Chapter 2
Emerging Standards for Smart Radios: Enabling Tomorrow's Operation

2.1 Standards in Evolution

In this chapter we detail the standardization roadmap towards an increase in hardware and policy flexibility, described in Chap. 1. This is shown in Fig. 2.1.

First, we discuss the increase in hardware flexibility. While standards typically do not discuss implementation-related aspects, we describe how parameters have become more and more dynamic. This trend is clearly driven by the innovation in the SDR, which is a reconfigurable platform solution that supports a range of air interfaces. Without flexible implementation methodologies, this level of flexibility could not have been introduced by standardization bodies. As shown in Table 2.1, we discuss standards for both cellular and distributed technologies.

Afterwards, we discuss the increase in policy or spectrum access flexibility. As shown in Chap. 1, the ISM bands, where unlicensed devices coexist using only high-level spectrum etiquettes, have been a clear driver towards more dynamic spectrum access. In this chapter, we discuss two ways to counter the QoS problem with dynamic spectrum access. First, we discuss how the spectrum access is taken a step back, by introducing more control mechanisms between the different standards in the ISM bands. Specifically, we discuss the IEEE 802.11h standard, where algorithms are developed to avoid interference from unlicensed ISM bands towards satellite and radar systems and the IEEE 802.19 standard, which takes care of cross-technology coexistence. The second way to counter the QoS problem of dynamic spectrum access is to introduce a more hierarchical scheme, known as opportunistic spectrum access. In opportunistic spectrum access, unlicensed devices can use licensed spectrum as long as they do not interfere with licensed users.

In Chap. 1, we have discussed the CR as an intelligent control layer to handle the increasing flexibility, introduced by SDR and OSA. In this chapter, we show two standardization efforts that are in line with this view. We first present the IEEE 802.21 Media-Independent Handover, which dictates how the a reconfigurable radio can decide to switch between different standards. Afterwards we discuss the IEEE DYSPAN Standards Committee (formerly SCC41), where techniques are standardized in line with the CR paradigm to allow for a more advanced adaptation and monitoring for Cognitive Radios.

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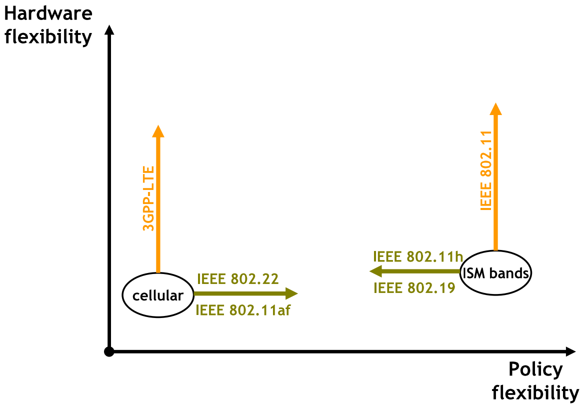


Fig. 2.1 Standards in evolution: hardware flexibility, policy flexibility towards true cognitive control

2.2 Hardware Flexibility

Some of the major wireless standards are discussed to illustrate how increased flexibility and control is becoming abundant, even within a single wireless technology. This demonstrates the diversity of the wireless scene, where many different air interfaces and applications coexist. It is shown in Sect. 2.2 that within each standard, the number of communication modes is increasing with each generation. While standardization bodies do not discuss implementation, the number of modes is increasing by such an amount that dedicated ASIC implementations become unrealistic. First, the IEEE 802.11 generations are discussed focusing on the flexibility and control options within the standard. Afterwards, we discuss 3GPP-LTE as the most prominent candidate for next generation cellular technology. Again, for this class of standards, a trend exists towards more flexibility and distributed control.

Table 2.1 Standards in evolution: hardware flexibility, policy flexibility towards true cognitive control

Radio	Scenarios	Standard
Hardware Flexibility	WLAN	IEEE 802.11
	Cellular/Licensed	3GPP-LTE
Spectrum Access Flexibility	Coexistence in Unlicensed Bands	IEEE 802.11h and 802.19
	Opportunistic Radio	IEEE 802.22, 802.11af
Cognitive Radio Control	Medium Independent Handover	IEEE 802.21 MIH
	Terminal and Network Control	IEEE DYSPAN, ETSI RSS

2.2.1 IEEE 802.11: A Flexible Radio Becomes Smarter

Wireless Local Area Networking (WLAN) has always been the most important technology for wireless data solutions, although competition from the next generation cellular technologies is increasing. The main standard for those WLAN networks has been the IEEE 802.11 standard since 1999.

IEEE 802.11 specifies a connectionless MAC on top of multiple PHY layers in the unlicensed bands at 2.4 GHz and 5 GHz and recently also the 60 GHz band [20]. In this chapter, we first give a short overview of the IEEE 802.11 standards in the unlicensed bands below 6 GHz. Afterwards, the flexibility offered by this standard at PHY layer and the spectrum sharing options at MAC layer are discussed.

The initial 802.11 standard achieves a rate of 1 Mbps and 2 Mbps in the 2.4 GHz band, while the 802.11b enhances this to support 5.5 Mbps and 11 Mbps. The 802.11a and 802.11g extensions allow up to 54 Mbps. The most recently standardized physical layer is the 802.11n, which supports bitrates up to 600 Mbps thanks to the use of advanced techniques including channel bonding, the use of multiple spatial streams, aggressive coding, short guard intervals and optimized usage of all subcarriers.

The next significant update of the technology will be the 802.11ac standard, adding even more advanced modulation and coding, up to 8 spatial streams and channel bonding up to 160 MHz. With this continuing expansion of the number of streams, channels bonded and modulation and code rates supported, the flexibility offered by the standard is increasing with each generation.

The MAC layer of the 802.11 standard only focuses on the channel coordination functions. In the baseline IEEE 802.11 MAC protocol description, a distributed channel coordination function and a centrally controlled point coordination function are specified. Both however do not provide sufficient QoS guarantees. QoS extensions are specified in the 802.11e standard.

The flexibility offered by the WLAN standard will be exploited to illustrate concepts for smart and cognitive radio design in this book. In Chap. 6 we focus mainly on the physical layer flexibility offered by the 802.11a standard. Considering the modem, we rely on the implementation proposed in [21] with additional flexibility. This will already result in significant energy and performance improvements when the flexibility is exploited smartly. For newer generation devices, the possible gains are higher, at the cost of increased control complexity. Next, in Chap. 7 we focus on the flexibility of the MAC offered for the spectrum sharing. The MAC options considered are applicable to the 802.11a/b/g/n standards, and most likely also the new 802.11ac.

2.2.1.1 The IEEE 802.11a Physical Layer

The 802.11a physical layer has been introduced to achieve bitrates of up to 54 Mbps in the 5 GHz bands. The modulation scheme used for 802.11a is OFDM, where

Table 2.2 802.11a transmission rates

PHY mode	Modulation N_{Mod}	Code Rate B_c	Data Rate (Mbps)
1	BPSK	1/2	6
2	BPSK	3/4	9
3	QPSK	1/2	12
4	QPSK	3/4	18
5	16-QAM	1/2	24
6	16-QAM	3/4	36
7	64-QAM	2/3	48
8	64-QAM	3/4	54

information is transmitted via multiple orthogonal subcarriers. For 802.11a, 48 subcarriers and 4 pilot subcarriers are used, covering a total of 20 MHz in bandwidth including zero carriers. This modulation scheme is very effective for broadband, hence high-speed, transmission since it efficiently handles the frequency selectivity of the channel. Moreover, it can be implemented elegantly using Fast Fourier Transform (FFT) and Inverse FFT (IFFT) digital blocks.

