Chapter 2
Cognitive Radio Primer

In this chapter, wireless communication technologies relevant to cognitive radios are reviewed. This includes a discussion of some of the capacity limitations in wireless systems, nonideal effects in radio systems, and an overview of orthogonal frequency-division multiplexing (OFDM) encoding methods. Cognitive radios are detailed in this chapter. The architectural components as well as algorithms for frequency sensing and spectrum management are reviewed. Finally, some recent standardizations that are based on cognitive radios are reviewed along with a survey of some recent deployments of TV white space (TVWS) technologies, which is an implementation of cognitive radio.

2.1 Wireless Communication Technologies

One of the areas that has seen explosive growth over the past two decades is wireless communication technology. It took nearly a century of research and development to finally invent the radio in 1910. Research in this area started from the early works of electricity and magnetism that began in 1820 with the work of Hans Oersted [1]. It finally culminated in the practical invention of the wireless telegraphy in 1907 from the work of several people, including Guglielmo Marconi [2]. It took nearly another century to take this invention and provide true wireless connectivity between people where voice and data can be exchanged. The global launch of the Global System for Mobile Communications (GSM) in 1987 [3] marked the beginning of true wireless connectivity between people.

2.1.1 Wireless Connectivity Networks

A typical wireless connectivity network is shown in Fig. 2.1. This system is composed of two types of devices. A base station (BS) and a user premise equipment (PE). Both types of devices are capable of two-way communication. There is

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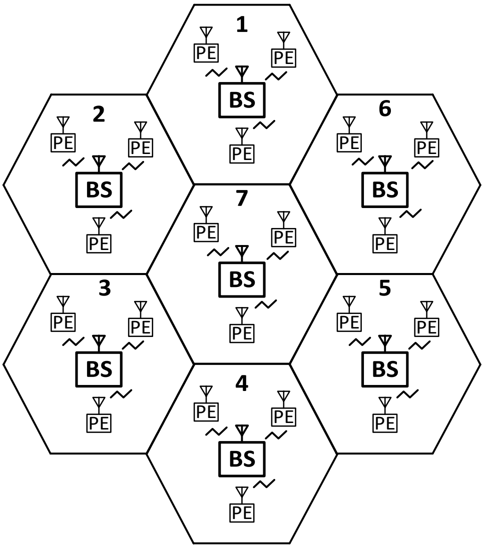


Fig. 2.1 Components of a basic wireless connectivity network

typically one BS per wireless communication area, called a cell unit. The PE typically only communicates with the BS, whereas the BS can communicate to any or all of the PEs in the network. The BS is responsible for allocating frequency spectrum to each PE. One way to increase coverage area is to increase the transmission power of the BS. Another way to increase coverage area is to add more BS units, each with a dedicated coverage area. To provide wireless communication to an entire area, the BS nodes are added to the network in such a way as to create adjacent but minimally overlapping wireless cell areas. Wireless communication in each cell area is regulated by the BS associated with that cell area. The size of the cell area depends on the physical terrain, maximum output transmission power of both the BS and the PE, and the receiver sensitivity of both the BS and PE.

In earlier cellular networks, a high-power BS would be used to cover a large cell area. It was noticed early on, however, that such networks suffer from several impairments. First, PE close to the BS can have their receivers saturated by the high output transmit power of the BS, thereby significantly reducing their sensitivity. The other major impairment is that the overall network capacity per unit area is limited since no wireless frequency spectrum can be reused within the cellular area. If the transmit power of the BS is reduced and the cell unit is broken up into several smaller cell units, then the wireless frequency spectrum can be reused and network capacity is significantly enhanced. This concept has been one of the driving technologies in the development of the next-generation wireless technologies, namely the migration of macro BS to small cells (pico BS and femto BS development) [4]. This concept is pictorially shown in Fig. 2.2.

There are other types of wireless networks that have received a significant amount of attention in both the academic and industrial circles. One such type of network is the unstructured wireless network. In this type of wireless network, the

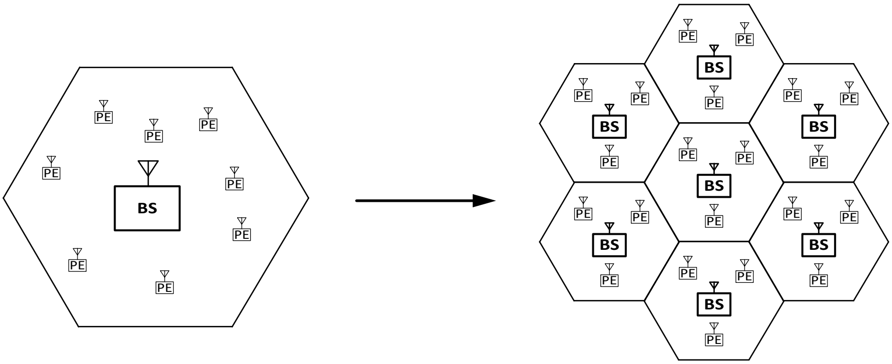


Fig. 2.2 Migration of macro base stations (*BS*) to small cells

location of a BS can be arbitrarily chosen or even mobile. An example of such a network is a wireless local area network (LAN, Wi-Fi) [5]. Another type of network is a distributed wireless network [6]. In this type of network, all nodes are typically identical and communicate with one another directly. In other words, they are self-configurable. Wireless sensor networks are an example of a distributed wireless network [7].

2.1.2 Wireless Channel Impairments

There are several impairments that a typical wireless channel suffers. A comprehensive treatment of all wireless channel impairments is beyond the scope of this book [8–11]. Only the more important impairments relevant to the discussion of cognitive radios are reviewed. The first such impairment is caused by the fact when a wireless signal is transmitted from an antenna; it is radiated outward in a spherical shape. This means that the received signal is a fraction of the transmitted signal and is proportional to the fraction of the surface area of the spherical wavefront that reaches the receiver. Assuming the receiver is represented as a point, the received power in mathematical terms is given as

$$P_r = P_t G_t G_r \frac{\lambda^2}{(4\pi d)^2} \tag{2.1}$$

where P_r is the received power, P_t is the transmitted power, G_t and G_r are the transmitted and received antenna gains, respectively, and λ is the wavelength of the electromagnetic signal, and d is the separation between the transmitter and receiver. Equation (2.1) is known as Friis formula, or the "path loss" formula, and is valid only for free space [12]. When atmospheric conditions are taken into account, the attenuation can become more severe and is frequency dependent. Figure 2.3 below shows the atmospheric attenuation as a function of frequency [13].

