Chapter 2
Opportunistic Spectrum Access

2.1 Sensing Based Opportunistic Spectrum Access

In the literature, the *opportunistic spectrum access* (OSA) architecture is the de facto architecture for spectrum sharing. Most studies on dynamic spectrum access have assumed this model, e.g., see [1–12] and references therein. The motivation for the OSA architecture is based on the observation that the licensed spectrum is underutilized. Specifically, the licensed spectrum is significantly underutilized in the time, space, and frequency domains. In other words, there are many spectrum holes or white space in the temporal, spatial, and frequency domains, as illustrated in Fig. 2.1a. A spectrum hole is a quiet or idle period of a spectrum band at a certain location. It is also often called white space in the literature. The key feature of the OSA architecture is that the SUs dynamically search for such spectrum holes or white spaces, and opportunistically access spectrum. Figure 2.1b illustrates two snapshots of the spectrum usage at time $t1$ and $t2$, respectively, at a certain location. An SU dynamically finds and selects the spectrum band for access. In the OSA architecture, the PU and the SU have mutual exclusive access to the spectrum band. The PU has the absolute privilege for spectrum access. The SU that is accessing a spectrum band must yield to the PU whenever the PU starts to access the band, in order to avoid harmful interference to the PU. That is, SUs are constrained to opportunistically utilize the spectrum holes or white spaces in the temporal, spatial and frequency domain for communications. The SU uses the cognitive radio to sense the surrounding spectrum environment, then selects one idle spectrum band to transmit data packets. In the OSA architecture, there are three fundamental components: spectrum sensing, spectrum access, and spectrum handoff, which work together to search and access spectrum holes.

2.1.1 Spectrum Sensing

Spectrum sensing is a fundamental component for the OSA architecture. First, before an SU starts communications, it needs to sense spectrum to find an idle spectrum

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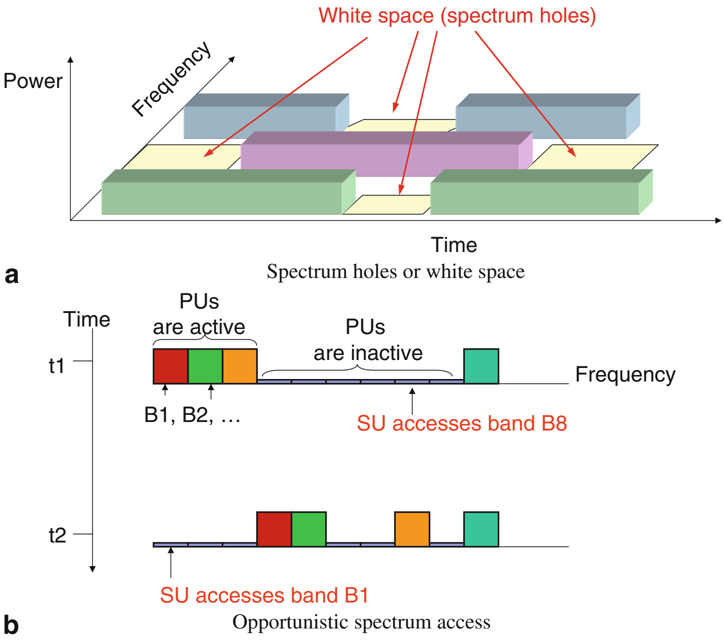

Fig. 2.1 Spectrum holes and the access to spectrum holes by secondary users in opportunistic spectrum access

band to transmit/receive packets. Second, during the SU communications, the SU needs to sense the spectrum band being used for SU communications, to detect if a PU signal re-appears on this band. If there is a PU signal on the band, the SU needs to vacate from the band immediately to avoid harmful interference to PU.

Ideally, spectrum sensing should detect the PU receiver, which is the device we really should protect from SU interference. However, the receiver is often a passive device and hence rather difficult to be detected. Therefore, most studies on spectrum sensing are on the transmitter detection. The spectrum sensing techniques can be approximately classified as in Fig. 2.2. In the next two subsections, we discuss *local sensing* and *cooperative sensing*, respectively.