Eight transmission rates have been standardized (Table 2.2), making transmission rate a possible control dimension. A transmission rate is set by configuring both the symbol modulation (N_{Mod}) and the Forward Error Correction (FEC) code rate (B_c). The current value chosen is communicated in the `RATE` field in the Physical Layer Convergence Protocol (PLCP) header of the PHY Protocol Data Unit (PPDU).

Finally, the output power P_{Tx} is limited to 30 dBm or 1 W. The output power can be considered as a PHY control dimension, next to the already introduced digital PHY control dimensions modulation and code rate. As the output power is a result of the Power Amplifier (PA) settings, it is referred to as an analog or front-end PHY control dimension in the remainder of this book. In Chap. 6, we model the impact of those control dimensions on the effective energy and performance, assuming a realistic implementation of the analog and digital modem. However, the output power also has implications on the channel access of a CR, as is discussed in Chap. 7.

2.2.1.2 The IEEE 802.11n Physical Layer

The IEEE 802.11n standard supports data rates up to 600 Mbps. This is mainly achieved using Multiple-Input-Multiple-Output (MIMO) techniques, where up to 4 spatial streams are used in parallel. MIMO techniques that are supported by the standards are space division multiplexing (SDM), transmitter beam-forming and space-time block coding (STBC). The use of MIMO systems mainly increases the throughput and coverage as compared to single antenna systems. Clearly, the possibility to vary the MIMO scheme as function of throughput requirements and channel condition can be considered to be a new flexibility offered by the 802.11n PHY.

Next, the 802.11n offers the possibility to use up to 2 802.11a channels in parallel, which is referred to as channel bonding. As a result, the bandwidth can vary between 20 and 40 MHz, which can be considered to be another new flexibility option. To increase the spectral efficiency even further, also at MAC level, several optimization features have been added, such as frame aggregation or block acknowledgments. Also, to improve the efficiency of the physical layer, a short guard interval option is included, as well as advanced coding such as code rates up to $\frac{5}{6}$ or the option to use low density parity check (LDPC) coding.

2.2.1.3 The IEEE 802.11ac Physical Layer

The IEEE802.11ac Task Group has recently been formed within the IEEE802.11 Working Group. Its goal is to draft a standard for "Very High Throughput" WLANs, with performances significantly higher than those of the IEEE802.11n standard. Because the task group TGac has just started its activity, the standard is not yet available. TGac is currently drafting the detailed functional requirements. The trend of 802.11n towards more flexibility in the MIMO options, channel bonding and more spectrally efficient physical layer options will however persist in the newest standard. More specifically, bandwidths up to 80 or 160 MHz will be supported. Also, advanced multi-stream operation supporting up to 8 streams that can be destined for multiple users is included in the specs. Finally, constellations up to 256 QAM are being discussed.

2.2.1.4 Multiple Access Through Collision Avoidance with Carrier Sensing

We introduce the terminology and communication principles that are standardized in the 802.11 Medium Access Control (MAC) baseline protocol description. According to the 802.11 standard, wireless networks can be arbitrarily complex, and consist of a hierarchy of basic communication networks. A basic wireless communication network is referred to as a *Basic Service Set* (BSS) which is a set of stations controlled by a single *Coordination Function* (CF). The CF manages the access to the radio channel. The *Distributed Coordination Function* (DCF) is mandatory for each BSS and is described first. It standardizes a technique for distributed contention-based channel access. The *Point Coordination Function* (PCF) for centralized contention-free channel access is optional. The PCF operation relies on the DCF. To improve the QoS that can be achieved on top of 802.11 WLAN systems, the *Hybrid Coordination Function* (HCF) has been introduced to improve the baseline DCF and PCF operations.

Further, a BSS can operate in Infrastructure mode (also referred to as regular BSS), with an Access Point (AP) and multiple Stations (STAs). In this scenario, the AP works as a bridge and every transmission is between AP and STA(s). Next, the STAs can operate in Ad-Hoc mode, in which case the BSS is referred to as Independent BSS (IBSS). In this scenario, there are multiple STAs, and no AP. Each STA can be a router to connect the ad-hoc network to the wireline network.

The mandatory 802.11 DCF relies on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. When a packet (i.e., MAC frame) is to be transmitted, the channel access procedure should be carried out. This channel access relies on a constant sensing of the channel. The channel needs to be sensed idle for a well-specified duration before the packet can be transmitted.

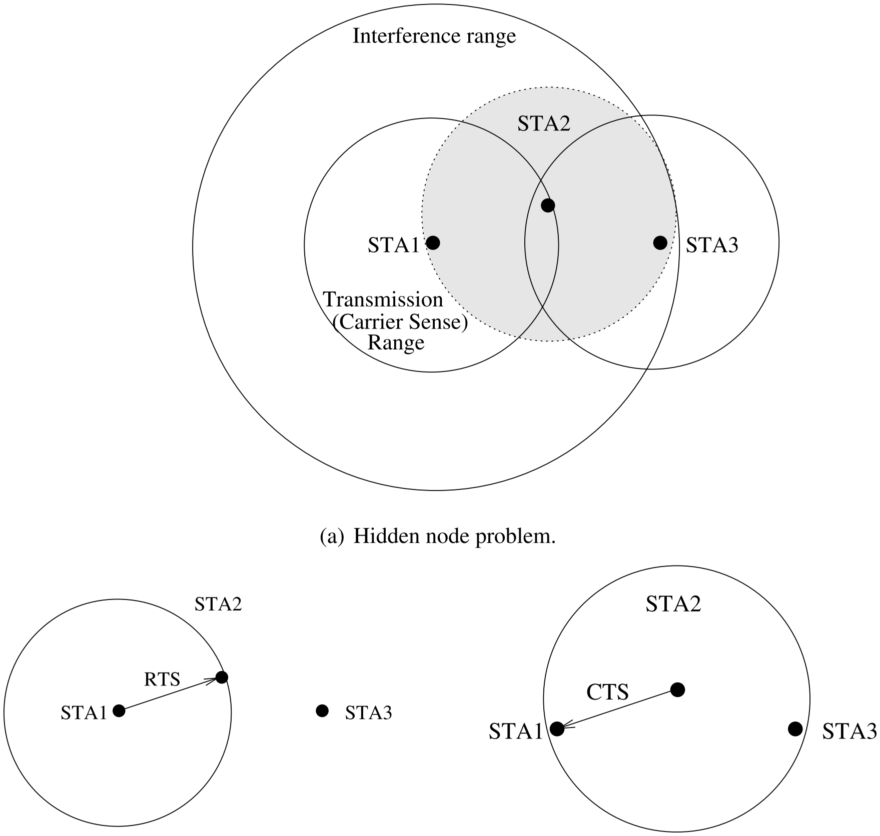
First, before each packet transmission, an Interframe Space (IFS) needs to be considered. Then, to prevent STAs from accessing the channel simultaneously, a random binary exponential backoff counter is introduced. Two different types of channel or carrier sensing are standardized. The physical carrier-sense is provided by the PHY, and depends on the PHY Clear Channel Assessment (CCA) procedure. Further, a virtual carrier-sensing mechanism is provided by the MAC via a Network Allocation Vector (NAV) counter. This counter can be set since each frame carries the `Duration` field in the header. Hence, any correctly received frame can result in an update of that NAV counter, if the new NAV is larger than the current setting. This NAV overrides the physical layer carrier sensing.

