1 Introduction

The main themes of this book are to explore evaluation methods for quantifying the mutual effects of interference on the performance of wireless networks and to investigate system-level solutions for their coexistence in the same environment.

The coexistence of wireless communication systems operating in the same environment has become a "hot" topic in recent years as more systems are choosing to use the unlicensed bands and forfeiting the need to purchase spectrum.

There are two specified unlicensed bands for the operation of wireless systems, namely:

(i) the industrial scientific and medical (ISM) band that includes the 900 MHz, 2.4 GHz, and 5.8 GHz frequencies;
(ii) the unlicensed national information infrastructure (UNII) band that includes the 5.2 GHz band. This band was opened in 1997 in the United States in order to expand broadband access opportunities.

Few rules apply in the unlicensed bands such as the ISM band. For example, the rules defined in the Federal Communications Commission Title 47 of the Code for Federal Regulations Part 15 [2] relate to the total radiated power and the use of the spread spectrum and frequency hopping modulations. It is commonly understood that all users of the unlicensed bands can equally affect the quality and the usefulness of this spectrum. Thus, the major downside of the unlicensed band is that frequencies must be shared and potential interference tolerated.

We distinguish between several types of users in these unlicensed bands. Apart from emerging wireless networks, users include low cost devices such as video/audio transmitters for entertainment, security and surveillance, microwave ovens, and broadcast links for high power FM television.

Although the discussion and the examples provided in this book relate to wireless networks, the performance evaluation approach and the solutions may apply to other wireless systems.

There are three types of wireless networks that we consider depending on the bandwidth and the coverage area supported. Wireless personal area networks (WPANs) are intended for cable replacement systems and short distance ad hoc connectivity. Communications in WPAN are normally confined to a person or object and extend up to 10 meters in all directions. WPAN specifications include infrared [15], Bluetooth [1,7], Zigbee [11], and IEEE 802.15.3 [10]. This is in contrast to wireless local area networks (WLANs) that typically cover a moderately sized geographic area such as a single building or campus. WLANs operate in the 100 meter range and are intended to augment rather than replace traditional wired LANs. They are often used to provide the final few feet of connectivity between the main network and the user. WLAN specifications include Home RF [3] and the family of IEEE 802.11a/b/g standards [5,6,8]. Finally, wireless metropolitan area networks (WMANs) [14] are mainly designed for broadband connections over long distances (up to several tens of kilometers). Although they can be used to provide last mile connectivity to mobile and vehicular users, they are mainly intended for interconnecting WLAN hotspots and cellular coverage areas.

Thus, each wireless network type may be seen as filling a specific niche area and supporting a different application need, altough the co-location and simultaneous operation of all these networks in the same environment poses an unprecedented challenge since they are all competing for the same spectrum.

During the decade 1995–2005 we witnessed the emergence of a few dominant wireless technologies, such as IEEE 802.11b and Bluetooth, with more or less distinct requirements; the future for wireless networks will most likely combine different technologies in order to support constantly changing and evolving usage models and applications. For example, WPAN can be used to connect a headset or PDA to a desktop computer, which in turn may be using WLAN to connect to an access point placed several meters away that is connected to a WMAN deployed in the city.

The vision for interconnecting heterogeneous networks makes the coexistence problem extremely important and the solutions considered even more challenging. If the availability of the unlicensed bands makes the proliferation of wireless networks at all possible, coexistence is the only strategy to ensure their proper operation.

1.1 Interference modeling and performance evaluation

Since one of the objectives for this book is to identify methodologies for quantifying the effects of interference on network performance, a few observations are in order regarding the state of the art in the assessment of interference.

Published results can be generally classified into at least three categories depending on whether they rely on analysis, simulation, or experimental measurements in order to provide quantitative measurements.

1.1.1 Mathematical modeling

Analytical results are mainly based on modeling the collision of packets from multiple transmitters at the receiver and computing a corresponding packet error probability

[18,23,25,26,44,51,71]. This error probability is a function of several parameters; for example, the number of transmitters, the distance between the transmitters and the receiver, the difference in power level between the transmitter and the interferers, and the receiver technology considered. The results obtained are generally useful in order to gain a first order approximation on the impact of interference and the resulting performance degradation. However, these analytical models often make assumptions concerning the traffic distributions and the operation of the media access protocol which can make them less realistic. More importantly, in order for the analysis to be tractable, mutual interference that can change the traffic distribution for each system is often ignored. Therefore, mathematical modeling is often used to complement measurements obtained from experimental and simulation data.