2.1.1.1 Local Sensing

Local sensing is the spectrum sensing activity performed by each SU individually. There are three major techniques for local spectrum sensing at an SU: energy detection, matched filter detection, and cyclostationary feature detection. The matched filter detection relies on the a priori knowledge of the PU signal, e.g., the modulation, pulse shaping, and the packet format [13]. With such a priori knowledge of the PU signal, an SU can correlate the received signal with a corresponding PU signal, and

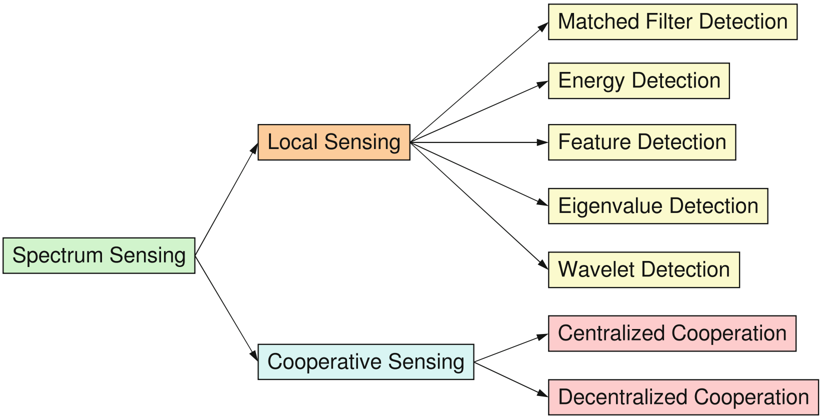

Fig. 2.2 Spectrum sensing techniques

samples the output to detect if the received signal is the PU signal. In contrast, the energy detection does not need any a priori knowledge of the PU signal. It also has other benefits such as low complexity and easy implementation. The received signal energy is measured and compared with a pre-defined threshold [14]. If it exceeds the threshold, then the received signal is treated as a PU signal, and the spectrum band is found busy. Otherwise, the spectrum band is treated as idle. The disadvantage of energy detection is that it is vulnerable to high noise power, which may result in a high false alarm probability. In the scenario with high noise power and/or low signal power, the performance of energy detection may suffer, to result in a high miss-detection probability and/or a high false alarm probability. The cyclostationary feature detection has been developed to address such scenario [15, 16]. This is because, different from noise, most signals have the cyclostationary feature, as their means and autocorrelations exhibit a periodicity feature. Besides these three techniques, there are also other techniques for spectrum sensing such as the eigenvalue detection and the wavelet detection. The eigenvalue detection technique utilizes the eigenvalues of the covariance matrix of the received signal to detect the presence of the PU signal [17]. The wavelet technique is a widely used mathematical tool for analyzing signals. It can also be used to detect the existence of PU signal, particularly in a wide range of spectrum [18].

2.1.1.2 Cooperative Sensing

Local sensing at each individual SU is a starting point for spectrum sensing. Nevertheless, local sensing is often not sufficiently accurate for detecting the PU signal, due to fading, shadowing, and other factors in wireless communications. Therefore, cooperative sensing has been developed to improve the detection accuracy through cooperation among SUs on spectrum sensing. It can operate either in either a decentralized or a centralized mode [19, 20]. With the decentralized mode, SUs exchange local sensing results with each other. After receiving the sensing results from other SUs, an SU can make its own decision on the status of a spectrum band. With the centralized mode, a fusion center such as a base station collects sensing results from all SUs. The fusion center then makes decision on the spectrum band status. The decision making on the spectrum band status can take two approaches: data fusion or decision fusion. With the data fusion approach, all SUs send either raw or processed sensing data, such as the received signal power, to the fusion center, which makes a decision based on the sensing data. With the decision fusion approach, each SU locally processes the sensing data and makes a decision on the band status (often a binary decision of either busy or idle). This decision is then sent to the fusion center. The fusion center makes a final decision based on the local decisions, through a "voting" scheme, e.g., an "OR", "AND", or "Majority" voting.