Wireless communication is sensitive to the so-called hidden node problem. It can be seen in Fig. 2.2(a) that STA1 and STA3 can hear STA2, but they cannot hear each other. As a result, their physical layer carrier sensing and their virtual carrier sensing mechanisms cannot detect ongoing transmissions from each other. However, since the interference range is typically at least as large as the transmission (and approximately the carrier sense) range, they can interfere with, hence corrupt, ongoing transmissions of each other. To prevent this, the collision avoidance mechanism has been proposed (Figs. 2.2(b) and 2.2(c)). It consists of two short control frames that are transmitted before each data frame transmission. The first short control frame is referred to as Request To Send (RTS), and is sent by the node that wants to transmit a data frame (Fig. 2.2(b)). If the destination node received the RTS correctly, it replies with a Clear To Send (CTS) message to inform the source it can send its data frame (Fig. 2.2(c)). In the header, the total duration of the planned transaction is listed. STA3, overhearing the CTS, can then set its NAV and delays channel access for the total transaction duration. As a result, the hidden node problem is solved. However, this RTS/CTS exchange results in a considerable additional protocol overhead for each data frame to be transmitted. As a result, it is not mandatory, and is often dropped for short packet transmissions, more specifically for packets that are smaller than the `RTS Threshold`.

It is clear that the hidden node problem can be solved by using a much lower CCA threshold, or alternatively, transmitting the packets at a much higher power. The impact of lowering the sensing threshold or the transmission power on the spatial reuse is a complex problem and not well understood. It is very difficult to derive analytical models to predict the performance of a network for a given setting of those thresholds, since the exact performance depends on a lot of parameters such as traffic density, exact topology etc. As a result, the optimal setting can only be determined at run-time when more information about the exact operating conditions is available. This will be illustrated in Chap. 7.

On top of the DCF, an optional PCF can be used. It enables a poll-and-response MAC for nearly isochronous[1] service. It can be used in the infrastructure BSS only,

[1]Isochronous refers to processes where data must be delivered within certain time constraints.



(a) Hidden node problem.

(b) RTS frame exchange.

(c) CTS frame exchange.

Fig. 2.2 The hidden node problem in wireless communications and the RTS/CTS collision avoidance to solve it

since the Point Coordinator (PC) resides in the AP. When the PCF is deployed, channel access is organized in alternating Contention-Free Periods (CFP) and Contention Periods (CP). The PCF suffers from unpredictable, and potentially very large, frame transmission times. Once a station gets access to the channel, it can send a packet up to 2312 Bytes. Assuming that the slowest transmission rate is used, this can take up to 3 ms which is long. The lack of QoS guarantees on top of DCF and PCF has prohibited the use of delay-sensitive applications such as Voice over IP (VoIP) and video conferencing on top of WLAN. To improve on this, the 802.11e has been introduced. One of the mechanisms it includes to improve the QoS is the Transmit Opportunity (TXOP), which is an interval of time when a STA has the right to initiate transmissions. Once a TXOP is acquired, multiple (short) frames can be transmitted. Further, if the TXOP is too small for the current transmission (e.g., since the transmission rate chosen is low), fragmentation needs to be carried out.

This is more fair in networks with varying transmission rates and packet sizes. As long as the TXOP constraint is met, the smart radio can locally optimize it's channel access. In Chap. 6 it will be shown how this can be achieved on top of an 802.11a PHY where the HCF Controlled Channel Access of IEEE 802.11e is used.

2.2.2 3GPP-LTE Evolutions

The 3GPP organization standardizes successive evolutions of cellular standards. This includes first 2G and 2G+ systems, which are were specified in various releases from 3GPP, up to release 7.

Long Term Evolution (LTE) is the latest standard in the 3GPP cellular standards family. It is often referred to as a 4G standard, but it does not yet meat the IMT advanced requirements for 4G since for instance the peak data rate requirement of 1 Gbps is not met. LTE is actually a 3.9G technology, a pre-4G standard and a very important step towards LTE-advanced which is then the true 4G cellular standard. The work on LTE advanced has started mid-2008 focusing of 4G solutions and it is assumed to be standardized in the 3GPP specification Release 10 [22]. The first publicly available LTE service was deployed in December 2009 in Scandinavia. Denmark followed in 2010, while the mobile operators in the US announced a first roll-out only for 2011.

In this section, focus will be mainly on the LTE Rel 8, or the 3.9G of LTE. Then, it will be summarized how LTE advanced builds on this technology.

2.2.2.1 The 3GPP-LTE Air Interface

LTE has ambitious goals with respect to data rates, coverage, latency, operation costs, multi-antenna support, flexibility and seamless integration. Specifically, the goal is to achieve 100 Mbps in the downlink (DL) and 50 Mbps in the uplink (UL).

These peak data rates are based on the assumption that a single user is allocated the whole bandwidth with the highest data rate modulation during a transmission time interval (TTI $=$ 1 ms). With different MIMO configurations (2×2, 4×4), these peak data rates increase with the number of parallel streams transmitted. However, when the number of active users in a cell increase, these rates will decrease.

LTE supports different multiple-antenna modes. The baseline configuration of the number of antennas for MIMO is 2×2. Also, 4×2 and 4×4 configurations can be considered. In the DL, the supported modes are: spatial division multiplexing (SDM), beamforming, and single-stream transmit diversity mode(s). In the transmit diversity modes each antenna transmits the same information but possibly with different coding. Receive diversity is mandatory in LTE. A typical example is maximum ratio combining. These modes depend on the capabilities of the UE and the number of receive antennas and should be adapted slowly to reduce control overhead (at the beginning of the communication or at most every 100 ms). Thus switching between MIMO modes is possible depending on channel conditions. In the UL, MIMO schemes should be adapted to reduce complexity in the terminal. The baseline is to have one transmit antenna to save cost and battery power. MU-MIMO can be used. Multiple user terminals may transmit simultaneously on the same resource block through spatial division multiple access (SDMA). The UEs sharing the same resource block have to apply mutually orthogonal pilot patterns [23].

The physical layer of LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) in the DL and Single Carrier–Frequency Division Multiple Access (SC-FDMA) in the UL. OFDMA is a practical multiuser technique that allows data to be sent to multiple users on a subcarrier-by-subcarrier basis. On the other hand, SC-FDMA, being a single subcarrier system, offers the advantage of reducing the peak-to-average-power-ratio (PAPR), hence increasing the transmitter RF power amplifier (PA) efficiency and reducing the power consumption of the terminal or User Equipment (UE). The main difference between SC-FDMA and OFDMA is a DFT processing block. In an SC-FDMA signal, each subcarrier used for transmission contains information of all transmitted modulation symbols since the data has been spread by the DFT over all the subcarriers. Oppositely, in OFDMA, each subcarrier carries information from one modulation symbol [24].

LTE also allows for flexible bandwidths going from 1.4 MHz to 20 MHz [25]. The possibilities are: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz. It applies to both FDD and TDD. Half Duplex FDD is also supported. This allows operators to provide a whole suite of new services with different bandwidth allocations, or in addition makes it possible to deploy LTE with high peak data rates even when the spectrum availability does not allow for 20 MHz bands. Smaller bandwidths allow for a more flexible and even opportunistic frequency allocation.

Note that the transmission bandwidth is slightly smaller than the channel bandwidth to allow a frequency separation from other bands. The sub-carrier spacing is constant (15 kHz) regardless of the transmission bandwidth. To allow for operation in differently sized spectrum allocations, the transmission bandwidth is instead varied by varying the number of PRBs which will be explained in Sect. 2.2.2.3.

