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Introduction

It is common for both the general public and sophisticated engineers alike to take the concept of wireless communications for granted. Since the early research into the properties of the electromagnetic spectrum, scientists have sought understanding of the so called "Luminiferous Aether" [1]. Even with the vast amount of wireless devices in play today, the subject is often treated as a form of black magic: you put energy into a medium and it simply shows up where you want it. Though human understanding of the electromagnetic world has come a long way since the days of the Aether, there is still much that we do not understand about the propagation of electromagnetic waves in complex environments such as the natural and manmade landscapes we expect our wireless devices to operate in. As our understanding of the electromagnetic spectrum has changed over time, so have the methods by which we use that spectrum. While communicating over long distances was the original, and still most popular, use of spectrum there are now several aspects of an average person's day-to-day life that are made better by use of the spectrum. Outside of the communications role, we also use spectrum every day for things like sensing our environment, transferring energy from one place to another, heating objects, and many more. Every single one of these applications requires that the operator "use up" some amount of electromagnetic spectrum while accomplishing their goal. In order to understand why the efficient use of this spectrum is important, it is essential that we first understand what makes the electromagnetic spectrum a shared resource.

Wireless Coexistence: Standards, Challenges, and Intelligent Solutions, First Edition.
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1.1 A Primer on Wireless Coexistence: The Electromagnetic Spectrum as a Shared Resource

In this section, we will seek to establish a fundamental baseline of understanding around wireless communications. This section is targeted at the wireless communications novices utilizing this book as a crash course in wireless coexistence standards. However, even seasoned RF scientists and engineers may find it useful as a number of key principles critical to the analyses in the remainder of the book are spelled out explicitly. This section, then, establishes a baseline of thinking from fundamental principles that can be used to reason about the how and why of coexistence from a consistent perspective. This common baseline allows for a like-to-like comparison when dealing with different styles of coexistence and gives the reader a consistent rubric for considering the potential tradeoffs of those styles.

1.1.1 Basic Description of Spectrum Use and Interference

When examining spectrum use, there are three orthogonal bases that are used to separate different users: time, space, and wavelength. When trying to understand these bases it is common to use sound as an analogous system to help reason about the properties of waves. Electromagnetic waves behave in many of the same ways that sound waves do, with the primary difference being which physical medium is excited with energy.

The first basis, time, is the easiest to understand. If someone is currently transmitting radio waves, they will be occupying the same portion of the spectrum at that time. The second basis, location, is similar but with a caveat. When someone transmits from a particular place, they are occupying the spectrum around that place. However, there are a number of factors that influence the degree to which they are *using* the spectrum there which will be discussed later in the propagation section. The third basis is the wavelength, or frequency, of waves used to transmit your radio signal. The signal sent through the air will always occupy a contiguous band of the spectrum; the width depends upon the amount of information being sent over the air. Figure 1.1 shows an example of a time-frequency map that might depict the transmitters in use at a given location. The larger a block is along the frequency axis, the more bandwidth it consumes at that time.

These types of maps can be helpful to visualize the spectrum usage by different users in a particular area. Which users are able to transmit in each section of a frequency band are typically displayed using a band plan.

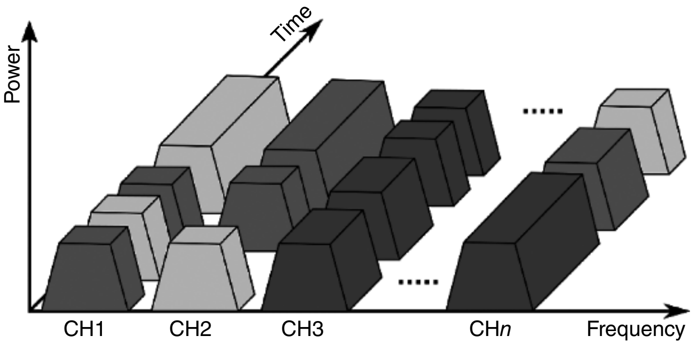

Figure 1.1 An example of a time frequency map.

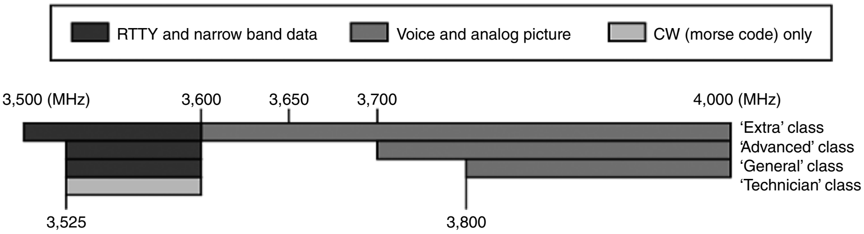

Figure 1.2 An example of a band plan.

For example, Figure 1.2 shows one of the United States amateur radio band plans for the 80 m allocations. Different users, separated into different classes by their capabilities, are allowed to use different sections of the spectrum according to this plan at any time.

One deficiency in a band plan is that it does not specify the physical location from which a user may transmit. This is typically enforced through a combination of the licensing authority and limits on the transmit power that a user can broadcast with. For example, broadcast AM radio stations transmit from known locations (where antenna the tower is), and are assigned a maximum amount of power they can use to transmit. Because the propagation characteristics of the AM Broadcast band are well understood, limiting the power to a certain level performs the same function as ensuring the signal will only be received within a given geographic area. Similarly, mobile users usually have the same power restrictions but have the additional restriction of ensuring that they are operating within a specific boundary, typically the jurisdiction of the licensing authority.

With these three potential bases, it is relatively easy to answer the question "*what is interference?*" IEEE 1900.1 [2] defined **Interference** as:

> In a communication system, interference is the extraneous power entering or induced in a channel from natural or man-made sources that might interfere with reception of desired signals or the disturbance caused by the undesired power.

Interference, in the context of wireless coexistence, means impairing the transmission of another user. This is caused when multiple users operate at the same time, within the same bandwidth, and in the same geographic location as each other, with no means to de-conflict that resource. Chapter 4 will discuss in depth several multiple access strategies such as Code Division Multiple Access (CDMA), which is intended to allow concurrent use of a spectrum resource in time, frequency, and space; but suffers from *interference* caused by the multiple independent users on one spectrum resource. This is type of interference called Multiple User Interference (MUI). Chapter 10 will expand on that discussion and delve into Non-Orthogonal Multiple Access (NOMA), which revolves around concurrent use of spectrum resources and the interference this causes.

1.1.2 Understanding What It Means to Occupy a Band

Using the earlier definition of interference, "operating at the same time, within the same frequency band, and in the same geographic location as another user," leaves a number of practical questions about what it actually *means* to be in the same band or the same place. The logical representation of band usage, such as that shown in Figure 1.1, shows an idealized representation of what it means to occupy a band. In reality, wireless transmissions are a physical process that do not cleanly start and end at the exact edges of the allocated band. A more realistic interpretation of the spectrum usage is shown in Figure 1.3.