1.1.2 Experimental modeling

Results obtained from experimental modeling are considered by far the most accurate at the cost of being too specific to the implementation tested. Examples of experimental measurements can be found in refs[21,34,40,52,61]. In the case where the implementation details are completely known, including various optional add-ons and parameters, then the evaluation can be extremely informative. However, access to the complete implementation details is often restricted by the vendors or the implementors leading to the so-called testing of black box equipment. Thus, the results obtained are not applicable outside the experimental set-up of the equipment tested. Furthermore, since parameters cannot be modified, their effects on performance is not easily understood. Therefore, experimental modeling is useful mostly in the context of specific product development and testing.

1.1.3 Simulation modeling

Simulation modeling constitutes a third alternative to the other two approaches described above. It consists of using computer simulations to model the behavior of the protocols under consideration. This approach can provide a flexible framework where detailed parametrized models for the media access control and physical layer protocols are combined and the interactions between the various system parameters are identified and accurately quantified. Simulation modeling is ideal for evaluating numerous “what if” scenarios without the cost associated with building and testing the equipment. Simulations play a critical role in evaluating scalability issues and complex system behavior where parameters are modified and their effects on the overall performance quantified. Examples for simulation models developed to evaluate wireless network interference can be found in refs [20,48,55,67].

The question we ask here is, how do these methods relate to the performance analysis techniques discussed in this book? Basically, the evaluation approaches we consider are broken up into two categories. First, we consider an open-loop interference evaluation technique where the effects of mutual interference are ignored. Secondly, we describe a closed-loop evaluation approach where the interactions amongst interfering systems are considered. Results comparing both approaches are also discussed. Observe that all three modeling approaches presented above can be used in either open-loop or closed-loop evaluations, although closed-loop modeling is often associated with simulation modeling and open-loop evaluation is more related to mathematical modeling.

1.2 Interference avoidance and coexistence strategies

As far as meeting the second objective for this book and exploring coexistence strategies, the second half of the book is devoted entirely to exploring the solution space. The focus is on adaptive and system-level solutions that can augment or enhance traditional filtering, anti-jamming, and physical layer techniques. Basically the emphasis is placed on solutions that do not require major changes to the hardware and the technical specifications of the technologies considered.

Interference mitigation has always been and remains a big part of any communication system design cycle. Since wireless system engineers have always had to contend with interference from both natural sources and other users of the medium, the classical communication design cycle has consisted of predicting channel impairments and choosing adequate modulation and error correction schemes. Error correction can even be made to be adaptive to the error characteristics in the operation environment, as was shown by Eckhardt and Steenkiste [35], in which the effects of using an adaptive error correction scheme are investigated and adaptive schemes adjusted based on the environment. Power control is another adaptive technique generally used in spread spectrum systems such as carrier division multiple access (CDMA). In addition to these design choices and adaptive techniques, there are several known physical layer interference suppression techniques such as notch filtering and adaptive equalization [56]. In contrast to these so-called classical approaches to interference mitigaton, our contribution becomes valuable when redesigning systems from scratch is not considered to be a viable option. Therefore, we favor in our discussion adaptive control strategies, system parameter adjustments over other signal processing, and physical layer strategies that are well documented and widely available in the literature. The techniques presented in this book are meant to complement what is generally done in signal processing at the physical layer.

1.2.1 Industry led activities

There are few industry led activities tackling the issue of coexistence. Two efforts that we mention here are under the auspices of the IEEE 802 LAN/MAN standards committee that develops local and metropolitan area network specifications. The IEEE 802.19 Technical Advisory Group (TAG) on coexistence was formed in 2003 in order to develop and maintain policies defining the responsibilities of IEEE 802 standards working groups regarding coexistence. This is a standing group that advises the 802 executive committee on coexistence matters and assists various 802 working groups to assess and develop coexistence strategies accurately. Prior to the formation of the IEEE 802.19 TAG, the IEEE 802.15.2 Task Group on coexistence published a recommended practices document [9] for the coexistence of Bluetooth and IEEE 802.11b devices. This document considers solutions for mitigating the interference between these two technologies. Solutions range from collaborative schemes to be implemented in the same device to fully independent solutions that rely on interference detection and estimation.

- Mechanisms for collaborative schemes are based on a MAC time domain solution that alternates the transmission of Bluetooth and IEEE 802.11 packets (assuming both protocols are implemented in the same device and use a common transmitter) [22]. A priority of access is given to Bluetooth for transmitting voice packets, while WLAN is given priority for transmitting data.
- The non-collaborative mechanisms considered range from adaptive frequency hopping [24] to packet scheduling and traffic control [43]. They all use similar techniques for detecting the presence of other devices in the band, such as measuring the bit or frame error rate, the signal strength or the signal to interference ratio (often implemented as the received signal indicator strength (RSSI)). Other MAC scheduling techniques known as packet encapsulation rules [19], or overlap avoidance (OLA) [32], use the variety of Bluetooth packet lengths to avoid the overlap in frequency between 802.11 and Bluetooth. In other words, the Bluetooth scheduler knows to use the packet length of proper duration in order to skip the so-called “bad” frequency.