In terms of mobility, LTE is optimized for low speeds (0–15 km/h). A high performance should be achieved between 15 and 120 km/h. Mobility across the cellular network should be maintained between 120 and 350 km/h (up to 500 km/h depending on the frequency band) [26].

2.2.2.2 Multiple Access in 3GPP-LTE

In this section, it is explained how the resources are used among users for a single LTE cell, and among LTE cells. First, the OFDMA resource allocation is explained, which results in a lot of degrees of freedom and hence opportunities to adapt to the run time channel and load conditions of the different users. Next, frequency planning is introduced. It is illustrated that an important trend exists to go from a design time planning of the network toward a distributed planning of the network during the run time, taking into account information that is only present during

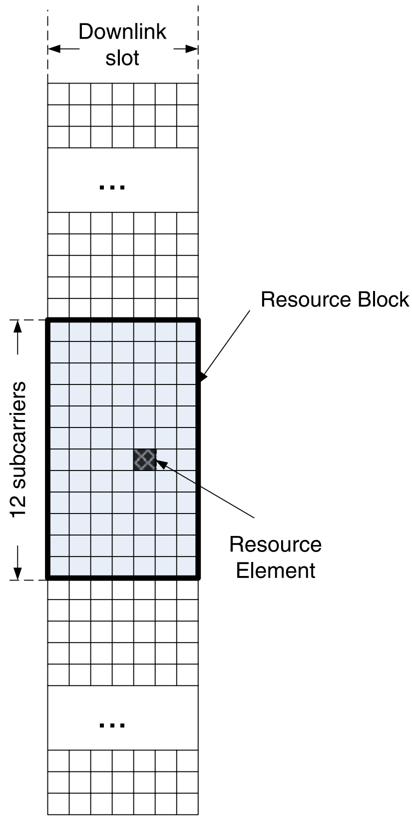


Fig. 2.3 Flexible resource allocation in time and frequency for LTE

the run time. Finally, handover between cells is briefly summarized, which is an additional flexibility present in current wireless networks.

LTE uses a time-frequency-space grid to allocate resources to users in the DL and in the UL (Fig. 2.3). Users are allocated a certain number of resource blocks consisting of 12 consecutive subcarriers during a time slot of 0.5 ms. In the time domain, DL and UL transmissions are organized in radio frames of 10 ms, both for TDD and FDD.

The same coding and modulation is applied to all groups of resource blocks belonging to the same L2 PDU (packets at MAC level) scheduled to one user within one TTI (subframe) and within a single stream. Therefore, the smallest granularity for assigning different modulations or profiles is 12 consecutive subcarriers during a 1 ms period.

In total, each resource block (PRB) consists of 84 resource elements (12 subcarriers during 7 OFDM symbols). However, some of the resource elements within a resource block will not be available as they are already occupied for reference signals or control information.

Even though a downlink resource block is defined in terms of PRBs the downlink resource block assignment is carried out in terms of pairs of PRBs, where each pair

Table 2.3 Transmission bandwidths in LTE

Channel bandwidth [MHz]	1.4	3	5	10	15	20
Number of resource blocks [NRB]	6	15	25	50	75	100

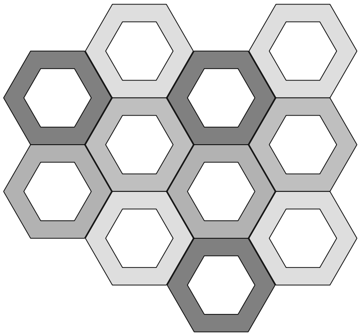


Fig. 2.4 Frequency planning for inter-cell interference (*white* denotes the central region and the *shaded regions* have a less efficient frequency reuse)

consists of two, in the time domain, consecutive resource blocks within a subframe. Additionally, QPSK is used for all control information and data can be transmitted with different modulations like QPSK, 16-QAM, and 64-QAM.

Thanks to the flexible resource allocation in time, frequency and space, and the scalable bandwidths supported by LTE, it is expected that at least 200 users per cell should be supported in the active state for a bandwidth of up to 5 MHz and at least 400 users for higher bandwidths. More users are expected to be supported in a passive (sleeping) state [26].

In a 20 MHz bandwidth, which is the maximum allowed bandwidth, up to 100 Resource Blocks (RB) could be allocated to different users (Table 2.3). A RB is the minimum frequency-time unit allocated to a single user and consists of 12 sub-carriers. Assuming 400 active users per cell should be supported, each user should be allocated 1 RB every 4 consecutive sub-frames (1 ms TTI). The throughput per user in this worst-case scenario will be around 250 kbps. This throughput is for the downlink (DL) direction and will slightly decrease when considering the overhead of the control information.

The cell-edge performance is a more challenging task since inter-cell interference can degrade the system capacity. A way to limit this interference is through inter-cell interference coordination, which can be achieved by restricting the transmission power in different parts of the spectrum in combination with a flexible frequency planning. A possible flexible frequency planning is a soft frequency reuse scheme which is characterized by a frequency reuse factor 1 in the central region of a cell, and a less efficient frequency reuse near the cell edge as in Fig. 2.4.

When the mobile station (or UE) is near the base station (or eNB), the received power of the user signal is strong, and the interference from other cells is weak. So at the inner part of the cell, all the sub-carriers can be used to achieve high data rate communication (Fig. 2.5).

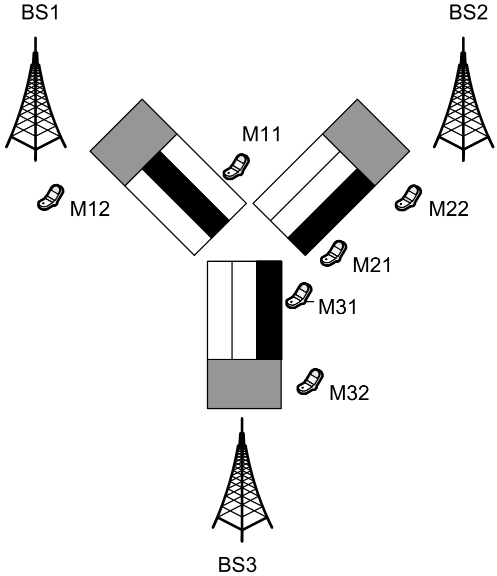


Fig. 2.5 Frequency planning for inter-cell interference (the entire band is used in all cells for the central regions)

In Fig. 2.5, mobile stations 11 and 12 are connected with base station 1, while mobile stations 21 and 22 are connected with base station 2, and mobile stations 31 and 32 are connected with base station 3. It can be noticed that mobile stations 11, 21 and 31 are located at the intersection of 3 cells, while mobile stations 12, 22 and 32 are in the center of their respective cells. For the three mobile stations at the cell edge, different sub-carriers are allocated to avoid the co-channel interference. For the mobile stations near the base station, all the sub-carriers can be allocated and a lower output power can be used, to achieve a high frequency reuse. In this example, the frequency reuse factor is 3 for the cell edge and 1 for the inner part of the cell. For the inner part of the cell, through the limitation of the transmission power, some isolated islands are formed that do not interference each other. To conclude, the benefits of using this flexible frequency planning with soft frequency reuse scheme are:

- High bitrate at the cell center;
- Less interference at the cell edge, making easier the channel estimation, synchronization, and cell selection;
- Overall improved spectral efficiency of the network.