Due to the physical nature of modulating data onto signals, it is impossible for a transmitter to keep all of the energy only in the band of interest. This means that there will always be interference outside of the allowed band, even if it is only a very small amount.

1.1.3 Spectral Masks

It is an unfortunate fact of radio communications that an information-carrying signal cannot be made to occupy a finite bandwidth. Because transmitted signals will always produce some amount of noise outside the primary transmission band, the majority of the regulations and licensing requirements in place today focus on ensuring that the interference introduced outside the allocated bands is limited to a manageable amount. These limits are usually defined through the use of what are called **Spectral Masks**. A spectral mask outlines the amount of power that a licensee's devices can

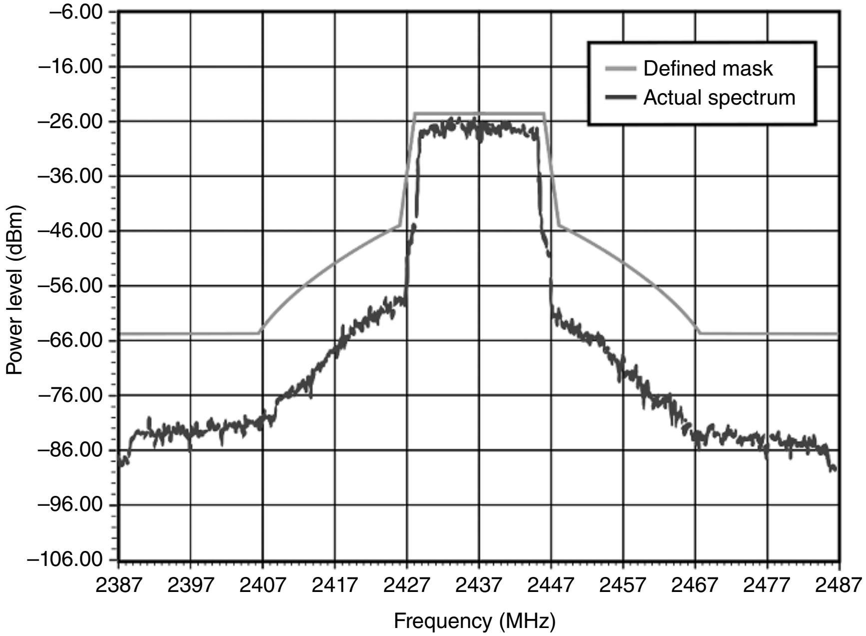

Figure 1.3 Example of realistic spectrum usage for one signal.

radiate over bandwidth. Power over bandwidth is called the **Power Spectral Density** (PSD). Spectral masks are determined from a variety of constraints including but not limited to international regulations, other users in the same band or adjacent bands, and the likelihood of interference with other equipment. For example, Figure 1.4 shows the spectral mask imposed on 802.11 devices when using Direct-Sequence Spread Spectrum (DSSS) [3].

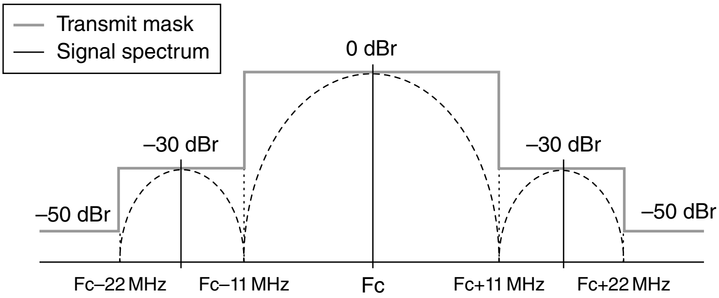

Figure 1.4 Example of a transmit mask. *Source*: IEEE 802 [3].

The bold line in Figure 1.4 is the spectral mask and it limits the power spectral density of the signal that may be transmitted in terms relative to the peak as a function of frequency. The limit is imposed in decibels relative to the reference level (dBr). 0 dBr is at the *reference level*. The reference level is the highest spectral density of the transmission. The channel, in this context defined as the intended transmission bandwidth, spans from ±11 MHz of the center frequency. Outside the intended transmission range, ±11 MHz from the channel center frequency, the power spectral density must not exceed −30 dB relative to the peak power spectral density. Past ±22 MHz from the center frequency, the radios are only authorized to transmit below −50 dBr. By imposing this limit past ±22 MHz from the center frequency, the spectral mask attempts to limit interference caused to other wireless systems. This is a typical representation of a spectral mask, showing the allowed interference that a transmitter can introduce to the signal around it. However, in some cases, masks can be much more complicated than simply *in-band* and *out-of-band* emissions. For example, Figure 1.5 shows the spectral mask for the FCC's amendment to the Part 15 code that allows use of "ultra wide band" unlicensed devices.

This mask shows that devices compliant with this regulation will not have an overall radiated PSD of −41.3 dBm/MHz across the majority of the band with two main exceptions. First, transmitters must not radiate more than −75.3 dBm/MHz in the band used by the Global Positioning System (GPS), which is highly sensitive to local noise from other ground-based devices. Second, these devices are limited to −61.3 dBm/MHz in bands where other sensitive satellite communications networks and radio astronomy receivers typically reside.

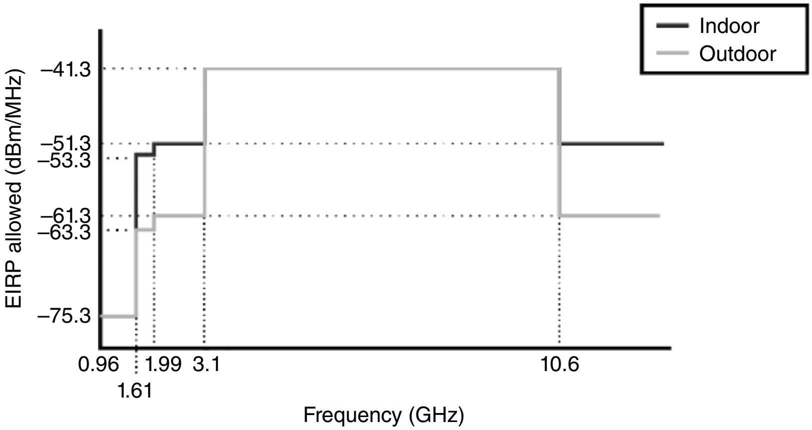

Figure 1.5 US FCC Part 15 spectrum mask. *Source:* Based on Radio Frequency Devices [4].

In both cases, the UWB transmitters would overpower the relatively weak signals coming from space and therefore these critical services are protected from UWB devices with a stricter mask in the bands that they typically operate.