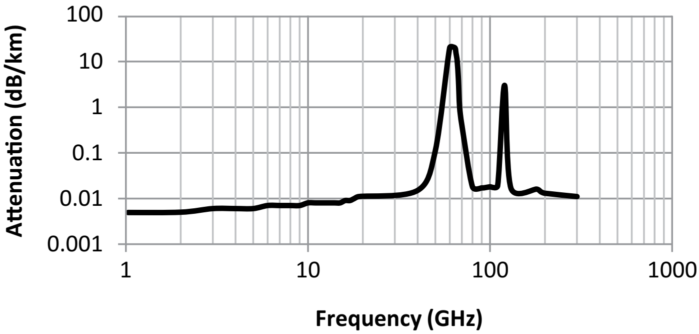
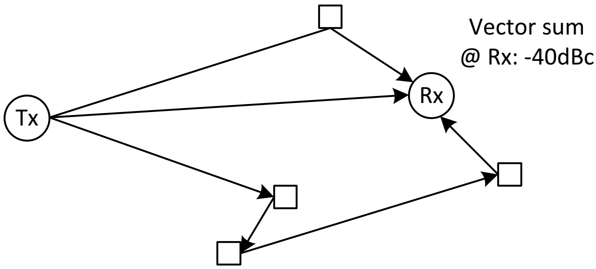


Fig. 2.3 Atmospheric attenuation as a function of frequency

Fig. 2.4 Multipath fading in a wireless channel



Another important impairment is known as multipath fading. This is caused when the received signal at the antenna arrives from multiple paths, as shown in Fig. 2.4. The received signals arrive at the antenna at different times, and hence are offset from one another in phase, which can also be a time-varying phase change. In the worst case, two received signals are exactly 180° out of phase and hence perfectly cancel each other at the antenna. In practice, there may be a condition where several reflections of the same signal arrive at the antenna from different angles that cause the signal to be severely attenuated. This attenuation can be as much as 40 dB. Moreover, this attenuation can be time-varying, causing the signal to fade. This effect is known as multipath fading.

Another effect that can occur in a wireless channel is known as shadowing, shown in Fig. 2.5. This usually occurs in an urban environment, where there is a clear path of sight between the BS and the user, which is periodically blocked by moving objects, usually a truck or large vehicle. When the large object blocks the main path between the BS and the user, the user relies on secondary reflected paths, which are usually much less in amplitude, causing severe and sudden attenuation in received signal.

One important phenomenon that occurs in wireless communication is known as intersymbol interference (ISI). ISI can be caused by multipath propagation, where reflected versions of the signal undergo different phase distortions, causing certain symbols to smear together, as shown in Fig. 2.6. ISI can also be caused by band-

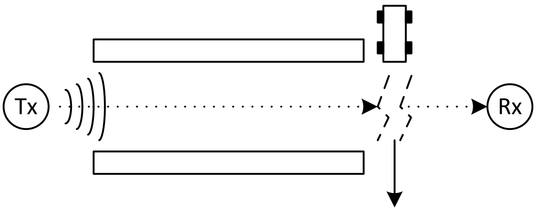


Fig. 2.5 Shadowing in a wireless channel

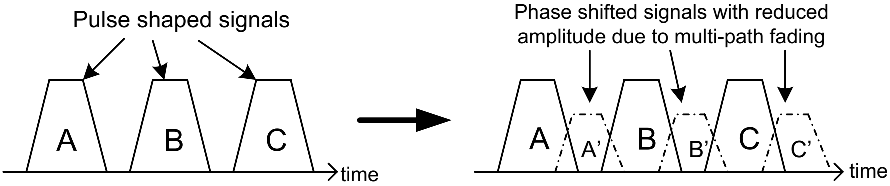


Fig. 2.6 Effect of ISI on received signal

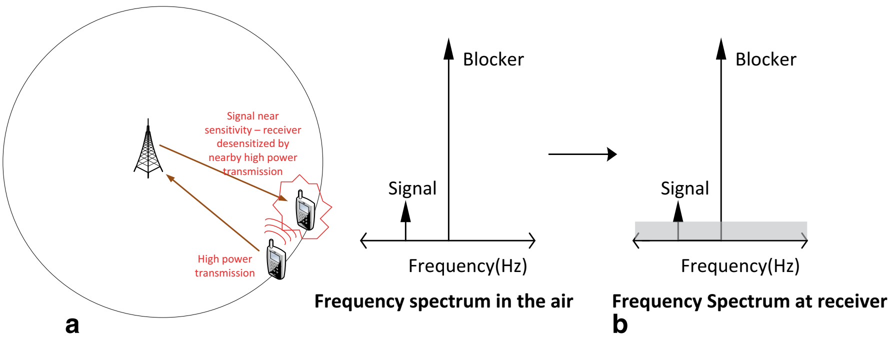


Fig. 2.7 Blocker desensitization in the receiver **a** scenario and **b** effect of receiver sensitivity

limited channels, whereby the high-end of the signal band receives more attenuation than lower-frequency components.

There are other impairments that result from sharing the frequency spectrum with other users. Blocker desensitization, shown in Fig. 2.7, is an important effect that occurs in wireless channels, especially in wireless cellular networks. It is caused when a nearby user is transmitting on a nearby channel with a large signal. The receiver detects the desired channel, but is also unable to completely filter out the high power transmission on the nearby channel. The undesired signal ends up saturating the receiver, reducing its sensitivity. Reduced receiver sensitivity reduction, in this scenario, is usually caused by the receiver, automatically reducing the gain in its front-end amplifiers to avoid the high power blocker from saturating the receiver. Figure 2.7a illustrates this scenario and Fig. 2.7b shows its effect on the receiver.

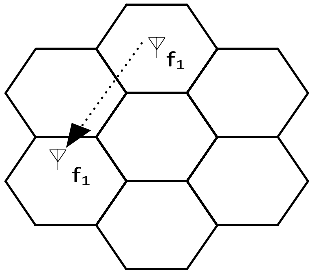


Fig. 2.8 Co-channel interference

Another impairment that is caused by sharing the frequency spectrum with other users is the co-channel interference, shown in Fig. 2.8. As stated earlier, one advantage of a cellular network is that a specific channel frequency can be reused by a different cell. This can result in a cellular network, where the same channel in the frequency spectrum is reused in another cell. Since, it can be seen from (2.1), the signal attenuation is finite, a small residual signal from one cell will leak into another cell. This signal leakage is worst if one cell is operating at maximum transmit power and the other cell is attempting to detect a very weak signal. Co-channel attenuation is usually minimized by disallowing two adjacent cellular areas to use the same channel. In other words, there is at least a two cellular area separation before the same channel is used, as illustrated in Fig. 2.8.

2.1.3 OFDM Primer

In order for two nodes to transmit digital data, the data must be encoded in a spectrally efficient method. One such method that has received widespread acceptance in many modern wireless communication networks is known as OFDM [14]. OFDM has been adopted by Digital Video Broadcasting (DVB)-T/T2 (terrestrial television), Institute of Electrical and Electronics Engineers (IEEE) 802.11a, g, n, ac, ad (wireless LAN), and Long-Term Evolution/Long-Term Evolution-Advanced (LTE/LTE-A, 4G cellular) standards, and many more [15–19]. OFDM has the advantages of high spectral efficiency, robustness to ISI, fading, and co-channel interference.

OFDM is a method of encoding digital data on multiple carrier frequencies, as shown in Fig. 2.9. The carriers are closely spaced and orthogonal to one another. Each carrier is modulated with the digital data to be transmitted. The encoding method on each carrier is quadrature amplitude modulated (QAM) for high data rates or phase-shift keying (PSK) for lower data rates. The close spacing of the carriers allows the transmitted signals to be treated as slowly modulated narrowband signals, which makes it possible to eliminate ISI [20].