1.2.2 Fair scheduling and wireless QOS research

A research topic that has received more attention recently and is closely tied to wireless coexistence is fair scheduling and the support of quality of service (QOS) requirements in a wireless environment.

For example, Fragouli *et al.* [38] propose a strategy that combines class-based queuing [36] with channel-state based scheduling [31] that eliminates the head of line problem caused by first in first out (FIFO) queuing when certain devices suffer from a bad link. In ref. [38], link sharing guidelines are provided to maximize channel utilization and limit the access of misbehaving sources.

Furthermore, a number of algorithms have been proposed on fair scheduling [57,58,62]. While there may be some differences in implementation and complexity, the basic idea in all these algorithms is for sources experiencing a bad wireless link to relinquish the unutilized bandwidth to other sources that can take advantage of it. Compensation in bandwidth occurs when the channel conditions improve in order to achieve the so-called long term fairness objective.

While the interference mitigation problem that we are trying to solve bears some resemblance to some of the problems addressed in refs [38,57,58,62], there are important differences to note. Regarding interference mitigation, it is important to consider an instantaneous measure of fairness rather than a long term fairness objective. The reason is as follows. All previous work uses a two state Markov channel model for each link. The transition probabilities between the good and bad states are in the order of several seconds to account for periods of fading, multipath and various other wireless effects. The situation in the case of interference is somewhat different due to the interactions of the systems. Since different devices in the same piconet will be subject to different interference levels due to parameters such as geometry and transmitted power, not all frequencies will be equally good to all devices. Therefore, the goal is to assign frequencies optimally such as to maximize channel utilization and guarantee fairness among all the devices.

2 Basic concepts and wireless protocol overview

This chapter is designed to give the reader a comprehensive understanding of the fundamentals in wireless protocol design. First, we overview some of the physical layer and the medium access control layer design choices. Then, we give the details of select major protocols as examples of the concepts described.

2.1 Physical layer

The physical layer has the main function of transporting the information bits passed by the higher layers over a physical medium and recovering them on the other side of the medium. We can view the physical layer in terms of a digital or analog communication channel and modules that map digital information to an analog signal in case the channel is analog. Figure 2.1 illustrates the main components of the physical layer that are discussed in the following sections. For an in-depth treatment of communication systems, the reader is referred to other texts [70,75].

2.1.1 Communication channel

A communication channel consists of a physical medium, such as radio waves, copper wire, optical fiber, and the associated equipment necessary to transmit information over the medium. Communication channels can be used for either digital or analog transmission. Digital transmission consists of transmitting a sequence of pulses corresponding to a sequence of information bits. Analog transmission involves the transmission of waveforms associated with the transmitted signal. The bandwidth of a channel, W, measures the width of the window of frequencies that are passed by the channel. A low-pass communication channel passes low frequency components, while a bandpass channel passes power in some frequency range f_1 to f_2. The bandwidth of the channel, W, is thus equivalent to $f_2 - f_1$. In order to modify the frequency components of a signal, filters are commonly used in the transmitter and the receiver circuitry.

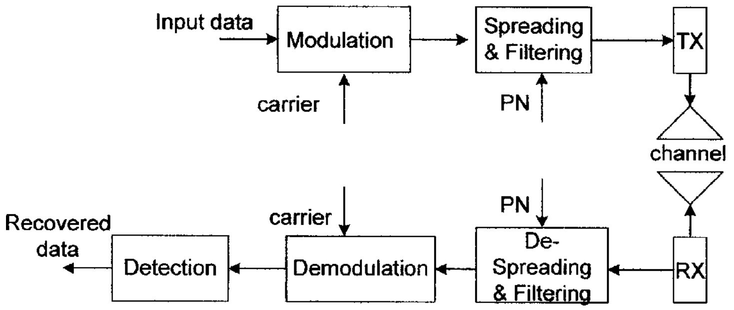

Fig. 2.1. Physical layer system components.

2.1.2 Modulation and filtering

Modulation is required to map digital information into a waveform sent over an analog channel. Digital modulation is the process of transforming a group of k bits, also called symbols, into waveforms. There are $2^k = M$ symbols in an alphabet. A waveform is expressed as follows:

$$s(t) = A(t)\cos[w_0 t + \phi(t)] \tag{2.1}$$

where $A(t)$ is the signal amplitude, $\phi(t)$ is the angle or phase, and w_0 is the center frequency.

There are three basic modulation techniques known as amplitude shift keying, frequency shift keying, and phase shift keying.