1.1.4 Bandwidth and Information Rate

While band plans and spectral masks might tell a user how much spectrum they are able to occupy, what does that actually mean for the user in real world terms? Practically speaking, the more spectrum or bandwidth that a user consumes, the more information they are able to convey. Information, in this case, can be anything that conveys meaning from one user to another, whether that be analog voice communication, a video signal, or digital data of any type [5]. The amount of information that can be sent within a specific chunk of spectrum is limited in theory by the Shannon Limit [5], which says that there is an upper limit on the amount of information that can be conveyed through any given bandwidth (*channel*). Ultimately, the conclusion is that as more spectrum is assigned to a given user, that user will be able to send more information.

1.1.5 Benefits of Different Frequencies

One of the major concerns different users of the wireless spectrum have revolves around the frequencies of electromagnetic waves they are allowed to utilize. The utility of spectrum for various communications and sensing applications is not just about *how much* but also *at what frequency*. For example, if a user is granted 10 MHz worth of spectrum at a very low frequency such as 30 kHz, the way that spectrum can be used is drastically different than how 10 MHz of spectrum at a shorter wavelength in the 300 MHz range can be used. One major factors that affects all communication systems is antenna size. In order to be efficient, the size of the antennas in a radio system are directly impacted by the frequency used. For example, operating at a very low frequency requires a large antenna that would make it unsuitable for mobile operations. In addition, different propagation characteristics might make one band more useful than another for different applications. For example, some frequencies can travel extremely far around the globe by bouncing off the Earth's ionosphere. While this makes that frequency range very useful for terrestrial communications, it would be nearly useless for satellite communications as the signal would not be able to escape the atmosphere. Similarly, frequencies that are absorbed by walls and buildings would not be good for city-wide communications but make excellent candidates for in-home wireless networks.

In addition to the propagation characteristics of different frequencies, the maximum data rate that can be used with practical circuitry goes up with the carrier frequency used [6]. This means that if a user wants to send a lot of data in a short amount of time, a radio can be more easily built if it utilizes a higher carrier frequency. In general, this makes the higher frequency bands more valuable as data rates and overall system bandwidths grow alongside user appetites for data.

1.2 The Role of Standardization in Wireless Coexistence

Wireless communication standards are an agreement between users of a shared wireless link to communicate in a predictable way that allows all users to both share the spectrum and understand one another. This agreement includes both physical concerns such as the modulation scheme, bands of operation, and data rate as well as the instructions for negotiation of channel use and network formation. Having such a common set of definitions for a given wireless link is a prerequisite for interoperability between devices designed and manufactured by different vendors. Therefore, wireless standards are necessary in order for wireless communications to be viable in a large marketplace with many end-users.

The average end-user may not know of the importance of these standards. What the end-user is concerned with is that the product they have purchased works, that it satisfies their needs. For wireless devices, the user will need their purchased device to connect with other devices and base stations in order to establish a wireless link. The interoperability of all these devices rests upon conformance to a wireless standard. It can therefore be said that without the wireless standards defining bounds for these devices, there is no wireless link and therefore no wireless connectivity. Ultimately, meeting the user's needs is what drives the standards.

IEEE 802.11 is an excellent example of this need for standardization. Since the inception of that standard in the late 1990s, Wireless Local Area Network (WLAN) connectivity has become ubiquitous. Without the IEEE 802.11 standard, Wi-Fi connectivity could not be seen as a common amenity offered by hospitality and retail services.

The above argument establishes the need for standardization in wireless communication links; but what about wireless coexistence? Section 1.1 introduced the concept of spectrum regulation. Why is not spectrum regulation, as dictated by a government authority, sufficient to provide coexistence? One example of the need for industry associations to define coexistence standards can be seen among wireless service providers such as cellphones. As will be seen in Chapter 4, which tackles mitigating contention across equal priority users, wireless service providers must share their allocated spectrum resources across many subscribers. There are many end-user devices attempting to access the same licensed spectrum resource. Therefore, these wireless service providers must define a common means of accessing those limited spectrum resources. Once again, it is the need of the application which drives the standardization.

Standards for wireless communication links are often organized into **protocol stacks**. A protocol stack is a series of layers of processing, each *stacked* upon the other. The functions necessary to establish and maintain the wireless communications link are divided across those layers. The seven-layer Open Systems Interconnection (OSI) model [7] provides a common ontology for the layers and their functional components. As will be seen in Chapter 4, standards for wireless communication links must often define a **Medium Access Layer** (MAC) that dictates the rules for devices wishing to access shared spectrum resources. However, relying on the MAC layer alone to resolve the problem of increasing contention in spectrum access will not be sufficient in the growing complexity of the wireless marketplace.

Reference [8] provides a survey of spectrum sharing, specifically across different technologies. Figure 1.6 illustrates a "technology circle" based on the seven-layer Open Systems Interconnection (OSI) stack. Layers 1 through 7 are the traditional seven layers of the OSI stack. Layer 0 represents government regulations. These government regulation (layer 0) drives the design decisions of a physical layer of a communications standard (layer 1).

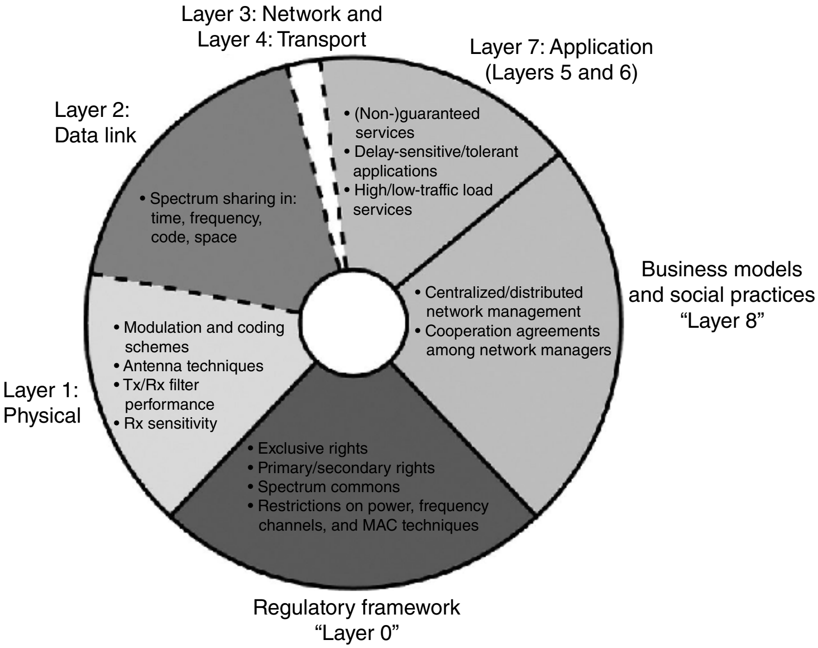

Figure 1.6 The technology circle of wireless coexistence. *Source:* Voicu et al. [8]. © [2020] IEEE.