2.1.2 Spectrum Access and Spectrum Handoff

In the OSA architecture, SUs cannot access a spectrum band when a PU is using it. Moreover, the communication channels (spectrum bands) are dynamically available. Thus, an SU needs to dynamically jump onto different channels over time. That is, an SU usually has to utilize multiple channels for data communication. Therefore, spectrum sharing in the OSA architecture somehow is related to the multi-channel MAC protocols in traditional wireless networks that aim to reduce co-channel interference (and hence increase throughput) by using multiple channels. Nevertheless, the MAC protocols of traditional wireless networks, e.g., the ones in [21, 22], usually cannot be directly used by SUs because they require static channels (i.e., channels are accessible all the time). Hence new protocols and algorithms have been developed for spectrum access for the OSA architecture. These studies primarily take two approaches, depending on whether relying on a control channel. In the first approach (e.g., see [5–12]), a common control channel is used to coordinate SUs for negotiating channels for communications.

The second approach eliminates the dependence on a common control channel among SUs. This is because a common control channel is vulnerable to traffic congestion and jamming attack. However, without a common control channel, the rendezvous between a transmitter and a receiver is a great challenge. For instance, when two SUs are communicating with each other, if the PU signal appears on the channel, the two SUs need to vacate from the channel immediately. In general, they both need to switch to another channel to continue the communication. While the two SUs may negotiate a backup channel before the current channel is disrupted by the PU signal, there is no guarantee that this pre-negotiated backup channel is still available after the current channel becomes unavailable since the availability of every channel is dynamic. The two SUs may frequently check and update the

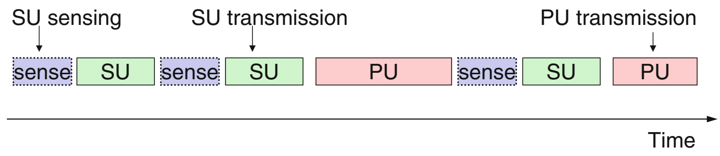

Fig. 2.3 Spectrum access in the OSA architecture

backup channel if necessary, to make sure it is up-to-date. However, the overhead for maintaining the backup channel would be high.

A more popular approach is to let an SU hop on channels by a channel hopping sequence, without maintaining a backup channel [23–29]. Instead of continuing the communication with the peer after the current channel becomes unavailable, an SU simply hops to the next channel in the hopping sequence every time slot, and communicates with the SUs currently on that channel. After hopping to the last channel in the sequence, the hopping starts again from the first channel. Such a hopping cycle from the first channel to the last channel is called a *frame*. The communication with the current peer SU is halted, and will be continued when the two SUs hop to the same channel. A critical requirement of this approach is that the channel hopping sequences have to be designed such that any two SUs are ensured to hop to the same channel at some time slot in a frame. Fortunately, this is possible, e.g., through a *quorum* system [25]. Another approach without using a control channel is to estimate the current channel of the receiver SU [30–32]. With this approach, each SU randomly selects the operational channel. The SUs are hence evenly distributed on to all available channels, which minimizes the co-channel interference between SUs, and maximizes throughput. When an SU has packets to another SU, it estimates the current operational channel of the receiver SU, and then switches the radio to the receiver's channel. The channel selection scheme for the operational channel selection by each SU is intelligently designed such that the success probability of channel estimation is high, when an SU estimates the channel of another SU. Hence the transmitter SU can meet the receiver with a high probability.

The spectrum access of SUs generally typically takes a sensing-transmission cyclic mode, as illustrated in Fig. 2.3. After two SUs switch to the same channel, before starting packet transmissions, the SUs first sense the channel to ensure that there is no PU signal. If the channel is idle, the transmitter SU begins to send packets to the receiver for a period of time. Then the SU communication needs to be paused, and the SUs need to sense the channel again to make sure that the PU signal has not become active during this period. Only if the PU signal is not detected, the SU communication resumes. This sensing-transmission cycle is repeated until the SU communication is completed. The periodic spectrum sensing is necessary as when during the SUs packet transmission period, the SUs cannot detect if a PU signal appears on the channel, since the full duplex wireless communication, i.e., sensing while transmitting by the SU, is difficult with today's technology. Whenever a PU signal is detected on the channel, the SUs can wait until the PU signal disappears, or switch to another channel (spectrum handoff) as discussed earlier.