In mathematical terms, the OFDM signal is given as

$$y(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T} \tag{2.2}$$

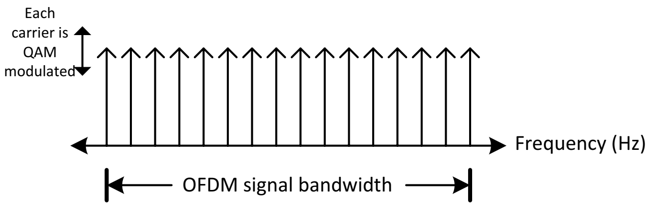
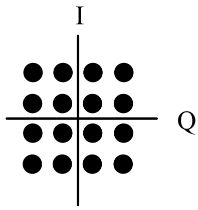


Fig. 2.9 A typical OFDM signal

Fig. 2.10 A 16-QAM signal



where X_k is the data to be transmitted, k is the number of carriers, and T is the period of the data symbol. It is important to note that $1/T$ is the frequency separation of the carriers in an OFDM signal. Recognizing that (2.2) is the in the form of a discrete inverse Fourier transform and restricting k to be a power of 2, an OFDM signal can be generated by simply running that data stream through an inverse fast Fourier transform (IFFT) operation. To guarantee orthogonality between all the carriers in an OFDM signal, the following condition must be satisfied:

$$\frac{1}{T}\int_0^T X_n e^{j2\pi nt/T} \bullet X_m e^{j2\pi mt/T} dt = 0, \quad m \neq n \tag{2.3}$$

which can be easily shown to be the case for any $m \neq n$.

Each carrier can be modulated by a QAM signal. A 16-QAM signal is shown in Fig. 2.10. A total of 16 symbols can be generated in the signal constellation, each symbol containing 4bits. In mathematical terms, a QAM signal is given as

$$y(t) = I(t) \bullet \cos(2\pi f_0 t) - Q(t) \bullet \cos(2\pi f_0 t) \tag{2.4}$$

where $I(t)$ and $Q(t)$ are amplitude modulated signals. For the 16-QAM example, $I(t)$ and $Q(t)$ would take one of four values, each.

One of the most important disadvantages of OFDM is the stringent linearity requirements on transceiver, due to the high peak-to-average power ratio (PAPR) in OFDM signals [21]. The gain of the receiver (and transmitter) is typically adjusted to track the average power of the signal. In order to accommodate the sudden peaks in amplitude, the transceiver must have high linearity. In order to understand why OFDM exhibits high PAPR, consider the two scenarios. In the first scenario, the data modulated on the carriers are entirely uncorrelated. Under this condition, signal power at any given time is equal to the expected average power. In the other scenario, the data modulated on the carriers exhibit high correlation. Under the worst-case condition, all the carriers in the OFDM signal have the same phase and add up coherently. For this instance in time, the amplitude increases by 10 log N, where N is the number of carriers. Typically, a more statistical approach is taken to determining the PAPR of an OFDM signal. For example, if the data is considered random and has a Gaussian distribution, the 3σ peak number is usually used. The maximum peaking of the signal is known as the crest factor. In general, the crest factor of an OFDM signal is given as

$$CF = 10\log N + C_{fc} \quad \text{(in dB)} \tag{2.5}$$

where C_{fc} is the crest factor of each carrier individually, and N is the number of carriers in the OFDM signal.

2.2 Cognitive Radio Systems

Maximizing network capacity is one of the key goals of any network engineering exercise. In a cellular network, the cell size is reduced to maximize the frequency spectrum reuse. In a cognitive radio system, an alternative method of frequency spectrum reuse is used. As was shown earlier in this chapter, the frequency allocation spectrum is extremely congested, not allowing any new standards to emerge in the conventional radio frequency (RF) range of 30 MHz–3 GHz. The utilization of this allocated spectrum, however, is very poor. Better utilization of the frequency spectrum can be achieved if an incumbent user is allowed to temporarily use a spectrum that is already allocated to a different user. The incumbent user, however, must be able to continuously sense the frequency spectrum to detect when the primary user is present. At this point, the incumbent user must give priority to the original frequency spectrum owner and cease transmission. A wireless system whereby users have this *cognitive* ability is known as a cognitive radio system [22].

Cognitive radio systems are distinguished from conventional radio system in that they have the ability to sense the frequency spectrum around them and make intelligent decisions on how to best use the spectrum to maximize network capacity. Figure 2.11 shows the key components in a cognitive radio. Managing the spectrum in a dynamic fashion as well as the spectrum-sensing unit (SSU), shown in Fig. 2.11, are the distinguishing features of a cognitive radio. The figure shows that the spectrum managing is done by the BS [9]; although this is usually the case for most practical networks, in general, the customer PE can also be allowed to manage the spectrum.

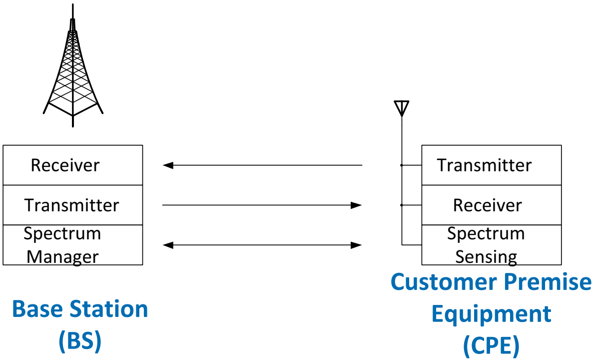


Fig. 2.11 Key components of a cognitive radio

2.3 Spectrum Management Techniques

A key issue in cognitive radio systems is how to reuse the frequency spectrum while not disturbing current transmissions. In other words, how can a cognitive radio system coexist with conventional static radio systems? There are three main methods that allow for this coexistence.

The first is known as a non-cooperative technique, shown in Fig. 2.12. Several types of PE are shown in this diagram, including fixed PE devices as well as portable PE devices. In this technique, each PE uses as much available spectrum as possible. Communication is only interrupted if the primary channel owner begins a transmission burst. The advantage of this approach is simplicity. The only type of channel analysis needed is if a channel is being used or not. Needless to say, this type of communication protocol is seldom used as it does not lead to the most efficient use of channel capacity.

Another more practical class of spectrum management method is known as a rule-based technique, shown in Fig. 2.13. In rule-based techniques, some centralized decision-making unit, usually the BS, is employed. Each PE would send its request for data bandwidth that is required as well as the PE's assessment of the frequency spectrum in its vicinity to the BS. Based on a set of rules, the BS would allocate frequency spectrum and instruct each PE to transmit at a certain level. Such rules may consist of static rules, such as maximum allowed bandwidth per user, limited transmit power levels, and checking with an online database to verify if a certain user is allowed to use the requested bandwidth (subscription fee-based). Other rule-based decisions may be dynamic, such as increasing the permitted power level when operating in a noisy channel, or decreasing the user's allowed bandwidth if several consecutive high bandwidth requests are made. Other rules are necessary to give the system a cognitive ability, such as following a listen-before-talk protocol. The advantage of rule-based techniques is that it provides relatively efficient use of the frequency spectrum with a small overhead in terms of decision making of how to efficiently use the spectrum. The disadvantage is that this system requires a centralized unit to allocate the frequency spectrum, namely the BS. Since the spectrum