Layer 8 represents standard practices of the users of wireless systems. It is the needs of the end-user (layer 8) that drive the regulations (layer 0). This connection between layer 8 and layer 0 closes the circle shown in Figure 1.6.

The key concept that the user should take away from Figure 1.6 is that the end-user applications are driving the need for more wireless coexistence. Wireless devices are already ubiquitous, and the volume of wireless devices in marketplace keeps growing. As the demand for more spectrum access grows, congestion across the spectrum grows more severe. As the problem of congestion in spectrum access grows more complex, the mechanisms providing coexistence grow more complex. An example of this is the wireless standard IEEE 802.15.2. This standard did not define a wireless communications link, but rather, it provided recommendations to alleviate contention and interference between two very popular wireless communication links.

Wireless coexistence strategies are a necessity to mitigate congestion in spectrum access. Over the past few decades, these strategies employed have grown more complex. The next section will detail those strategies, and provide a framework for grouping them. Wireless coexistence has developed from a strategy of simply keeping all emitters physically separated, to collaborative spectrum-sensing and spectrum re-use. These increasing complex wireless coexistence strategies require coordination and compliance among multiple devices. The best way to achieve that goal is to provide the vendors of those devices a wireless coexistence standard.

1.3 An Overview of Wireless Coexistence Strategies

There are many potential methods for sharing the same spectrum resources. This act of communicating simultaneously using the same spectrum resources is called "wireless coexistence." By working together and applying some fundamental communications principles, everyone can use the spectrum to communicate, sense, and transfer energy without worrying that their applications will fail due to interference.

This book will cover in depth the wireless coexistence strategies used in a variety of standards but different strategies can be categorized more generally by the method they use to deconflict the spectrum resources. The five primary strategies for deconfliction are Separation, Mitigation, Monitoring, Sensing, and Collaboration.

1.3.1 Separation Strategies

Multiple access schemes are an example of a separation strategy. Numerous multiple-access schemes exist. The ones in vogue have changed over time. For the first generation cellphones (1G), **Frequency Division Multiple Access** (FDMA) was used. As the density of cellphones per person increased, the second generation (2G) of cellphones employed **Time Division Multiple Access** (TDMA) to increase the number of users any one cellular base station could service. TDMA can transmit to multiple user-nodes on one carrier frequency, avoiding intermodulation distortion. The time-slotted channels could be more easily allocated than frequency-channels.

As the number of cellphones increased, **Code-Division Multiple Access** (CDMA) schemes were introduced in the third generation (3G) of cellphones. CDMA offered a new dimension (spreading codes) for channelization; and these spreading codes offered improved resilience to frequency-selective multipath and errant emitters (interferers). This "new dimension" meant that the individual nodes were interfering with one another. CDMA is not simply a channelization method in the traditional sense, but also a mitigation method.

The fourth generation (4G) of cellphones serviced even more users through **Orthogonal Frequency Division Multiple Access** (OFDMA) whereby small blocks of time and frequency resources on any one carrier could be directly assigned to a user.

One key feature these separation strategies share is that the system "owns" the spectrum in which it operates. There is an expectation of exclusivity, and a regulatory authority guarantees that exclusivity. Interference need not be mitigated because any interfering signal would be in violation of that regulatory authority.

These separation strategies will be discussed in more detail in both Chapters 2 and 4. In Chapter 2 the role of spectrum regulation will be addressed. In Chapter 4 separation will be explored as the primary existing means of alleviating contention between users of equal priority.

A separation strategy is insufficient in an unlicensed band like the Industrial, Scientific, and Medical (ISM) 2.4 GHz band. For successful operation in an unlicensed band, interference must be expected and some mitigation employed.

1.3.2 Mitigation Strategies

Mitigation strategies expect interference. These strategies include in the modulation scheme some mechanism to ameliorate the ill effects of interference. Examples of such a strategy include spread spectrum techniques. Two spread spectrum techniques seen in the 2.4 GHz ISM band are direct-sequence spread spectrum and frequency hopping. Spread spectrum techniques are the norm for devices operating in the 2.4 GHz ISM band. Spread Spectrum techniques will be discussed in Chapter 4.

1.3.3 Monitoring Strategies

When interference between signals causes problems in the wild, link monitoring and adaptive mitigation techniques can be used to share the spectrum. Frequency-hopping systems like Bluetooth employ "adaptive frequency-hopping" [9]. The gist of the concept of adaptive frequency-hopping is for the devices to automatically "blacklist" certain frequency channels that prove problematic. This requires the devices to *sense* which frequency channels either already have activity on them or which ones are rendered unusable by multipath. The difference between adaptive systems which require monitoring of the wireless link (monitoring strategies) and systems which simply march through any encountered interference (mitigation strategies) will be shown in both Chapters 4 and 8.

1.3.4 Sensing Strategies

Sensing strategies include concepts such as spectrum sensing and dynamic spectrum access where time-frequency resources that can be used are determined before transmission. This is distinct from the multiple access schemes discussed in the separation strategies because it is the individual nodes themselves performing the sensing operations. The individual nodes attempt to find **white space**, which is unused spectrum, within a target band of operation. This sensing may be augmented by accessing a database of known emitters in the geographic region of operation.

A common approach is simply to "listen before talk" which involves sensing for the presence of another active emitter in a frequency channel before transmitting. This approach is called **Carrier Sense Multiple Access** (CSMA). CSMA is employed in numerous standards including IEEE 802.11 more commonly known as Wi-Fi.

Examples of wireless standards defining systems which operate in white spaces are IEEE 802.22 [10] and IEEE 802.11af [11]. In both of those standards, spectrum sensing and rules for co-existence are defined in the individual standard. So long as a network of emitters adheres to one standard or the other, the emitters will be able to coexist and dynamically make the best use of the available spectrum.

1.3.5 Collaboration Strategies

A collaborative coexistence strategy is one that relies on different wireless systems sharing and exchanging information. Such collaboration can be seen in the standards IEEE 802.19.1 [12], IEEE 802.15.2 [13], and IEEE 802.22 [14]. In collaborative strategies, emitters share information between each other and coordinate spectrum use. If the emitters are coordinating access, it may not be necessary to employ any spectrum sensing or interference mitigation.

As will be seen in the standards covered in this book, collaborative strategies are often paired with other strategies. The results are that when one unit senses spectrum in one location, it can share that information with a larger network.

1.3.6 Combining the Strategies

The strategies discusses in this section need not be exclusive. A sensing strategy may also employ a mitigation strategy. A wireless system may have exclusive access to a specific bandwidth, and that exclusivity would be an example of a separation strategy, but within that system there may be licensed concurrent emitters employing strategies to coordinate and avoid interference.