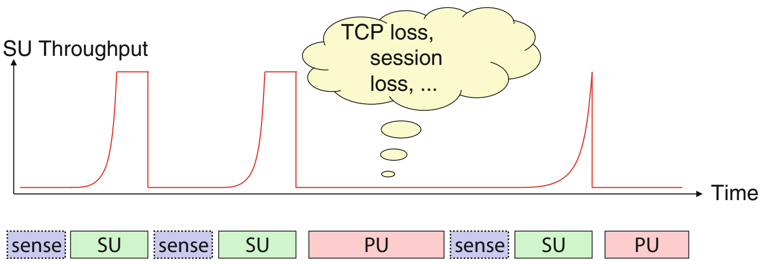

Fig. 2.4 Unstable SU throughput due to disruptions from re-appearance of PU signals

2.1.3 Challenges for the OSA Architecture

In the OSA architecture, SU needs to accurately detect the PU signal in order to avoid harmful interference to the PU. However, by today's technology, accurate spectrum sensing is very challenging, due to multipath, fading, and shadowing, and the ever growing radio interference [33, 34]. Cooperative spectrum sensing can relieve these problems, but also raises new problems such as complicated coordination, increased decision time, and vulnerability to the *spectrum sensing data falsification attack* [35]. Furthermore, spectrum access by SUs in the OSA architecture has to operate with a sensing-transmission cyclic mode, due to the technical difficulty of sensing while transmitting. This introduces significant overhead. Moreover, the re-appearance of PU signal disrupts the SU communications arbitrarily, since the SUs have to vacate from the channel whenever the PU starts using the channel. Such arbitrary disruptions result in highly unstable and unpredictable SU communications, which in turn results in poor quality of service (QoS). Figure 2.4 illustrates a typical SU throughput. Due to the disruptions from the re-appearance of PU signals, and the periodic sensing, the SU throughput fluctuates dramatically, resulting in poor quality of service for applications. The requirement that SUs must yield to the PU whenever the PU starts using the spectrum band also makes SUs vulnerable to the *primary user emulation* attack, where a malicious SU emulates a PU signal by transmitting the PU waveform through a cognitive radio.

2.2 Geo-Location Based Spectrum Access

While the spectrum sensing based OSA architecture is the spectrum sharing architecture assumed by most studies in the literature, for some bands with special usage patterns, an alternate approach based on the geo-location spectrum database can be used. In 2010, FCC officially announced the secondary access to TV white spaces, utilizing a spectrum database approach. Specifically, all the TV broadcasters and wireless microphone users need to register their usage in a spectrum database. For a TV white space device to access spectrum, it first contacts the TV usage database and gets the available channels based on its location.

The frequency of TV white space is seen as "golden standard" frequency for broadcast wireless access service. This is because the TV bands have excellent propagation property and building penetration capability. By the physical law, the radio coverage of a device such as a base station is proportional to the square of the frequency. This translates to that the coverage at TV bands is about 10 times larger than the 1800 MHz cellular band, and 20 time larger than the 2.6 GHz band, which was also a candidate for 4G cellular service. This in turn means it costs significantly less to build a network since the number of base stations at the TV bands are 10 times or 20 times less.

TV bands are below 1 GHz and have excellent properties for propagation, building and foliage penetration, and non-line of sight connectivity. They offer excellent opportunities to support various applications, including wireless broadband access, WiFi-like networks with better coverage and penetration, and traffic offload for another subscription based network such as 4G cellular network.

2.2.1 TV Band Usage

Definition 2.1 A *TV white space channel* is an unused or unoccupied TV channel, i.e., there is no active TV broadcasting on the channel. A *first adjacent (white space) channel* is a white space channel that is right next to an occupied TV channel. A *second adjacent (white space) channel* is a white space channel that is not neighboring to any occupied channel.