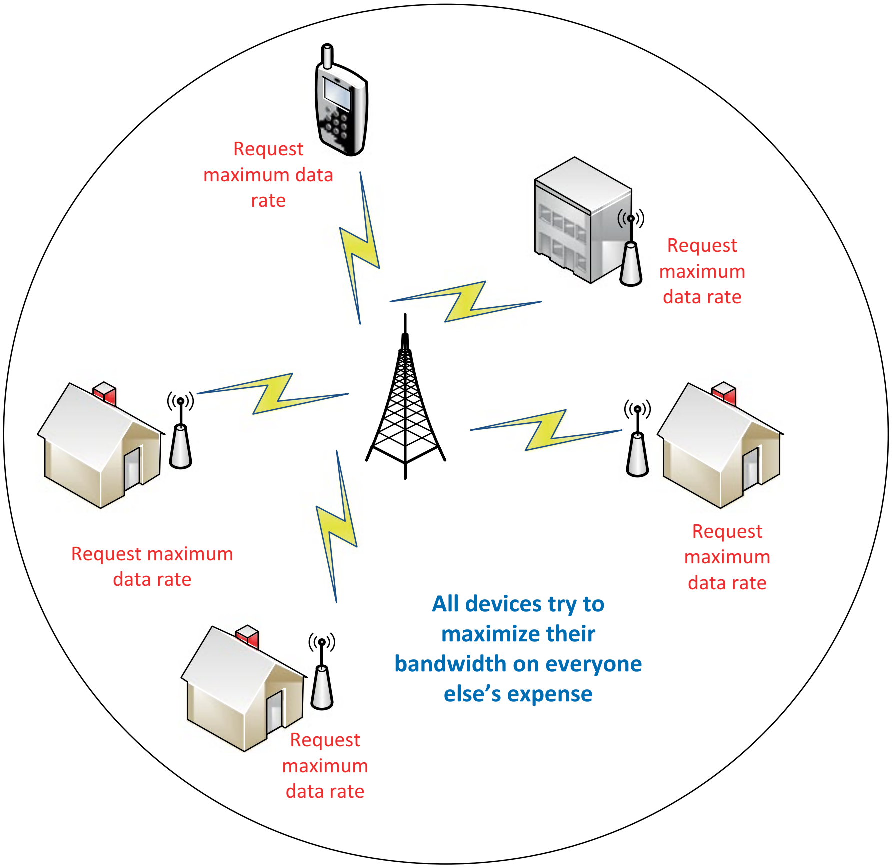


Fig. 2.12 Non-cooperative spectrum management technique

conditions near the BS may be different from the PE, the PE is required to send *its* analysis of the frequency spectrum. In other words, there is a centralized decision maker and all the PE can be thought of as frequency spectrum sensors without any decision-making capability.

The third category of spectrum management techniques is known as message-based techniques (Fig. 2.14). In message-based techniques, each PE is capable of making a decision on what frequency to transmit and with what power level. This decision, however, is made in coordination with nearby PE cells as well as the BS. This unique quality of the PE being able to make a decision independent of the BS can give a rise in spectrum usage efficiency (Fig. 2.14).

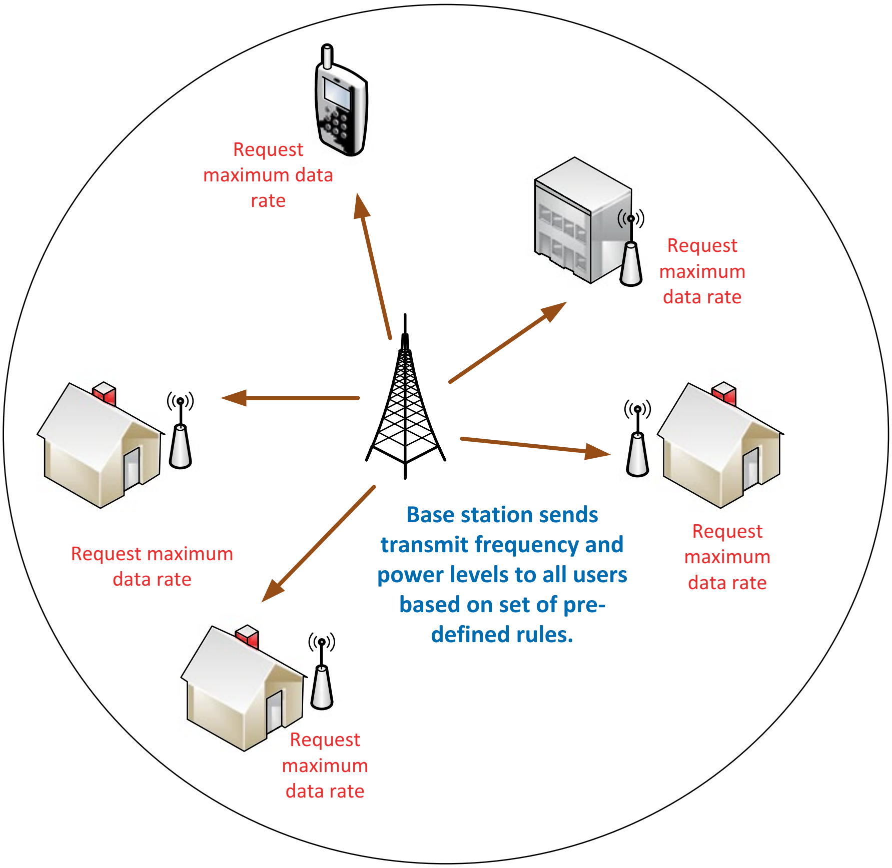


Fig. 2.13 Rule-based spectrum management technique

2.4 Spectrum Sensing

From a hardware perspective, the SSU is the distinguishing feature of a cognitive radio. As was discussed earlier, the PE should be able to sense its local frequency spectrum to detect if the channel owner is using its allocated frequency spectrum. The PE should also be able to detect if any other channels are available. To this end, the PE must be able to sense the entire frequency spectrum, also known as channel scanning, in addition to the channel that is currently used.

Sensing the current channel may be challenging. The obvious method of sensing the current channel is to require the PE unit to first cease transmission, then sense the current channel for the primary channel owner. This protocol is known as a blocking sensing method [23], as demonstrated in Fig. 2.15. In the first step, the transmission ceases on channel A, and instead the channel is sensed. The second step involves a decision process. If the primary channel owner is detected on channel A, then transmission is stopped and another channel is requested for transmission.