1.4 Standards Covered in this Book

This book will provide detailed overviews of selected wireless coexistence standards and delve into the background theory behind those standards. The wireless coexistence standards to be covered will include:

- IEEE 1900
- IEEE 802.22
- IEEE 802.11af
- IEEE 802.15.2
- IEEE 802.19.1
- And LTE LAA

IEEE 1900 is a series of standards that have been developed and refined since 2005. This series of standards is currently maintained by Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC). Among the series, one standard that will be referenced throughout this book is IEEE 1900.1 which provides a common set of terminology and definitions for wireless coexistence. The IEEE 1900 series is detailed in Chapter 7.

IEEE 802.22 and **IEEE 802.11af** are both wireless standards for communication links in the television band. As such, these standards define links for *secondary users*. The concept of tiers of users will first be addressed in Chapter 4. Spectrum sensing will be addressed in Chapter 5. Intelligent Radio functions will be addressed in Chapter 6. These two standards will be discussed as wireless coexistence standards in the IEEE 802 series in Chapter 8.

IEEE 802.15.2, as briefly discussed in Section 1.2, provides a recommendations for wireless coexistence between the Wireless Personal Area Network defined by IEEE 802.15.1 (now Bluetooth) and the IEEE 802.11 WLAN (Wi-Fi). IEEE 802.15.2 has been officially withdrawn, however, some of the recommendations made in that standard were adopted and are still present to this day. That makes IEEE 802.15.2 an important part of the history of the development of wireless coexistence standards. This standard will be discussed as wireless coexistence standards in the IEEE 802 series in Chapter 8.

IEEE 802.19.1 specifies a means of coexistence for nodes which do not otherwise share any standardization. This standard can be seen as providing an overlay onto the MAC layer of other standards. One example would be to mitigate contention between 802.22 and 802.11af which would both vie for secondary user access to TV Band white space.

UMTS Long-Term Evolution License Assisted Access (**LTE LAA**) is part of release 13 of the LTE standard. LTE LAA is a variant of *LTE-Unlicensed* in which LTE would operate in unlicensed bands. LTE is a ubiquitous telecommunication system, and it is operation in potentially congested unlicensed bands is relevant to the future of wireless coexistence. LTE LAA will be detailed in Chapter 9.

1.5 1900.1 as a Baseline Taxonomy

One of the biggest hurdles when trying to discuss wireless technologies in a coherent fashion relates to the idea of language. Technical terms very often mean different things to different people leading to mass confusion and generally unproductive discussion when it comes to comparing and contrasting different regulatory schemes. For example, what does it mean for a radio to be *Software Defined*? While most would agree this means that the radio functionality is programmed with some sort of software description, the gamut of potential interpretations is extremely wide. In a similar fashion, one could ask what it means to be a *Cognitive Radio*. Clearly, at its core, the term *Cognitive Radio* means just one thing: that the radio is using some intelligent decision-making processes to operate. Over time, however, the term cognitive radio has become muddied to include a radio that may or may not utilize things like dynamic spectrum access, spectrum monitoring, radio signal identification and more. While it certainly possible that a radio could use cognition to perform these tasks individually or, alternatively, use the results from these task as inputs to a cognitive process they are not necessarily, in and of themselves, what make a radio “cognitive.” It is critical that a well-defined taxonomy is used when comparing wireless coexistence mechanisms in a fair and reliable fashion. A good taxonomy will allow users to separate the irrelevant policy and system architecture differences and focus efforts on comparisons that tease out the core benefits of different schemes.

Although the IEEE 1900 standards will be discussed in more depth in Chapter 7, a focused discussion of the 1900.1 standard here has the benefit of providing a general taxonomy for wireless coexistence technologies.

One of the critical contributions of the IEEE 1900 standards is providing a baseline taxonomy for terms and concepts relating to wireless coexistence. The definitions and concepts laid out in 1900.1 allow the IEEE to define exactly what does and does not constitute dynamic spectrum access but also provides a wider categorization of coexistence strategies in general. This idea is clearly presented from the IEEE 1900.1 scope statement:

> This standard provides definitions and explanations of key concepts in the fields of spectrum management, spectrum trading, cognitive radio, dynamic spectrum access, policy-based radio systems, software-defined radio, and related advanced radio system technologies.

Through a combination of the definitions themselves and the informative annexes, the reader can use this model to classify any spectrum access scheme. This includes both concepts in wide use today, such as fixed frequency allocations and the ISM unlicensed bands, as well as future concepts for spectrum access that are being proposed to reduce spectral inefficiencies. The formal definitions described in 1900.1 provide five categorical breakdowns that can be used when describing any radio system including device architectures, devices capabilities, command and control concepts, radio network types, and spectrum management concepts.

1.5.1 Advanced Radio System Concepts

The first category defined in 1900.1, “Advanced Radio System Concepts,” provides a clean delineation between the terms surrounding radio systems. Figure 1.7 shows an Euler diagram of the advanced radio system concepts taken from the IEEE 1900.1 supplemental material which provides a useful visualization to the concepts discussed in the rest of this section.

The first primary distinction surrounds the concept of delineating which radio functions are implemented in either hardware or software. In order to provide a more accurate taxonomy, 1900.1 separates the idea of how radio functions are *defined* versus how they are *controlled*. For example, it is entirely possible for radio software to switch between different hardware signal processing functions as part of an adaptive spectrum access scheme. Separating the taxonomy alleviates some confusion about whether or not a system is considered a *software-defined radio* from a regulatory point of view if the radio functions are implemented in hardware but dynamic control occurs in software. In the IEEE 1900 taxonomy, the terms *Hardware Radio* and *Software Defined Radio* (SDR) imply that the signal processing functions themselves are implemented in either hardware or software respectively and whether they can be changed without physically modifying the device. If the signal-processing functions are implemented in software and “cannot

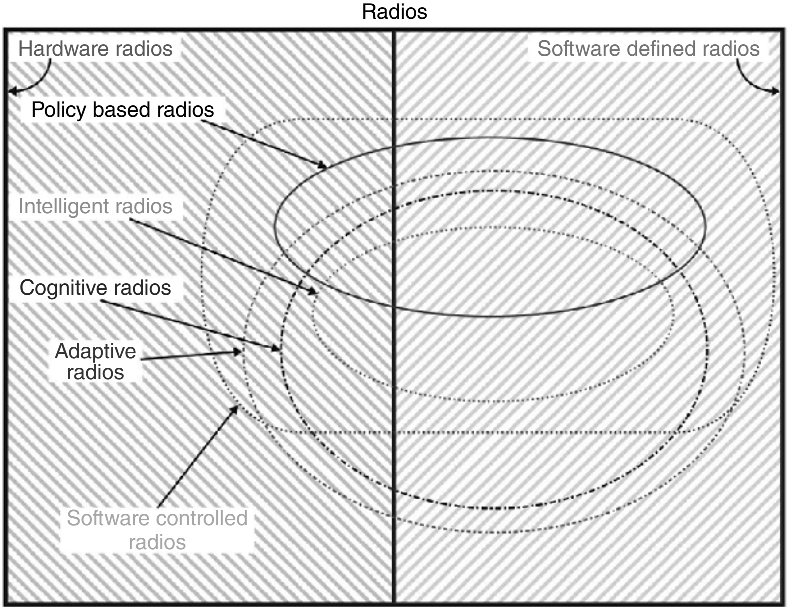

Figure 1.7 Radio classification guide for IEEE 1900. *Source*: I. S. 1900.1-2019 [2].

be changed in the field, post manufacture, without physically modifying the device" then the device is still considered a hardware radio.