To achieve the benefits of soft frequency reuse, a tight coupling between frequency allocation and output power is needed. This can be achieved by a thorough network planning carried out during the roll out phase of the network. However, with the trend towards smaller and smaller cells, a more distributed approach towards power and frequency planning is needed. In recent years, Self-management (Self-X) technologies that fully automate the tasks of managing (i.e. configuring, monitoring, and optimizing) a cellular network are emerging as an important tool in reducing costs for the service provider and will be a distinguishing feature of

LTE networks. In [27] this Self-X technology is used for the self-configuration of fractional frequency reuse for LTE that uses only local information. Their solution achieves a trade-off between locality of the information, optimality and stability of the solution. This trend to move from design time planning of the network towards self-configuration during the run time, taking into account specific information that can only be obtained during the run time, is the basis of the design methods proposed in this book.

2.2.2.3 LTE-Advanced

LTE advanced is the push towards 4G wireless technologies. It aims to even further data rates than LTE [24] in line with 4G requirements. The most important requirement is the very high data rate, which is 100 Mbps for high mobility and as high as 1 Gbps for low mobility. This low mobility mode is the focus, since LTE advanced mainly aims at achieving high data rates. However, mobility support across the cellular network up to 350 km/h (even up to 500 km/h depending on the frequency band) is also included.

To achieve 1 Gbps, the bandwidth is increased up to 100 MHz. For backwards compatibility with LTE, this is implemented by aggregating up to 5 carriers with a bandwidth of 20 MHz. In addition, the number of spatial streams is increased up to 8×8 for DL and 4×4 for UL. Next to SDM, the MIMO modes include beamforming to improve the performance at the cell edges. For this, multi-cell beamforming is also possible, which means that multiple eNB's cooperate to transmit data to a cell edge user. In addition to cooperative multipoint transmissions, cell edge performance can be improved by means of relaying. Both layer 1 and layer 3 relaying is considered. The target spectrum efficiency is 30 bps/Hz for the downlink and 15 bps/Hz for the uplink. Finally, the number of active users that should be supported in a 5 MHz band is increased to 300.

To make optimum use of all the possible frequency bands, and with a flexible bandwidth up to 100 MHz, it is clear that the frequency planning and configuration is even more flexible than for LTE. In addition to that, with relaying and multi-cell beamforming, the number of possible transmission modes is increased dramatically. As a result, the trend towards self-configuration and self-optimization is supported even more for LTE-advanced. Both flexible spectrum usage and more Self-X are important features of cognitive radio networking.

2.3 Spectrum Access Flexibility

Spectrum is becoming a major resource constraint when designing radio systems. The accelerated deployment of broadband personal communication coupled with the continuously increasing demand for large data rates results in an increasing spectrum scarcity. Wireless technology on the other hand is becoming more and more flexible so that a more opportunistic use of the spectrum or air interface becomes possible.

The need for, and possibility of, a more flexible use of the spectrum is currently recognized and investigated by the major regulatory/standardization bodies (IEEE, ITU, ETSI, FCC, EC) as well as many national spectrum administrations. Worldwide, frequency bands are being opened up for more flexible access. One well-known example of this, is the debate on flexible re-allocation of the so-called 'digital dividend' and 'TV white spaces' which is regularly grabbing headlines in the media. A recent decision by the FCC to open up unused TV spectrum for unlicensed use is fueling this debate even more. In Europe too, there is a call for more ambitious use of the free spectrum space (e.g. through the WAPECS initiative).

In addition to this new trend towards an opportunistic use of spectrum by secondary users, the coexistence problem in the unlicensed bands in a well-known problem that is not trivially solved. In this section, we discuss coexistence problems, both in the case of secondary and primary user coexistence in the TV white spaces or licensed bands, and coexistence in the unlicensed bands. In this book, it will be illustrated how to design more smart or cognitive radios based on a design example for both coexistence scenarios. In Chap. 5 it will be shown how to improve coexistence in the ISM bands. In Chap. 4 it will be shown how an opportunistic radio can avoid interference with a licensed technology.

2.3.1 The ISM Band: Coexistence in Unlicensed Bands

Spectrum sharing in the unlicensed bands is based on a best effort principle, i.e., nodes are equipped with some mechanism to guide spectrum access in a distributed way. However, no guarantees about the QoS can be set, and as a result it is commonly believed that spectrum sharing in the unlicensed bands offers a worse QoS to the end user compared to licensed or fixed access. The CR paradigm investigates how more guarantees can be given when the spectrum is to be shared among possibly heterogeneous technologies. This can for instance be achieved by making more optimal use of the existing flexibility options such as power control, rate adaptation or channel selection. In addition, the spectrum access in unlicensed bands is typically guided by means of a Listen-Before-Talk (LBT) etiquette. This means that node have to *sense* the channel before they can access it. A more optimal configuration of the LBT rules is another important configuration knob to control the spectrum access of a cognitive radio.

To explain the coexistence problem when heterogeneous networks with a similar licensing status have to share the same spectrum, focus in this book is on the coexistence between two major wireless standards that operate in the 2.4 GHz ISM band, namely 802.11g Wireless LAN [28] and 802.15.4 Sensor Networks [29]. Their overlapping frequency channels are shown in Fig. 2.6. The characteristics of both networks are very different, resulting in a problem that is asymmetric in nature. Indeed, the output power of 802.15.4 devices is typically as low as 0 dBm [30], whereas the

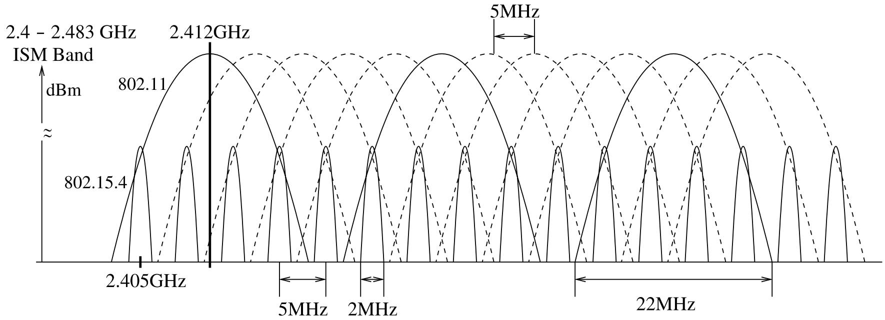


Fig. 2.6 802.11 and 802.15.4 channels in the 2.4 GHz ISM band

output power of 802.11g devices is typically 15 dBm or above. Also, 802.15.4 sensor networks are designed to monitor the environment or buildings, and can be very large, while 802.11 networks are mostly local hotspots organized around an Access Point (AP). Finally, sensor network applications are not demanding in terms of throughput, which means that their duty cycle is relatively low. Because these networks are very different in nature, achieving smooth coexistence between those networks is not trivially achieved since that would require the detection and channel access techniques of both technologies being harmonized. While their operating characteristics are very different, both rely on a LBT channel access mechanism. Nevertheless, the LBT mechanism cannot give any guarantee about the caused interference, and more cognitive adaptation will be needed to improve the coexistence performance.

2.3.1.1 IEEE 802.11h for Spectrum and Transmit Power Management Extensions

Interest in wireless technology has experienced explosive growth over the past decade. Due to the finalization of many standards, the development of wireless applications has eased, which has contributed to increased spectrum use by a variety of heterogeneous devices, standards, and applications. This holds especially true for the Industrial, Scientific and Medical (ISM) bands that are unlicensed and hence host the most heterogeneous mix of networks. To address the coexistence problems in those bands, the IEEE has started the 802.11h Working Group to make recommendations for better future coexistence [31]. It solves problems like interference with satellites and radar using the same 5 GHz frequency band. It was originally designed to address European regulations but is now applicable in many other countries. The standard provides Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) to the 802.11a MAC that especially coexists with radar systems. Both DFS and TPC will be used further in this book to improve coexistence performance of a CR.