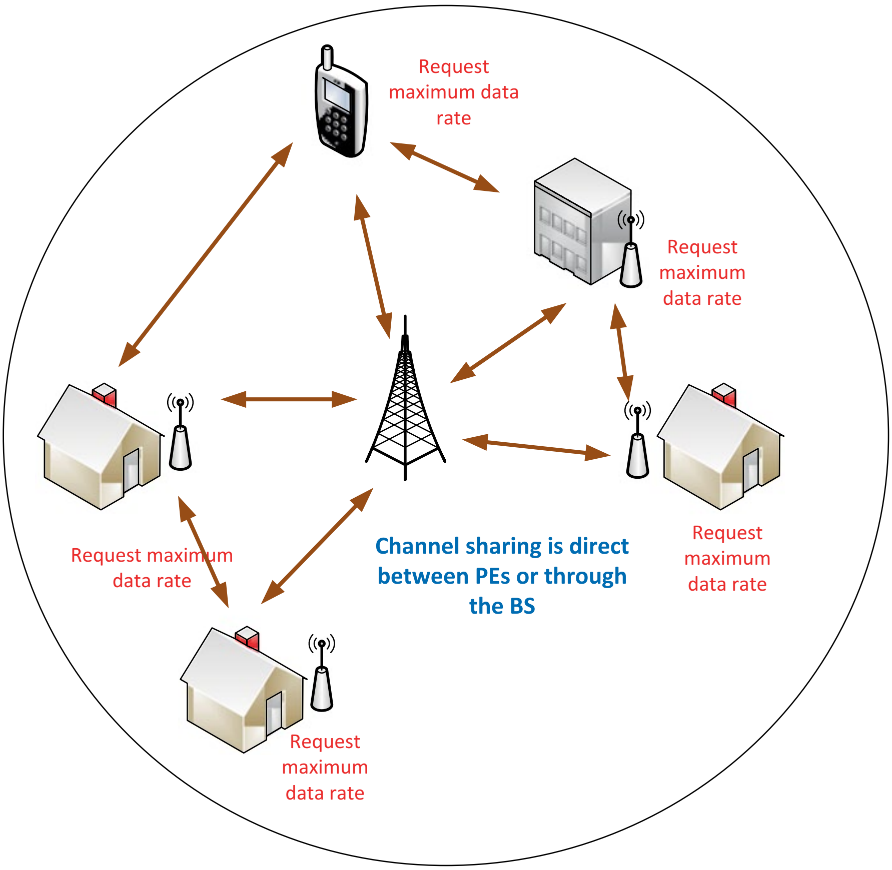


Fig. 2.14 Message-based spectrum management technique

Depending on the standard adopted, there is a minimum wait time where the channel must be vacant before the PE is allowed to transmit on the channel. For example, the IEEE802.22 standard (discussed in the next section) specifies a 30 s minimum time in which the channel must be vacant before used by the PE. Also, after the channel is used, it must stop periodically to ensure that the primary channel owner did not start transmitting on the channel.

The type of sensing algorithm used affects two important performance metrics: throughput penalty and latency penalty. Throughput penalty is the ratio of all the sensing times to the total transmission time plus the sense time. Latency penalty is the maximum duration of the sense operation. One way to minimize latency is to break up the sensing operation in to fast (and less accurate) sensing and slow (and more accurate) sensing [23]. If a signal is detected on the channel during the fast sense operation, then there is no need for an accurate sensing operation. If no signal is detected during a fast sense operation, then a more accurate, and slower, sense operation is required. This is illustrated in Fig. 2.16. To illustrate the effectiveness

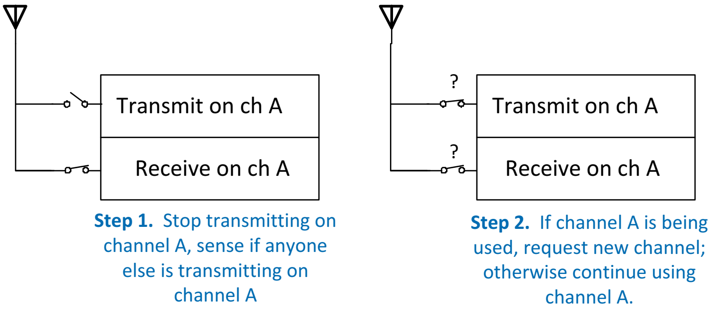


Fig. 2.15 Blocking sensing channel detection method

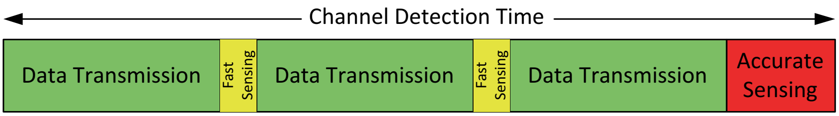
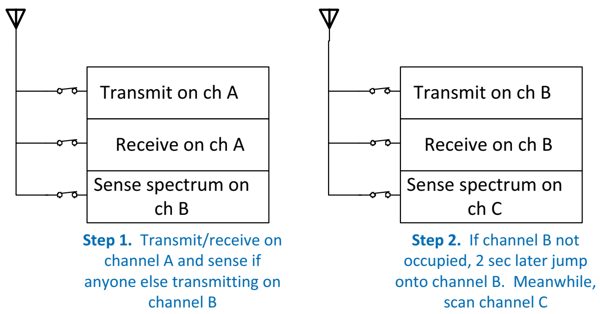


Fig. 2.16 Fast and slow sense operations to minimize the latency penalty

Fig. 2.17 Frequency-hopping channel detection technique



of this approach, consider a numerical example. If, for example, 500 ms of quiet time is required for the sense operation to complete, and the standard requires a channel sense every minute, the throughput penalty is calculated to be 0.5 %, but the latency penalty is 500 ms, a large number. If the sensing operation is broken up into 50 faster sense operations, the throughput penalty is unaffected (at 0.5 %). However, the latency penalty now is only 10 ms.

As was shown in Fig. 2.15, step 2 involves a decision process. If the primary channel owner is detected, then the PE must send a request for another channel to use. This means that the communication must be interrupted, thereby reducing the system throughput and increasing its latency. One method of avoiding this is by using a frequency-hopping technique [24, 25], shown in Fig. 2.17. This technique starts by transmitting and receiving on channel A, while simultaneously scanning for another available channel B. During the next sense operation, step 2, communication on channel A is stopped and resumed on channel B. While transmitting and

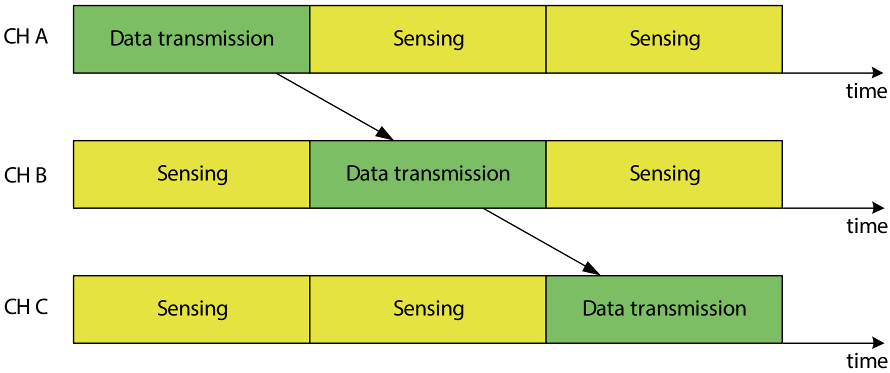


Fig. 2.18 Status of each channel over time for the frequency-hopping channel detection approach

receiving on channel B, yet another available channel C is detected, and prepared for use at the next sense time. This technique avoids requiring scanning the used channel for the primary channel owner, since the channel is given up at the next sense time iteration. For clarity, the status of each channel over time is shown in Fig. 2.18.

2.5 Signal Detection in Cognitive Radios

One of the primary functions of a SSU is to search for the primary user in the entire frequency spectrum [26, 27]. If the sensed signal is large, the detection operation is relatively simple. If the sensed signal is weak, however, the SSU must be able to distinguish a primary owner signal from random noise.

The simplest method of detecting whether a channel is used or not is to measure the energy in a given channel. This is particularly effective for signals that have signal-to-noise ratio (SNR) > 0dB. The energy of the channel is computed as

$$y(t) = \frac{1}{T}\int_0^T s(t) \bullet s^*(t) \bullet dt \tag{2.6}$$

where $s(t)$ is the signal over a channel, with bandwidth $1/T$, and $s^*(t)$ is the complex conjugate of the received signal. If the signal is very small, this operation must be repeated several times and averaged over several samples, in order to average out the random noise components. If the signal is weak, this operation can be very time consuming. In general, if N iterations of energy computations are performed, then $10 \log N$ reduction of the signal detector's noise floor is possible [28].