Additionally, a radio can be a *Software Controlled Radio* (SCR). In this case, in addition to the signal processing functions themselves, the idea of "control" is separated from the radio and "implies more dynamic operational flexibility from radio interfaces, in contrast with software-defined radio which might in some cases be seen as a static implementation of the radio interface by software."

The second set of definitions outlined in advanced system concepts relates to how the radios behave. In the 1900.1 taxonomy, radios whose functions can be changed by software to support changes in their environment are called *Reconfigurable Radios*. These radios can be *adaptive*, *cognitive*, *intelligent*, *policy based*, or a combination of all four depending on how they are reconfigured. For example, an *Adaptive Radio* changes its operating parameters in response to changes in its environment. The key point is that how it makes those changes does not necessarily have to be done in an intelligent way. For example, changing operation based on time of day or set thresholds on bit error rate can be adaptive actions, but they are simple reactions and not made by reasoning about the environment. This is in contrast to a *Cognitive Radio* which "exploits cognition to control its behavior." If a cognitive radio is using machine learning in addition to simple cognition, it can be referred to as an *Intelligent Radio*. The final behavioral control type is referred to as a *Policy Based Radio*. In this case the radio's behavior is dictated by a "policy," a set rules and regulations that the radio manufacturer agrees to abide by. Realistically, all current radios are *policy based radios* in the sense that they are typically only allowed to transmit in certain bands a set a policy limit. In this case, such as with a hardware radio, the policy in enforced by the fact that the radio is incapable of transmitting outside of the policy rules and remains in effect for the lifetime of the device. For future dynamic spectrum access radios, however, this policy may be enforced for only a short time or only in specific locations. IEEE 1900.1 makes this distinction clear in the supplemental material by stating that the policy definition may occur during manufacture of the device, during deployment, or via real-time control.

1.5.2 Radio Capabilities

The second set of definitions provided in the 1900.1 standard are the different capabilities that a radio may have when accessing spectrum. The 16 individual capabilities defined in the standard can be loosely grouped into three categories: system actions, system inputs, and cognitive abilities. System actions are things that the radio can do. This category includes all actions that the radio can take when adapting to the environment. It includes the ability to adaptively change the transmission parameters of the radio such as transmit power and modulation in response to external stimuli such as bit rate or link quality. It also includes the ability to be agile in frequency, changing where in the spectrum the radio is operating on demand. System inputs are attributes about the system that can be used by higher-level control software to access the spectrum. These include the radio's ability to maintain a representation of its own state and the environment around it. This may include keeping track of other spectrum users in range, the location of the radio both in terms of physical space and regulatory authority, and other environmental attributes that the radio can use to reason about what policies can be executed. The last group of attributes are the cognitive abilities of the system. These include the ability to reason about how and when to change the operation of the radio in order to access the spectrum according to the allowed policies. This may include learning about the RF environment as it changes over time, consulting regulatory policies, and reasoning about the correct course of action in a given situation.

1.5.3 Network Types

IEEE 1900.1 differentiates three types of advanced radio networks depending on the capabilities of the network as a whole to operate in a given environment. The first, a **Cognitive Radio Network** is a network where the behavior of the radios is adapted based on a cognitive process running in the network. It is noted that the individual radios in this type of network do not necessarily have to be cognitive themselves, just that they are controlled by a cognitive process. For example, a central cognitive node could collect the environmental awareness information from the individual nodes and instruct the network to adapt. The second network type is **Dynamic Spectrum Access** networks. These are networks that adapt their spectrum utilization in real time according to changes in the environment and predefined policies. The final network type, **Reconfigurable Networks**, is any network that can be configured on the fly. It is important to note that these networks do not necessarily need to be made up of adaptive or reconfigurable radios themselves. For example, in a network with fixed configuration base stations, the network could be reconfigured at a higher layer to route traffic over the best RF link available at the time without actual changes made to radios themselves.

1.5.4 Spectrum Management

Of all the terms and definitions set forth in IEEE 1900.1, those defined in Section 7 relating to spectrum management bring the most clarity to this confusing topic. Clear and accurate descriptions of what it means for a radio to have a *frequency allocation* or what the difference between radio networks that *collaborate* versus those that *cooperate* provide a common baseline for discussing different protocol aspects in reasoned way. This section will cover the most useful terms and definitions outlined in the “Spectrum Management Definitions” section of 1900.1 with the intent that these terms will be used coherently for the rest of the book when discussing particular technical aspects of different protocols or different wireless coexistence schemes.

1.5.4.1 Basic Terminology

Section 7 of 1900.1, “Spectrum Management Definitions,” outlines the basic terminology that frames who the actors are and what their goals are when it comes to wireless coexistence. In fact, 1900.1 even provides a formal definition for coexistence which is defined as “the state of two or more radio devices or networks existing at the same time and at the same place in a shared spectrum space.”

1900.1 establishes that a **Coexistence Mechanism** is any technique that different radios might use to avoid causing interference with one another. Interference includes any energy, both natural and man-made, in the operating bandwidth of a user. Mitigating harmful interference is the primary focus of Spectrum Management. Through effective spectrum management, the Spectrum Owner can establish a set of rules and procedures, known as **Spectrum Etiquette**, that meet the spectrum owner’s goals for that section of the spectrum. This etiquette could be very simple, such as in traditional licensing schemes dictating that only one license holder is allowed to use the band at all, or very complicated requiring users to adhere to any number of policy restrictions in order to access the spectrum. In addition, different etiquettes can be applied at different levels of the spectrum management hierarchy. For example, the ITU might define an allocation that specifies a high-level purpose for a given band which is then further restricted by federal or regional regulators. If the spectrum etiquette is adhered to, the final outcome should be the state of Electromagnetic Compatibility (EMC), which is when radios utilizing in the same TLF space can operate "without causing or suffering intolerable or unacceptable degradation."

1.5.4.2 Spectrum Access, Sharing, and Utilization

Ultimately, the goal of wireless coexistence is to ensure that there is fair and equitable access to a finite set of spectrum resources without interfering with one another. Because these resources are limited, how different users access and share the spectrum can dramatically affect the ability of users to meet the goals of the spectrum owner. In this paragraph we will outline the definitions from 1900.1 that provide what it means to use spectrum resources.

