading and the sensing diversity order need to be considered further.

Cooperative transmission technology with relay can effectively combat the channel fading and enhance the system throughput [5, 57]. As stated in [10], the relay technique has been generally considered as an effective method to improve the capacity and coverage for next generation wireless networks, which is also effective in cognitive radio networks. In [34], the authors have considered a secondary transmitter to act as a relay for primary transmissions. It has been shown that the secondary link throughput can be improved in certain network topologies. The CSS performance based on relay cooperation is investigated in [20] and [21], which focus on how to cooperate between SUs. Paper [33] has investigated the use of cooperative relay to assist the fulfillment of heterogeneous traffic demands in a secondary network with an unbalanced spectrum usage. They have proposed a scheme to improve diversity by cooperative relay in CRN. More recently, papers [58–63] investigate the relay spectrum sensing protocal including multiple relay and best relay, which mainly focus on the optimization of sensing overheads and the enhancement of received signal by relay to improve the sensing performance. In the research about the cooperative spectrum sensing with relay above, they mainly take more attention on how to reduce the interference to the PU and other SUs. As to how to improve the transmission reliability in the reporting channels, there is little research, which needs to be in-depth study.

The system performance can be effectively improved by the soft combination based CSS compared with the CSS based on hard combination. At present, the research on the soft combination based CSS mainly consider the data fusion method, in which, the SU can provide relatively detailed and effective local detection information for the FC, and which has been studied in [48, 49]. The authors proposed an optimal soft combination scheme and showed that the CSS performance increased with the increase of the sensing users, however, the infinite bits are required and this will result in a large communication bandwidth when there is large number of SU which will cause the great waste of communication bandwidth. A lot of work has been done on the quantization for the signal detection. In [50], an optimal soft combination scheme is proposed, based on some approximation in the target optimal function. In [47], a linear soft combination of raw measurements from individual cooperative SUs performed at the fusion center is considered. All of the research consider the channel between SU and FC is perfect. In fact, the imperfect reporting channels would induce the detection performance degraded greatly [35, 64].

The purpose of doing deep research to the spectrum sensing technology is to make the CR apply to the actual wireless system more effectually. 3GPP and IEEE either have put forward the some new requirements to the function of future wireless networks, such as self-planning, self-establishment, self-deployment, self-allocation, self-operation, self-optimization, self-healing and other features [65, 66]. As to how to use the cognitive technology in wireless telecommunication networks need to be further studied.

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http://www.springer.com/978-3-319-31094-7

Cognitive Wireless Networks Using the CSS Technology
Li, M.; Wang, A.; Pan, J.-S.
2016, XII, 160 p. 69 illus., 31 illus. in color., Hardcover
ISBN: 978-3-319-31094-7