Since the type of signal of the primary channel owner is known a priori, the signal detection operation can be made more intelligent. The class of techniques that

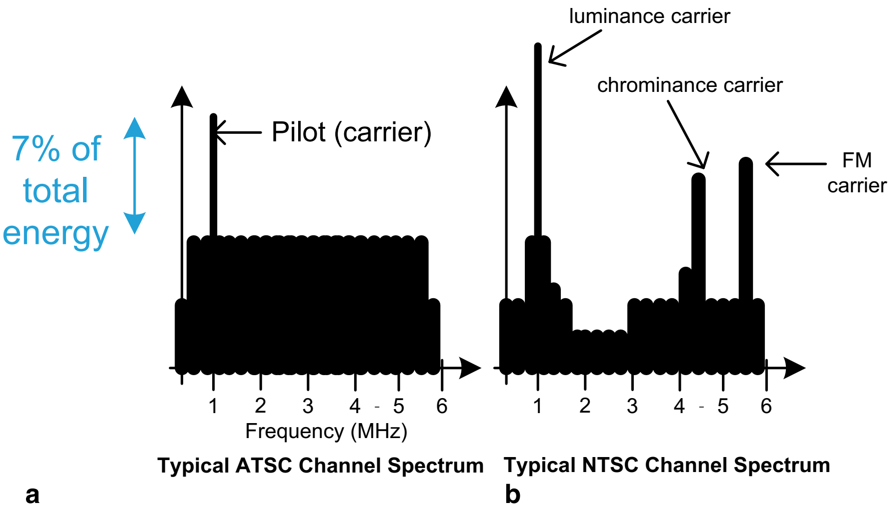


Fig. 2.19 Frequency spectrum of **a** ATSC and **b** NTSC TV signals. *ATSC* Advanced Television Systems Committee, *NTSC* National Television Systems Committee

use distinguishing features of the primary channel owner in order to make a decision as what whether a channel is used or not is known as feature-based techniques.

To illustrate the feature-based technique approach, consider television (TV) signals, shown in Fig. 2.19. A digital TV signal, Advanced Television Systems Committee (ATSC, Fig. 2.19a), has the distinguishing feature of having a pilot carrier at 310 KHz away from the band edge and 7% of the total power of the signal is contained in that carrier. The analog TV signal (Fig. 2.19b) has a distinguishing feature of having a large luminance carrier tone at 1.25 MHz away from the band edge. Since these features are narrowband, their power level can be measured accurately in a time-efficient manner.

A third type of signal detection method that has recently received widespread attention is based on measuring second-order signal statistics. The main assumption here is that any signals that are man-made are periodic and random signals are likely to be caused by natural phenomena. In other words, if the cross-correlation function of a given channel is computed, it should reveal any periodicity in the signal. If periodicity is detected, then it is assumed that the channel is being used; otherwise, the detected signal is random noise and the channel is available for use. As in energy-based detection, the noise floor of the detector can be improved by summing several cross-correlation measurements of the channel. The improvement in noise floor, however, is 20 log N, where N is the number of iterations [29]. A diagram of a cross-correlation-based signal detector is shown in Fig. 2.20.

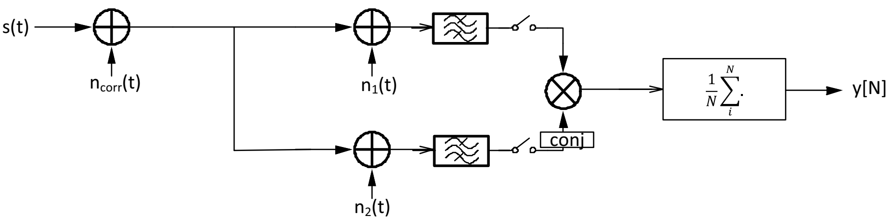


Fig. 2.20 Cross-correlation-based signal detector

2.6 Cognitive Radio Standardization

2.6.1 IEEE 802.22 and TVWS Technology

One of the first standardizations of cognitive radio was the IEEE 802.22 standard [30–33]. This standard describes how to apply a cognitive radio system to the TV broadcast band and is mainly applied in the USA. On June 12, 2009, high-power analog TV broadcasting was ceased in the USA and was replaced by digital TV broadcast. Several lower-power analog TV towers were allowed to operate until September 1, 2015. Wireless data providers, anxious to use this newly freed spectrum, attempted to lobby that two-way data communications is far more valuable to the public than digital TV broadcast. The result was a compromise solution, whereby data communication was allowed over the TV spectrum without any loss of TV signal quality and priority was given to TV broadcasters over the use of the spectrum. In addition to TV broadcasters, low-power wireless microphone users were allowed to transmit over the TV spectrum.

The relationship between cognitive radio, TVWS, and IEEE 802.22 is shown in Fig. 2.21. TVWS is an implementation of cognitive radio of the TV band, namely 40–860 MHz [34–43]. The IEEE 802.22 standard is not the only standardization of TVWS. There are others that have been adopted in Europe and Asia [44–47].

In terms of a data communication protocol, the IEEE 802.22 implementation of cognitive radio can be thought of as a long-range high data rate communication standard. The long range comes from the fact that the carrier frequencies in the TV

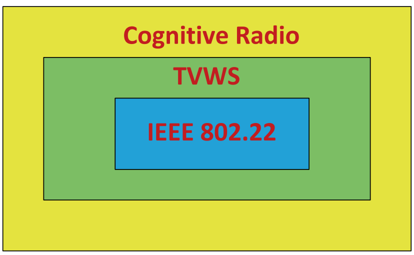


Fig. 2.21 Relationship between cognitive radio, TVWS, and IEEE 802.22. *TVWS* TV white space, *IEEE* Institute of Electrical and Electronics Engineers

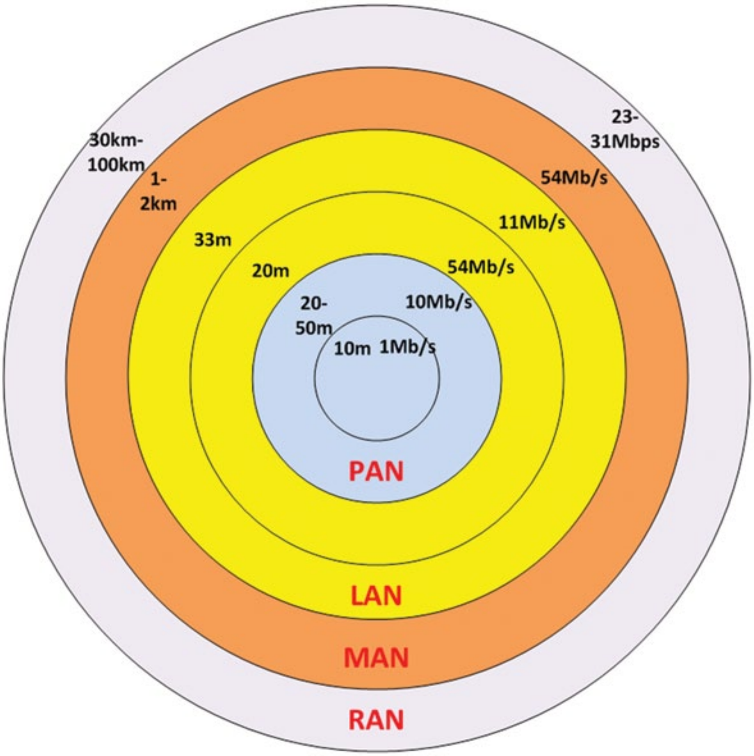


Fig. 2.22 IEEE wireless communication standards

band extend from 40 to 860 MHz. As was shown in (2.1), the received power is a function of the square of the carrier wavelength. Recognizing that $c=\lambda f$, where c is the speed of light constant and f is the carrier frequency, (2.1) can be rewritten as

$$P_r = P_t G_t G_r \frac{c^2}{(4\pi d f)^2} \tag{2.7}$$

This demonstrates that the received power is inversely proportional to the carrier frequency. In other words, if the carrier frequency is reduced by a factor of 10, the received input power level is increased by a factor of 20, for the same antenna and receiver gain factors.