2.3.1.2 IEEE 802.19 Coexistence Technical Advisory Group

The IEEE 802.19 Technical Advisory Group deals with coexistence between unlicensed networks, which is hence applicable to many of the IEEE 802 wireless standards. The first example of wireless coexistence was between IEEE 802.11 and IEEE 802.15.1 (Bluetooth), both operating in the 2.4 GHz ISM band. Coexistence for those networks was first addressed in the IEEE 802.15 Task Group, which produced a Recommended Practice on Coexistence of IEEE 802.11 and Bluetooth. Since March 2006 the IEEE 802.19 TAG addresses coexistence between wireless standards for unlicensed wireless networks under development within IEEE 802. When a new standard (or amendment to a standard) for an unlicensed wireless network is being developed the working group may develop a Coexistence Assurance (CA) document that is reviewed the IEEE 802.19 TAG. At this moment, CA documents exist for IEEE 802.15.3c, IEEE 802.16h, IEEE 802.11y, IEEE 802.11n, IEEE 802.15.4a and IEEE 802.15.4b.

TV bands are generating a lot of fuss and interest within IEEE 802 because working groups like 802.11, 802.15, 802.16 and 802.22 have their eyes on this new (and very good) part of the spectrum. The IEEE 802 Executive Committee approved the formation of a "TV white space coexistence study group" in the 802.19 Coexistence Technical Advisory Group. The Study Group stopped its activity after the March 2009 meeting. IEEE 802.11af is the new study group focusing on a PHY and MAC for the TV bands.

2.3.2 The TV White Spaces: Spectrum Sharing in Licensed Bands

The main interest in the TV bands is driven by the worldwide switchover from analogue to digital terrestrial TV which will release a large portion of spectrum known as the "digital dividend", and might also make available the guard bands between existing or new broadcasting channels (the so-called TV White Spaces or TVWS) available for opportunistic use. These frequency bands are very valuable as they provide propagation characteristics that enable signals to penetrate thick walls and travel long distances. The general consensus worldwide is that at least part of this digital dividend and TVWS spectrum should be allocated for mobile broadband services.

The debate on these so-called 'white spaces', is regularly grabbing headlines in the media with a noticeable interest from and role for new players in the wireless field. The debates centers on the free use of White Space Devices (WSD), i.e. devices that could opportunistically make use of free spectrum for various goals. Parties in favor of these devices see major opportunities for the freed up spectrum, including more mobile broadband services, offering better quality of service, to more users. Traditional users of the freed-up spectrum bands and adjacent spectrum bands such as broadcasters are concerned about the consequences of this type of unlicensed use that could interfere with licensed use. They demand a highly regulated approach.

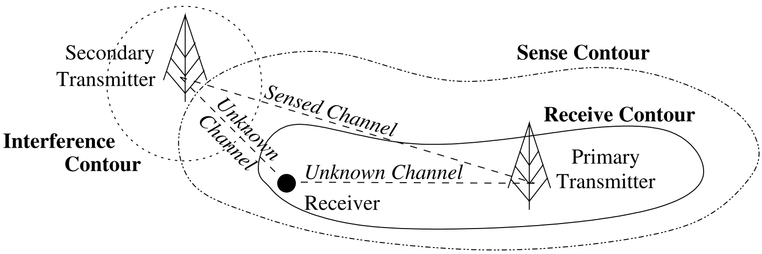


Fig. 2.7 Spatial reuse of the TV white spaces requires large safety margins to ensure that the receive contour of the primary transmitter is protected

In the US, the FCC adopted rules for unlicensed use of television white spaces already in 2008. This announcement was a major endorsement for Cognitive Radio and will softly introduce spectrum sensing technologies in the market in the coming years. The FCC has proposed to use geo-location technology as a primary measure to combat interference: i.e. to check in a database whether a certain frequency band is available or not at a certain location before authorizing the unlicensed use. However, the FCC also stipulates that the geo-location based devices should be complemented with sensing technology:

The Commission also has required that devices include the ability to listen to the airwaves to sense wireless microphones as an additional measure of protection for these devices.

To implement reuse of the TV white spaces, from a platform point of view, the main challenges are related to the sensing requirements. Indeed, as illustrated in Fig. 2.7, it is impossible to sense the exact impact of the secondary transmitter on the primary receiver that should be protected. It is only possible to sense the channel from the primary transmitter to the secondary transmitter, and huge safety margins are added in order to accommodate unknown blocking in the sensed channel. Indeed, if the sensed channel would be blocked, the primary transmitter would seem to be further away than it actually is, and the secondary transmitter could falsely assume that the channel is free. For the TV white spaces, sensing up to -116 dBm is hence targeted, which is well below the noise floor in those bands.

The FCC's conclusion however stated that *devices do not consistently sense TV or wireless microphone signals and the transmitter is capable of causing interference to these signals.*

September 23, 2010, the FCC issued a Second Memorandum Opinion and Order [32] determining the final rules for the use of WSD. The new rules remove the mandatory requirement that WSD should include sensing technology to detect the signals of TV stations and low-power auxiliary service stations (wireless microphones). The FCC states that the geo-location and database access method and other provisions of the rules will provide adequate and reliable protection for incumbent devices, thus making spectrum sensing not necessary since this mandatory requirement would not best serve the public interest. However, the FCC recognized the value of sensing for TVWS in the following statement: *We continue to believe that spectrum sensing will continue to develop and improve. We anticipate that some* *form of spectrum sensing may very well be included in TVBDs on a voluntary basis for purposes such as determining the quality of each channel relative to real and potential interference sources and enhancing spectrum sharing among TVBDs.*

Although spectrum sensing is no longer a mandatory requirement, the FCC has still defined the technical rules for its use. With regards to the geo-location database, the key specifications are still to be drafted and some key issues clarified, such as how many databases will be in place, who will create and manage them, will they public or closed, how will they be certified, and so on.

In Europe, work on a pan-European specification for cognitive radio systems (CRS) is taking place within the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT). In September 2010, a draft report [33] was released assessing the appropriateness of the sensing and geo-location techniques to provide protection to the existing radio services in the context of a diversified range of envisaged deployment scenarios for WSD. In this report, the spectrum sensing technique (local sensing in which detection is carried out independently by each device) employed in this study is regarded as not reliable enough to guarantee interference protection for DTT receivers and programme-making and special events (PMSE) systems. In the DTT scenario, spectrum sensing does not guarantee a reliable detection of the presence/absence of the broadcasting signals at the distance corresponding to the interference potential of a WSD. Therefore, the use of a geo-location database appears to be more reliable in this scenario. In the case of the PMSE deployment scenarios, temporal fading caused by multipath propagation is likely to be one of the main factors affecting the ability of WSDs to protect PMSE systems from interference. In some cases, this may lead to very low detection threshold, far below the WSD receiver noise floor, making spectrum sensing techniques quite impractical. Thus, the ECC argues that setting sensing thresholds very low in order to protect incumbent services, would result in increasing device cost and complexity as well as a in reduced number of available channels. In its view, this would limit the commercial deployment of WSD and reduce the potential value to end-users. Therefore, the report concludes about the primary need to employ geo-location/database access, since sensing alone would not guarantee interference protection. In case geo-location/database access can provide sufficient protection to the broadcast service, sensing should not be a requirement, since its potential benefit still needs to be further assessed.