The first part of using spectrum resources is the concept of access. Spectrum Access is defined in 1900.1 as "Transmission or reception on the radio spectrum." The standard makes it clear that even though transmission in a band is the outwardly obvious "use" of the band, preventing harmful interference to licensed receivers is just as important. The distinction is important because wireless coexistence mechanisms often rely on the fact that if there is no transmitting entity in the band that the band constitutes a *free* chunk of spectrum. This is not always the case and the standard makes it clear that protected receivers are "accessing the spectrum" just as equally as a transmitter would. When users are actively accessing the spectrum, either while transmitting or receiving, that section of spectrum is being **utilized**. Note that there is no distinction between whether the user is authorized to transmit there, the noise is from a natural source, or if the transmission parameters do not follow the etiquette laid out by the spectrum owner: the spectrum is "utilized" regardless. 1900.1 defines the utilized spectrum, expressed in Eq. (1.1) as U, as the product of the occupied bandwidth (B), the physical space being utilized (S) and the time period (T) that the access takes places over.

$$U\left(\mathrm{Hz}\cdot\mathrm{m}^3\cdot\mathrm{s}\right) = B(\mathrm{Hz})\cdot S\left(\mathrm{m}^3\right)\cdot T(\mathrm{s}) \tag{1.1}$$

From this definition, we can see that any TLF space that is not currently utilized is a *free resource* that is available for another user. In 1900.1 this free resource is referred to as Spectral Opportunity and is defined as any frequency segment that "satisfies availability criterion" for access based on the spectrum etiquette in play at that given TLF block.

The concept of utilization defined above leads directly into the idea of ensuring that the spectrum is being used to its maximum benefits, known as the Spectrum Efficiency. One of the primary metrics for determining if spectrum is being used efficiently is the Spectrum Utilization Efficiency (SUE) metric, expressed in Eq. (1.2), which is defined as the amount of information transferred (M) to the amount of spectrum that is used by the spectrum access (U).

$$\mathrm{SUE} = \frac{M}{B \cdot S \cdot T} \tag{1.2}$$

While the utilization of the resources is easily defined, the "amount of information transferred" is not necessarily clear cut. For this reason, the value of M should be adjusted to the value that makes sense for system design such as "raw data rate" (bits/Hz), Erlangs, "Number of radar channels available," etc. The goal of any future spectrum etiquette rules, then, should be to ensure that the spectrum owner is working to maximize the spectral efficiency of their bands.

One way to ensure that spectral efficiency is maximized is to implement an etiquette that allows multiple users to coexist in a shared spectrum space, defined as **Spectrum Sharing**. Technically speaking, both current models of frequency allocation are "spectrum sharing etiquette" albeit, highly simple ones. For example, in the unlicensed bands, the ISM style of granting anyone equal rights to frequency band is known as Horizontal Spectrum Sharing. Here everyone is allowed to access the band without regard for other users. In contrast, the traditional Spectrum Leasing model in which a single user has the right to access is known as Vertical Spectrum Sharing. Under vertical sharing, different users have different rights when it comes to accessing the spectrum. In this case the band is "shared" in the sense that one user has unfettered rights to access the spectrum and all others have no rights to access. The traditional model also exemplifies the concept of Frequency Sharing, a sharing paradigm in which set chunks of spectrum are allocated to specific users.

1.5.4.3 Dynamic Access and Spectrum Management Strategies to Improve Spectral Efficiency

While the current model of fixed frequency leasing is easy, it is certainly not efficient. It is clear that in order to improve spectral efficiency as a whole the traditional concepts surrounding fixed access will have to be amended and improved upon. **Dynamic Spectrum Access** is defined as "The real-time adjustment of spectrum utilization in response to changing circumstances and objectives." However, even though a radio may be capable of dynamic access, the spectrum is still managed in such a way that it may not be allowed to dynamically access certain resources. The set of rules that radio uses when deciding when and where to access the spectrum are referred to as a "policy" which is defined by the Policy Authority, the entity that has jurisdiction over spectrum usage. The ability to ensure that spectrum is properly managed via these policies called Policy Traceability, which says that all actions taken by dynamic spectrum access radios have evidence to support how that action meets the spectrum management policies. Through a combination of well written policies and clear etiquette on cooperation dynamic access to the spectrum will improve overall efficiency without generating harmful interference to existing technologies.

1.5.4.4 Collaboration versus Cooperation

By allowing radios to respond to the changes and react accordingly, spectrum opportunities can be exploited to provide an overall increase in spectrum efficiency without harmful interference to other users. From the perspective of 1900.1, these dynamic changes can be made through two subtly different methods: cooperation and collaboration. The first method, **Cooperation**, ensures that all the tasks necessary for co-existence are carried out by the entities engaging in dynamic spectrum access. This cooperation does not imply that the nodes are in communication with one another. For example, 802.11h mandates that 802.11 devices sense their environment before using a candidate channel for wireless networking [15, 16]. In this case the nodes are cooperating, because the 802.11 devices will not interfere with the primary users of the band but no formal communication occurred between the band users. In contrast to cooperation, nodes that are **collaborating** will actively communicate with one another, sharing spectrum sensing data and agreeing on the best deconfliction strategy. In general, collaboration would be preferred to cooperation because it allows the nodes to properly exchange their intentions and requirements in order to make an optimal plan for spectral use. However, in the case of legacy incumbent users who may not be capable of collaborating, cooperation allows newer radios to avoid the legacy users and still improve the spectral efficiency overall.

1.5.4.5 Fixed versus Dynamic Management

Obtaining access to the spectrum is dependent on the rules and regulations that are in force for any given TLF resource. For dynamic spectrum access, 1900.1 differentiates between access that is enabled via traditional spectrum management strategies and those that are enabled by newer, currently unimplemented, dynamic management concepts.

For traditional fixed allocation management, there are a number of methods by which dynamic spectrum access can be enabled. The first method is to allow Hierarchical Spectrum Access in which “...a hierarchy of radio users or radio applications determines which radios have precedence.” This concept reflects traditional spectrum sharing research model that includes a *primary user* and *secondary user* where the primary user has full access to the spectrum and the secondary user may access the channel provided that they will not interfere with the primary. This type of access is split into two different categories: overlay and underlay**. Spectrum Overlay** describes a system in which the secondary user monitors for and exploits spectrum opportunities through Opportunistic Spectrum Access. In this way, the secondary user fits "between" the unused resources left by the primary user, and manages to operate without harmful interference. In contrast, **Spectrum Underlay** allows secondary users to transmit at any time but restricts the amount of interference generated to some preset threshold that occurs below the level of harmful interference to the primary user.