Figure 2.22 shows the IEEE 802.22 standard's relationship to other IEEE wireless standards. The ZigBee standard, IEEE 802.15, is a small-range low data rate standard, meant for applications such as wireless metering. The familiar Wi-Fi standard, IEEE802.11, is meant for higher data rates but limited range. The WiMAX standard, IEEE 802.16, which had limited success as a 4G wireless cellular standard, is meant for longer-range communication, up to 2 km, with high data rates of up to 54 Mb/s. Finally, the IEEE 802.22, TVWS, standard is meant for very high data rates over ranges up to 100 km.

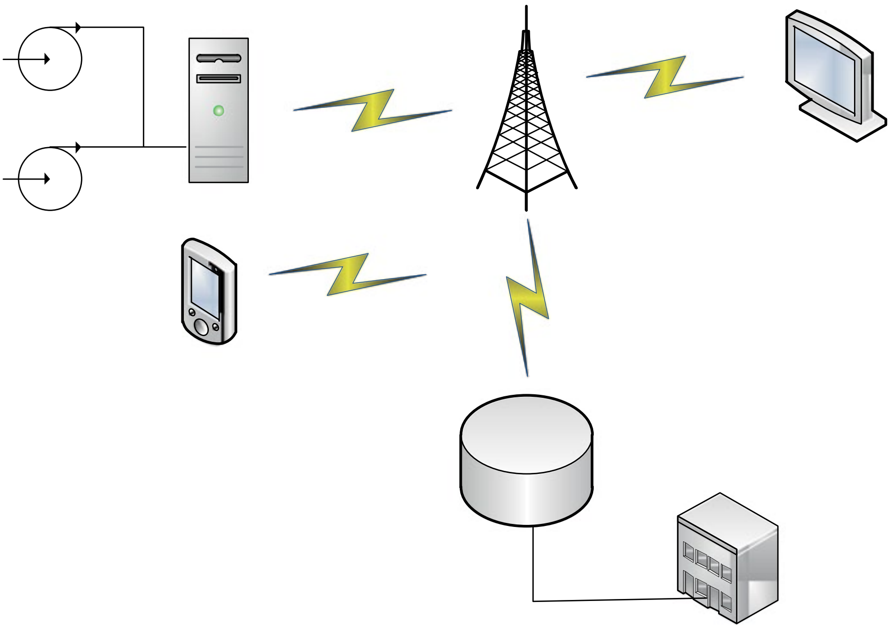


Fig. 2.23 IEEE 802.22 network applied to wireless metering

The IEEE 802.22 standard is meant to address several types of applications. The most obvious would be to use IEEE 802.22 as a form of long-range "Wi-Fi-like" for rural areas. Given the fact that TV broadcasting does not reach many rural areas in the USA, the unused frequency spectrum in the TV band can be shared between many cognitive PE. Data rates as high as 400–800 Mbps are possible.

Another application of IEEE 802.22 is for wireless metering [48]. The ZigBee standard (IEEE 802.15) is already being used for wireless metering. Wireless metering is characterized as having very low data rates and usually involves communication between wireless metering devices and an operator nearby. IEEE 802.22 standard would extend the range of wireless metering devices in such a way that the portable wireless metering devices can operate with a faraway BS directly, as shown in Fig. 2.23. The BS would then communicate to a database directly or an operator, if necessary. In other words, IEEE 802.22 applied to wireless metering offers the possibility of machine-to-machine (M2M) communication directly [49]. M2M communication is characterized as being very sporadic and bursty, ideal for TVWS technology, where cognitive PE devices transmit in bursts where the allocated frequency spectrum is not being used. TVWS devices optimized for wireless metering applications are currently available on the market have battery lifetimes measured in years [50].

Another application of IEEE 802.22 is for remote monitoring and supervisor control and data acquisition (SCADA), as shown in Fig. 2.24. This type of network would be applied to a limited urban area, such as a university campus or shopping center. The added value of an IEEE 802.22 standard is the direct connection of

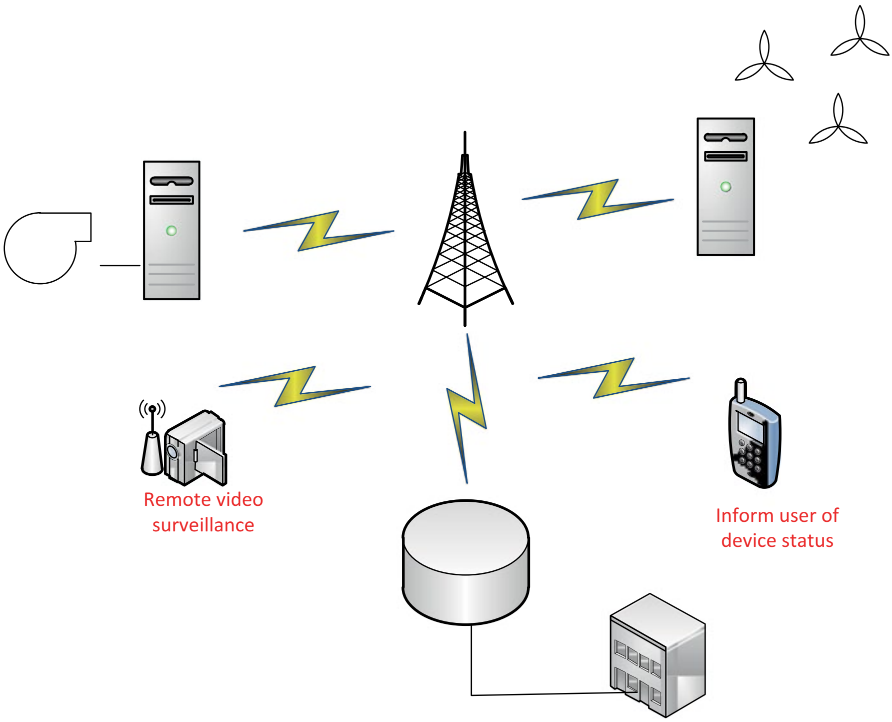


Fig. 2.24 IEEE 802.22 standard for SCADA application

SCADA devices to a BS device. As shown in Fig. 2.24, the communication in a SCADA network can be man to machine, machine to man, or machine to machine. In general, M2M type of communication is possible where remote machinery can be activated depending on analysis from remote video surveillance or based on data from a remote database.

Related to SCADA networks, remote medical patient monitor is possible with IEEE 802.22 networks, as shown in Fig. 2.25. Low-power patient monitoring equipment can transmit to the TV band directly. The BS has access to a patient database as well as the doctor or hospital monitoring equipment. In case of a medical emergency, the patient monitoring equipment would send a signal directly to the doctor/hospital monitoring equipment.

In general, it is possible to have a heterogeneous IEEE 802.22 network that serves multiple applications, as shown in Fig. 2.26. This figure shows that "Wi-Fi"-like users (both portable and fixed) can share a network along with long-range wireless metering and remote surveillance devices. The radius coverage of the IEEE 802.22 network is typically 30 km and can be as long as 100 km.