2.3.2.1 IEEE 802.22 Wireless Rural Access Networks

The IEEE 802.22 Working Group (WG) was formed in November 2004, after the FCC released its Notice of Proposed Rule Making (NPRM) for the TV bands in May 2004. This WG was specifying an air interface (including PHY and MAC specifications) for Wireless Regional Area Networks (WRAN) to coexist with legacy TV transmission relying on cognitive capability. It was the first standard designed for opportunistic spectrum access, and hence the standard is summarized here. IEEE

802.22 only focuses on fixed devices, while the IEEE 802.22a is to add mobile and portable device functionality to IEEE 802.22. First, the application domain is discussed briefly, to better understand the ultimate goal of the standard and hence the decisions made for spectrum sensing, analysis and decision. The main application target for 802.22 systems is wireless broadband access in rural and remote areas. Because of this specific rural application domain targeting lowly populated areas, the success of the standard was low. However, the sensing features for opportunistic spectrum usage introduced in the standard are interesting and hence briefly summarized in this chapter.

2.3.2.2 System Overview

The use of the lower frequency bands are particularly useful for rural access because of the favorable propagation conditions encountered for those lower frequencies. Although the population density is often very small in rural areas, large coverage areas might render the deployment of 802.22 Base Stations (BSs) a profitable business. These lower frequency bands are licensed for TV broadcasting and Wireless Microphones. However, many TV channels are largely unoccupied in many parts of the United States, and often TV is delivered through cable access or satellite. As a result, opening up those bands for WRAN systems could make a good case, both from business and technical points of view. Next to the main WRAN application domain, 802.22 networks can also be used for smaller markets such as small businesses or home offices. But the main goal is delivering broadband to households in rural areas.

An example of a deployed 802.22 network is given in Fig. 2.8. The 802.22 networks operate in a fixed point-to-multi-point topology where a BS controls a cell consisting of a number of Consumer Premise Equipments (CPEs). The BS is an entity installed by an operator, and controls the cell strictly. Next to more traditional medium access control, that addresses when to transmit, it decides on how CPEs should access the spectrum. Moreover, the BS maintains control of a distributed sensing strategy to keep track of potential primary users (TV or wireless microphone signals). Clearly, it possible to have multiple 802.22 cells that interfere. This is aggravated because of the very large transmission area of those systems. Coexistence issues of 802.22 cells are hence also addressed in the 802.22 standard.

2.3.2.3 Spectrum Sensing

One of the important components of the IEEE 802.22 document to achieve the required cognitive capability is related to spectrum measurements. The spectrum measurement in 802.22 is primarily based on transmitter detection. In order to check the presence of primary signals, 802.22 devices need to be able to detect signals at very low Signal-to-Noise Ratio (SNR) levels. Since the detection is done at low SNR, it is assumed that the detection of TV signals is done in a non-coherent manner, which means that no synchronization is needed [34].

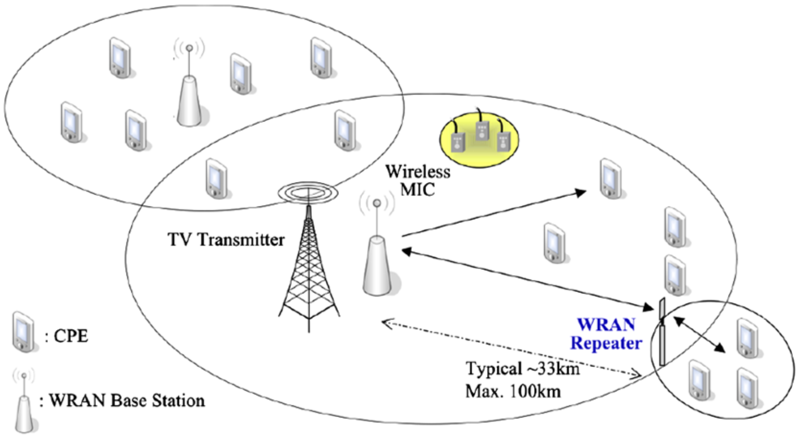


Fig. 2.8 802.22 deployment scenario

The required accuracy of the spectrum sensing, the frequency band and time period, is determined in a centralized way by the BS. Using the local measurements, the BS can establish a spectrum occupancy map. The BS does not require the same sensing accuracy of each CPE, and algorithms to optimize or distribute the sensing load across CPEs can be used. To optimize the sensing, 802.22 devices are supposed to be equipped with a dedicated omni-directional antenna for sensing. This is in addition to a directional antenna which is used for data transmission in the target direction, minimizing the interference area. To be able to optimize the sensing accuracy of the omnidirectional antenna, it would most likely have to be mounted outdoors [34]. 802.22 devices can be instructed to perform in-band or out-of-band sensing, where a band denotes the TV band currently used by the cell. For in-band sensing, the 802.22 communication needs to be temporarily halted, in order not to interfere with the sensing. There clearly is a trade-off between speed at which a primary TV signal can be detected, and the efficiency or throughput achieved by the 802.22 cell. To avoid too frequent long connectivity halts, a two-phase sensing mechanism is proposed (Fig. 2.9). Fast sensing, i.e. based on a simple and fast sensing technique, is performed more frequently. After one (or more) fast sensing periods, the BS can decide whether to perform a fine sensing. This fine sensing takes more time but should in fact only be carried out if the fast sensing results are not sufficient to draw conclusions. Given the fact that TV signals do not come on the air frequently, this two-phase sensing method proves highly effective [34].

If multiple 802.22 cells operate in the same area, it is required that their sensing strategy is synchronized (i.e., they should halt communication when other cells sense). Since coexistence among different 802.22 cells is an important issue, such synchronization is embedded in the 802.22 standard. Contrary to the TV signals detection, sensing of wireless microphone transmissions is much harder as these transmit at a much lower power and occupy much lower bandwidths. Therefore, in addition to transmitter detection, a second sensing option is enabled in the 802.22

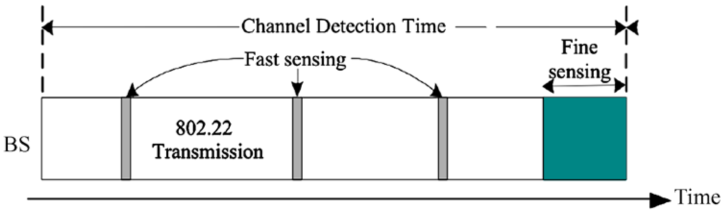


Fig. 2.9 802.22 two-phase in-band sensing

standards. This second option relies on the transmission of beacons by the microphones themselves or a special device carried by microphone operators. This primary network information monitoring is embedded in the 802.22 MAC.

The exact sensing algorithms to be used during the fine and fast sensing periods are not standardized, but an extensive list is provided as annex to the standard.

2.4 Operation Across Technologies: Cognitive Radio

In the previous section, coexistence between technologies was discussed. Optimal sharing is achieved when technologies are not only aware or each others presence, but also act as a function of the coexistence scenario and ideally cooperate. Cooperation between different technologies was first possible in the form of medium independent handover. Although the handover capabilities were merely a responsibility of the terminal, the fact that a standard and information sharing across technologies is present, can be considered as a first example of operation across technologies. Current standards focusing on cognitive radio or dynamic spectrum access networks are also discussed. These standards aim a step further towards the true seamless reconfiguration of multiple terminals and networks. For these future standards, both ETSI and IEEE initiatives are discussed.

2.4.1 Mobile Independent Handover: IEEE 802.21

This standard defines media access independent mechanisms that enable (especially through link layer information) an efficient handover between 802 mobile terminals (capable of supporting different link-layer technologies) and may facilitate the handover between 802 and cellular terminals. The coverage goes from the 802.15 pico-cells and the 802.11 micro-cells up to the 802.15 and 3GPP macro-cells with overlapping coverage. This standard is intended to improve users' experience of mobile devices for 802 heterogeneous networks in a wired or wireless environment and to allow a seamless handover, when the network conditions support it.