In 2008, FCC set rules to allow unlicensed devices to use TV white space. These devices are called *TV white space devices*. The devices are classified into fixed and portable, depending on the transmit power. The fixed devices are allowed to have 4 watts EIRP, while the portable devices are allowed to have either 40 or 100 milliwatts (mW) EIRP, depending on the distance between the operating channel and the closest occupied TV channel which has active TV broadcasting. The fixed devices such as base stations are allowed to operate only in the second adjacent white space channels as defined in Definition 2.1. The portable devices can be allowed to operate in both first and second adjacent channels, with distinction on transmit power. In the first adjacent channels, the transmit power of the portable devices is limited to 40 mW, while in the second adjacent channels, the transmit power of the portable devices is limited to 100 mW. Figure 2.5 illustrates the classification of channels and the allowed operation of the TV white space devices.

2.2.2 TV White Space Availability

Originally, there were totally 83 TV channels. With the channel relocations/repurposing over the years, after the analog to digital TV transition in 2008, there remains only 50 broadcast TV channels, from channel 2 to channel 51. These

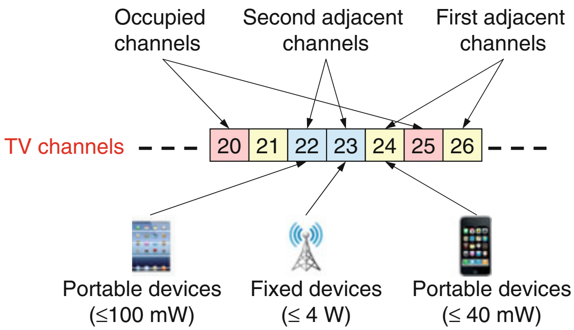

Fig. 2.5 Classification of TV white space channels, and the allowed operation of TV white space devices. The fixed devices such as base stations are allowed to operate on *second adjacent white space channels* only with up to 4 W transmit power. The portable devices can operate in both *first and second adjacent channels*, with the transmit power up to 40 and 100 mW, respectively

channels are distributed on three non-contiguous bands, 54–88 MHz, 174–216 MHz, 470–698 MHz. The fixed TV white space devices are allowed to operate on any TV channel from 2 to 51 as long as it is a second adjacent channel. The portable devices are allowed to operate from channel 21 to 51 only.

Many studies have shown that a large number of TV channels are not used in a vast portion across the United States. However, the use of available TV channels is constrained depending on the device type, as governed by the FCC rules discussed earlier. For instance, the fixed devices, which are essential for commercial applications such as wide area wireless broadband access, cannot use every available TV channel. Based on the rules for the fixed device, the TV channel availability shrinks. One profound observation is that the TV white space available for fixed devices is mostly available in sparsely populated areas, such as the mid-west, and rural areas, while the densely populated metropolitan areas have few available TV channels or even not at all.

2.2.3 TV White Space Access

The current framework of using TV white space is primarily a static approach for spectrum sharing. A key component is to build geo-location spectrum databases to track and assign TV white space channels. The PUs, TV broadcasters, TV translators, and wireless microphones, are all required to register their locations, TV channels under use, and the time periods of active TV channel usage. FCC requires that all spectrum databases have to synchronize with each other so that a PU device needs to register with one database only. An SU that wants to use TV white space has to first register with a geo-location database, by sending its ID, current location, as well as other parameters, through a non-TV white space communication channel across the Internet, e.g., a WiFi connection to the Internet, or a mobile broadband connection such as LTE. As discussed earlier, here an SU refers to either a portable device such as a mobile terminal, or a fixed device such as a base station. After an SU registers successfully with a geo-location database, the database assigns a list of available TV channels that can be used by the device based on the device location, subject to the device type and transmit power, to protect the PUs from harmful interference. The set of channels that can be used by a device may need to be dynamically updated due to mobility of the device, or the change of the TV channel availability. For example, the database may receive a channel registration from a new wireless microphone user.

To facilitate this procedure for some devices that do not have any kind of Internet connection, the devices are classified into *master devices* and *slave devices*. A master device has a non-TV white space Internet connection. Typically, this is a base station with a wired Internet connection. A slave device registers itself with a geo-location database through a master device, and hence does not need to have an Internet connection. Certainly the slave device still needs a non-TV white space connection to a master device. Typically, a slave device is a portable device that has a WiFi connection with a master device which is typically a base station with WiFi capability.

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