There are other competing standards for TVWS. Some of the most important are listed in Table 2.1 below. As the table shows, some of the standards are an extension of existing IEEE standards. Other standards, such as the European ECMA392 standard recognizes that cognitive radios are still in their infancy and limit the

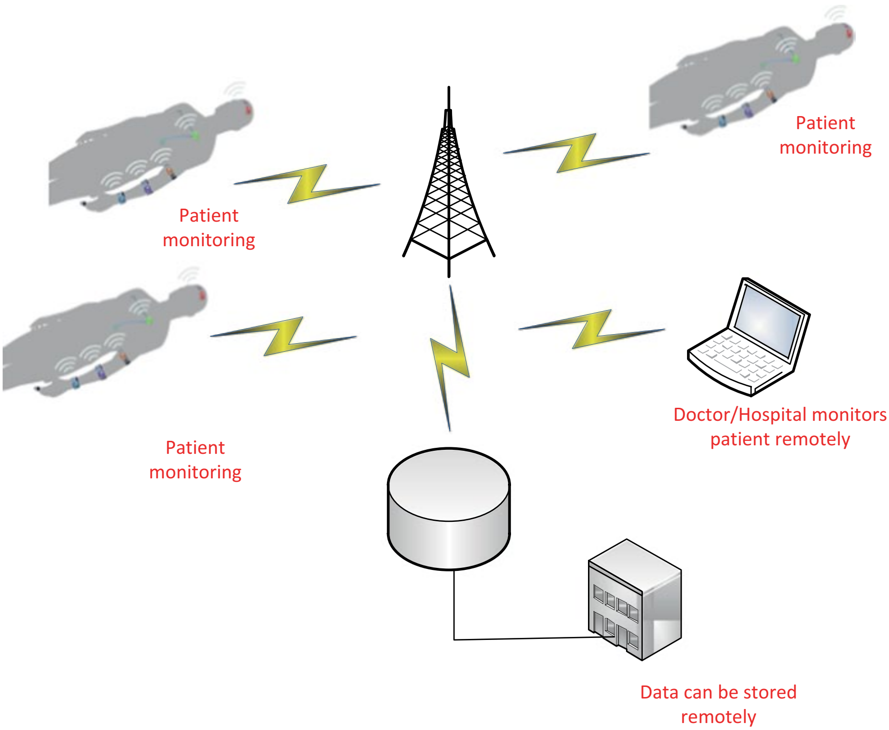


Fig. 2.25 IEEE 802.22 network for wireless medical sensing

application of cognitive radios to a very specific application. Yet others, such as the Infocomm Development Authority (IDA), target very specific applications in very specific regions.

2.6.2 TVWS Deployments

There have been many recent TVWS deployments worldwide. In February 2012, the first Federal Communications Commission (FCC)-approved IEEE 802.22 radio system was deployed in Wilmington, NC, in the USA. Wireless video cameras and remote sensors were installed for public utilities. Also, there were plans to provide public wireless access in public parks.

In September 2012, Singapore White Spaces Pilot Group (SWSPG), a consortium consisting of Microsoft, StarHub, and Institute for InfoComm Research, started a commercial pilot deployment of TVWS smart radio. The deployment was in the 700-MHz band and is marketed as a super-Wi-Fi access. The network extends to several nearby islands, providing a low-cost Wi-Fi access to the islands. The range per cell is 5 km, which is defined by the operating channel frequency.

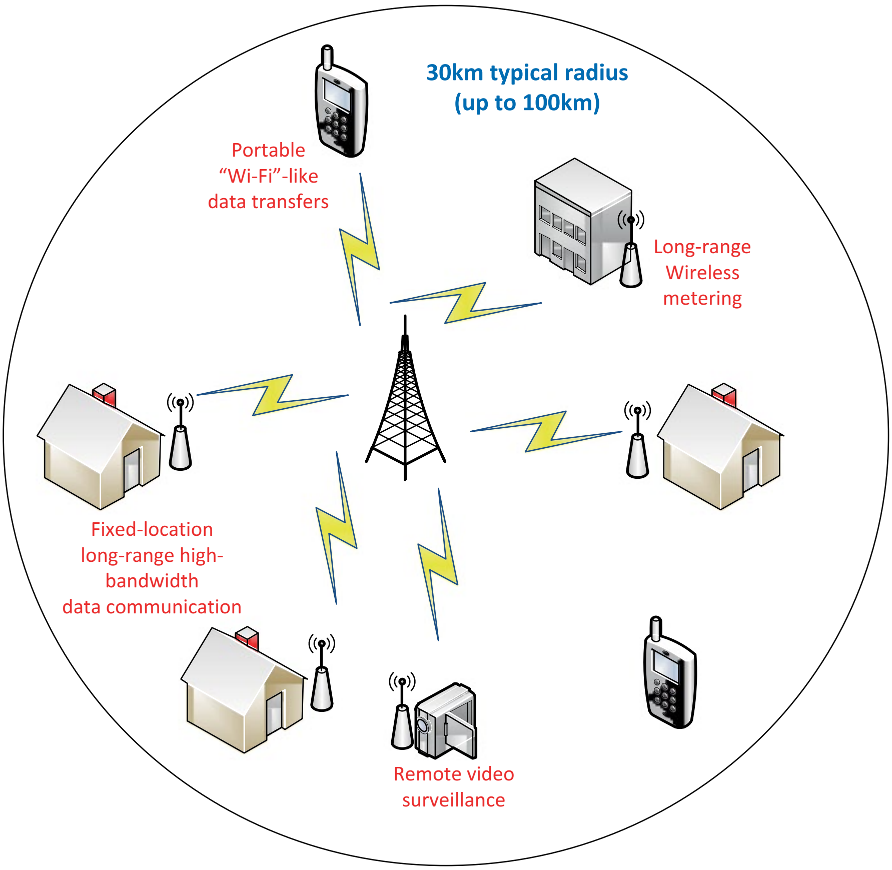


Fig. 2.26 Heterogeneous IEEE 802.22 network

Table 2.1 TVWS standards competing with IEEE 802.22

TVWS standard	Description
IEEE 802.11af	PHY and MAC for Wi-Fi operators in TVWS
ICogNeA/ECMA392	This is a European standard specifying the PHY and MAC, mainly for home network application in TVWS (HDTV streaming)
IEEE 802.15.4m	Amendments to the IEEE 802.15.4 support for TVWS in personal area network (WPAN)
Infocomm Development Authority (IDA)	TVWS task force in Singapore

TVWS TV white space, *IEEE* Institute of Electrical and Electronics Engineers, *PHY* physical, *MAC* media access control

In December 2012, a TVWS deployment was initiated in CapeTown, South Africa. Ten channels were made available for 2-Mbps internet access for schools over 10 km distances. Partners for this effort include Google, TENET, CSIR Meraka Institute, and e-Schools' Network and WAPA. It is also important to note that this is not an IEEE 802.22 compliant deployment.

Summary

In this chapter, wireless communication technologies relevant to cognitive radios were reviewed. This includes some of the capacity limitations in wireless systems, nonideal effects in radio systems, and an overview of OFDM encoding methods. Frequency reuse was identified as one key method of enhancing the network capacity of a wireless system. Cognitive radios were detailed in this chapter. It was shown how cognitive radios enhance network capacity by reusing time-sharing frequency spectrum with a priority rule-based algorithm. The architectural components as well as algorithms for frequency sensing and spectrum management were reviewed. Finally, some recent standardizations that are based on cognitive radios were reviewed. Although still in their infancy, the limited adoption these cognitive radio systems is creating valuable experimental data which will be used to further enhance cognitive radio systems.

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