The media types that this standard supports include those specified by the IEEE 802 wired and wireless family of standards, as well as those specified by the Third

Generation Project (3GPP), and Third Generation Partnership Project 2 (3GPP2). This standard also addresses the support for handover of mobile and stationary users. As expected, handover for mobile users will happen when changes in the wireless link conditions occur. Not so obvious is the case of stationary users. In general, when one network becomes more attractive to another due to network environment changes, a handover for a stationary user might occur, for example, when a user starts an application that requires higher data rate channel. In any case, the handover should be as transparent as possible to the user.

Furthermore, the IEEE 802.21 standard supports cooperative use of information at the mobile node and within the network infrastructure. This means that both the mobile node and the network can make decisions about connectivity based on measurement reports supplied by the link layer. These reports may include metrics like signal quality, synchronization time differences, and transmission error rates. It is assumed that the mobile terminals and the points of attachment such as the base stations and access points may be multimodal, i.e., capable of supporting multiple radio standards and simultaneous connections on more than one radio interface.

2.4.2 Dynamic Spectrum Access Networks: IEEE DYSPAN

The IEEE 1900P standards committee was established in 2005, in order to promote new standards and technologies for better spectrum management. It has been reorganized as Standards Coordination Committee 41 (SCC41). In December 2010 all activities of SCC41 were transferred to the Communication Society Standards (CSSB). And CSSB established a new committee to manage the SCC41 activities under the new name. IEEE DYSPAN Standards Committee. Two working groups are presented hereunder: 1900.4 and 1900.6, since they standardize the main features of a CR. 1900.4 focuses on the cognitive control and how this should be balanced between the network and the terminal. 1900.6 focuses on the information gathering for a CR.

2.4.2.1 IEEE 1900.4

The task of IEEE 1900.4 working group is to develop a standard defining "Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Radio Access Networks". The objective is to improve the overall composite capacity and the quality-of-service (QoS) of wireless systems in heterogeneous radio access networks (RANs). To achieve this objective the standard defines network resource managers (NRM), terminal resource managers (TRM) and the information to be exchanged between NRM and TRM. This information exchange between network side entities and terminal side entities (network-terminal distributed decision making) is exploited to optimize the radio resource usage including spectrum access control in heterogeneous RANs.

The standard is associated with the heterogeneous wireless environment which includes multiple operators, multiple RANs, multiple radio interfaces and multiple terminals.

NRM and TRM interact with each other and exchange the context information measured at the network and the terminal side. This context information is exploited for the network-terminal distributed optimization of the spectrum usage. The standard considers the reconfigurable base stations and reconfigurable mobile terminals. Any network side radio node is called the base-station which can be a Wi-Fi access pint (AP), a UMTS node-B or a WiMAX base station (BS) etc. The reconfigurable terminals that are considered in the standard may or may not have multi-homing capability, which refers to the capability of a reconfigurable mobile terminal to have more than one simultaneously active connections with RANs.

The standard defines three use cases:

- *Dynamic Spectrum Assignment:* In this use case the frequency bands are dynamically assigned to RANs. It means that the frequency bands are not fixed and can be dynamically changed to be used by RANs and terminals by an operator spectrum manager (OSM).

  Spectrum sharing and spectrum renting among RANs are examples of this use case. In spectrum renting the frequency bands of one RAN is assigned to the other RAN. In spectrum sharing the frequency band of a particular RAN is shared among several RANs. For example a frequency band previously used for WiFi (IEEE 802.11) wireless Internet access can be shared/rented to mobile broadband wireless access WiMAX (IEEE 802.16).
- *Dynamic Spectrum Sharing:* In this use case fixed frequency bands can be dynamically assigned to RANs and terminals. The frequency bands assigned to RANs are fixed but can be shared among several RANs.

  As an example of such use case might be the opportunistic spectrum access of unlicensed secondary systems (IEEE 802.22 or unlicensed WLAN IEEE 802.11 in a possible future CR environments) with the primary licensed but un-utilized part of VHF/UHF spectrum in time or space.
- *Distributed Radio Resource Usage Optimization:* In this use case the decision making is done in a distributed manner by the network and the terminal.

  An example of this use case may be the scenario in which the context of the CWN changes e.g. network load is increased or decreased, change in the channel fading statistics and the availability of a high throughput/user preferable RAN etc. In such a case the TRM analyze the context information and dynamically make its own decisions to optimize the radio resource usage, QoS and its own objectives.

According to the standard there shall be an entity on network side, called Network Reconfiguration Manager (NRM), responsible for managing the CWN and Terminals for network-terminal-distributed optimization of spectrum usage. There shall be an entity on terminal side, called Terminal Reconfiguration Manager (TRM), responsible for managing the terminal for network-terminal-distributed optimization of spectrum usage. The TRM shall manage the terminal within the framework defined by the NRM and in a manner consistent with user's preferences and available context information. This evolution towards policy derivation by the NRM that will guide the TRM do execute it's cognitive control mechanisms in a way that are in line with the overall network objectives is an important enabler for CR. In addition to the decision framework, the entities for information extraction, collection and storage have been standardized. Also for this functionality, it is assumed that TRM and NRM cooperate.

From April 2009, 1900.4 Working Group works on two projects:

- 1900.4a: Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks – Amendment: Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands. This working group hence focuses on the extension of the 1900.4 standard for the TV White Spaces specifically.
- 1900.4.1: Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks. This standard targets the next step with respect to the cognitive control standardization.

2.4.2.2 1900.6

The intended standard defines the information exchange between spectrum sensors and their clients in radio communication systems. The logical interface and supporting data structures used for information exchange are defined abstractly without constraining the sensing technology, client design, or data link between sensor and client. The standard defines a Cognitive Engine (CE), a Data Archive (DA) and a Sensor, and defines all logical interfaces between those entities. This definition is hence in line with various approaches for obtaining information about spectrum use, such as local sensing, distributed sensing or geo-location database. The standardized interfaces are very general to facilitate any sensing hardware, algorithm of architecture. A follow-up project for the 1900.6 working group is under discussion, to see how the standard can be instantiated for more practical sensing approaches or geo-location database.

2.4.3 Reconfigurable Radio Systems: ETSI RSS

Similar to the IEEE DYSPAN initiative, the ETSI standardization is starting to standardize Reconfigurable Radio Systems. RRS is a generic concept to exploit the capabilities of reconfigurable radio and networks for self-adaptation to a dynamically-changing environment with the aim of improving supply chain, equipment and spectrum utilization. The Technical Committee has four working groups on System Aspects, Radio Equipment Architecture, Functional Architecture and Cognitive Pilot

Channel (CPC) and Public Safety. For the hardware flexibility, it is mainly the Radio Equipment Architecture working group that is interesting. About the cognitive control, the Functional Architecture and CPC are the most important initiatives. It is worth to mention that the CPC is an alternative to the sensing or geo-location database approaches. It allows a CR to obtain information about available services and the spectrum use by means of listening to a dedicated channel. The CPC was primarily a European alternative for the CR control and information sharing problem. In [35] it was shown that third-party approaches to facilitate a CR operation clearly have their drawbacks since the current stakeholders in the wireless landscape of course do not like to rely on such a third party for their services. Similar arguments can be considered for the geo-location database that is most likely or possibly also going to require a third party (such as e.g. Google).

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