Another method of fixed management relies on cooperation between different spectrum owners. **Spectrum Pooling** is defined as the situation where multiple spectrum owners pool their resources to ensure more efficient use of the spectrum overall. For example, if mobile telephony operators in geographically distinct regions each held licenses for fragments of band, they could agree to pool those resources and utilize this newly formed contiguous chunk of spectrum without interfering with one another. Finally, the concept of **White Space Spectrum Band** builds on the hierarchical and spectrum overlay concepts by providing a method for accessing unused spectrum via formal means. When White Space, a spectrum allocation that is not currently being used by the owner, is available it can be added to a list of unused resources called a White Space Database. By compiling the geographic information in the database, secondary users can determine which spectrum resources are available for use in their area. This style of management often requires that secondary users utilize spectrum sensing to detect potential incumbents and regularly update their database information to minimize the risk to primary users.

In the future, spectral efficiency could see large gains through the use of a more flexible management style. **Dynamic Spectrum Management** is "A system of spectrum management that dynamically adapts the use and access of spectrum in response to changing circumstances and objectives." In this case, some method of collaboration between the users ensures that the spectrum is being utilized as efficiently as possible, adjusting the spectrum management policies as necessary to meet that goal. In order to adjust for these changes in the policy over time, the spectrum owner must utilize a spectrum broker. A **Spectrum Broker** is any system that can subdivide and assign a pool of spectrum rights to other users. For example, a broker could be everything from a human at a company selling allocations to third parties all the way down to an automated system assigning time domain slots in a multiple access system. This broker controls the dynamic policy of the spectrum owner to ensure that spectrum access rights are optimized according to the metrics set forth in that policy.

The rules set forth in the policy can use a number of different techniques to ensure that the spectrum is being used most efficiently at any given time. One use case described in IEEE 1900.4 [17] is **Dynamic Spectrum Assignment** which closely matches traditional assignment models, but allows the broker to change the assignment dynamically to meet policy goals in real time. Another use case is **Distributed Radio Resource Usage Optimization** which goes one-step further by having composite wireless networks exchange sensing and network information in real time to dynamically adjust the spectral resources between these networks in both time and frequency.

1.5.4.6 Environmental Knowledge

The ability to perform dynamic spectrum management could, in theory, rely entirely on negotiated agreements at different levels of abstraction such as between radios, between networks, and between spectrum owners. This would, however, leave inefficiencies in many locations. For example, noncollaborative incumbents that are sparsely distributed would still consume their entire allocation. In addition, changes in the interference environment or inconsistencies in the allocations could result in unusable or otherwise occupied channels being assigned to a new user. It is for this reason that the ability to sense the environment is critical for making decisions in a dynamic spectrum management scenario. For this reason, the 1900 standards treat network and environmental awareness as a critical enabling component to improving spectral efficiency [17].

In an IEEE 1900 system, the **Sensor** is any logical entity that provides information about the operating environment for a radio. This information is obtained through **Spectrum Sensing**, which is the act of measuring the RF environment for both detecting the presence of signals as well as characterizing those signals to determine how they behave. Information that can be provided by the sensors is broken up into two separate classes: *Sensing Information* acquired directly by the sensors about the environment and *Sensing Control Information* that provides metadata about the sensor itself. The first includes collected information from across the entire communications stack such as raw RF samples, a Clear Channel Assessment, data rates, the radio owner, and many more. The second category provides status and configuration about the sensor itself including any data archives or cognitive processes running on the sensor.

Data collected by the sensors can either be used locally on the radio node itself or, alternatively, provided to a central repository on the network. These repositories, called the **Data Archive**, are a place to store the distributed data from all sensors about the RF environment. This combined data allows Distributed Sensing, a method in which geographically separated nodes provide data to the archive to cooperate and collaborate on the total knowledge.

Similar to spectrum management, nodes that perform **Cooperative Sensing** are acting independently to achieve the common goal while **Collaborative Sensing** implies the nodes are actively communicating (perhaps through the data archive) to optimize the sensing. For example, a full picture of regional spectrum occupancy built through collaborative sensing would have the sensors communicating to fill holes in the sensed data while in the cooperative case sensors may simply do a random sweep the spectrum and report occupancy back to the data archive building a complete picture over time. This complete picture of spectrum occupancy and RF measurements over a regional area is referred to as an RF Environment Map that is combined with outside data such as geographic location, local regulations, and relevant policies to generate a full operating picture of the shared spectrum called the Radio Environment Map. This map, generated from sensor data and stored on the data archive, provides the complete picture necessary to make intelligent decisions about dynamic spectrum access in any given area.

1.6 Organization of this Work

Standards are written such that a device can be tested for conformity. Standards are not written to explain the theory behind the design decisions made in that standard.

The standards offer little to no justification for the limits imposed or choices made for that standard. One of the primary goals of this book is to elucidate wireless standards pertaining to wireless coexistence. To meet this goal, a theoretical background for the wireless coexistence must be provided. Those concepts can then be used to detail existing wireless coexistence standards including the motivation and tradeoffs surrounding different decisions made by the standards bodies.

The first portion of this book will largely follow the layers illustrated in Figure 1.6. Regulations will first be discussed, followed by a discussion on select concepts in communication theory relevant to physical signals. Those concepts will then be used to discuss initial contention mitigation among users equal in priority. This follows the regulation, to physical layer, to MAC layer paradigm in Figure 1.6. From there, more advanced concepts will be addressed detailing spectrum sensing and cognitive functions. These cognitive functions do not necessarily fit into a one dimensional protocol stack. As will be seen in Chapter 8, the IEEE 802.22 standard specifies a separate cognitive plane in its protocol stack to encapsulate these functions. Once the regulatory landscape, communication theory, and cognitive radio theory topics have been explored, the next chapters will detail the standards outlined in Section 1.4.

Chapter 2	Covers the regulation of spectrum access including licensed bands, unlicensed bands, and the introduction of user tiers in the Television Band
Chapter 3	Provides background theoretical information necessary to understanding the physical layer, that being the layer that handles modulation/demodulation, multipath channels, and other physical effects
Chapter 4	Focuses on mitigating contention between equal priority users. This chapter will focus on mostly MAC layer concepts, but some physical layer concepts are also relevant to the discussion on equal-priority user access
Chapter 5	Provides a background on spectrum sensing necessary for both secondary users and CSMA among primary users. Relevant theory and implementation issues will be detailed in this chapter
Chapter 6	Discusses intelligent radio concepts. The role of machine learning in wireless communication systems is growing as methods for wireless coexistence become more complex. This chapter will provide a detailed overview of intelligent radio concepts
Chapter 7	Details the IEEE 1900 series of standards
Chapter 8	Details the wireless portions of the IEEE 802 series of standards
Chapter 9	Details the 3GPP LTE Unlicensed standards
Chapter 10	Presents future trends in wireless coexistence

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