In amplitude shift keying the signal's amplitude is varied in order to encode M symbols:

$$s_i(t) = A_i(t)\cos[w_0 t + \phi] \quad \text{for} \quad i = 1, \ldots, M \tag{2.2}$$

Similarly, for frequency shift keying, the frequency is varied according to

$$s_i(t) = A\cos[w_i(t) + \phi] \quad \text{for} \quad i = 1, \ldots, M \tag{2.3}$$

And finally for phase shift keying, the phase or angle is varied:

$$s_i(t) = A\cos[w_0 t + \phi_i(t)] \quad \text{for} \quad i = 1, \ldots, M \tag{2.4}$$

This process of mapping the information bits into waveforms and transmitting them over a low-pass communication channel is also known as baseband modulation. However, additional signal processing is required in order to match the signal to be transmitted with the channel characteristics, or the bandpass channel. Thus, a bandpass modulation is a baseband modulation whose spectrum has been shifted to a frequency band passed by the channel considered.

The basic function is to transmit a low-pass signal $I(t)$ over a bandpass channel centered at f_c. In order to translate the spectrum of $I(t)$ to another signal centered around f_c, we can multiply it with a carrier $C(t)$ of the following form:

$$C(t) = A\cos(2\pi f_c t + \theta) \tag{2.5}$$

where A is the amplitude of the carrier, f_c is the carrier frequency, and θ is an arbitrary phase constant. The product $X(t)$ has the following form:

$$X(t) = I(t)C(t) = AI(t)\cos(2\pi f_c t + \theta) \tag{2.6}$$

Filtering is performed throughout a communication system and for a variety of reasons. The primary reasons to adopt filtering is to select the desired signal, minimize the effects of noise and interference, modify the spectra of signals, and shape the time-domain properties of digital waveforms in order to improve their detectability. For example, receivers use filters to reject out-of-band noise, while transmitters use filters to meet regulatory constraints on the shape of the spectra transmitted. In some cases, filters are required to be adaptive in terms of changing their response to changing properties of the signal. A filter is introduced to remove signal distortions introduced by a channel as it is expected to change its reponse as the channel characteristics change. The adaptive tapped delay line is the most common adaptive filter structure, also referred to as an equalizer.

2.1.3 Channel propagation properties

The modulated signal propagates in a medium at a speed of v m/s, where

$$v = \frac{c}{\sqrt{e} f_0} \tag{2.7}$$

and where $c = 3 \times 10^8$ m/s is the speed of light in a vaccum and e is the dielectric constant of the medium. In free space, $e = 1$, and $e \geq 1$ otherwise. The wavelength λ of the signal is given by the length in space spanned by one period of the sinusoidal signal:

$$\lambda = \frac{v}{f_0} m \tag{2.8}$$

The modulated signal is also attenuated as it travels through the media. The attenuation in wireless media is proportional to d^n, where d is the distance travelled and n is the path loss exponent; $n = 2$ for free space and for environments where obstructions are present $n > 2$. The attenuation in decibels (dB) is proportional to $n \log_{10} d$ dB. The attenuation phenomenon is determined at the receiver in terms of the signal to noise ratio (SNR) and bit error rate (BER).

2.1.4 Signal detection

The transmitted signal is recovered at the receiver as follows. Any signal can be expressed in terms of a linear combination of N orthogonal waveforms:

$$s_i(t) = \sum_{j=1}^{N} a_{ij}\phi_j(t); \quad i = 1, \ldots, M; \quad N \leq M \tag{2.9}$$

Let s_j for $j = 1, \ldots, k$ represent reference signals belonging to a set of M waveforms. The received signal r is $r = s_j + n$, where n represents noise. The receiver has to decide whether r closely resembles either of the reference signals s_j by measuring the distance of r with all reference signals s_j as illustrated in Figure 2.2. The chosen reference signal s_j is the one that leads to the minimum distance, $d = ||r - s_j||$.

Additionally, in coherent detection, the receiver exploits the knowledge of the carrier's phase, while in non-coherent detection, no phase information is used. Further reading on coherent detection is found in refs [70,75].

2.1.5 Spread spectrum

Spread spectrum was originally developed in the 1940s for military communications in order to make the signal less obvious to enemy interception and jamming capabilities. The basic idea is to transmit the signal over additional bandwidth, using less power per frequency, but more frequencies. Thus the information signal $s(t)$ is multiplied by a pseudo-noise (PN) signal $c(t)$

$$m(t) = c(t)s(t) \tag{2.10}$$

and the resulting signal $m(t)$ has the same wideband characteristics as the PN signal, as illustrated in Figure 2.3. Thus each bit in the original digital signal $s(t)$ is chopped

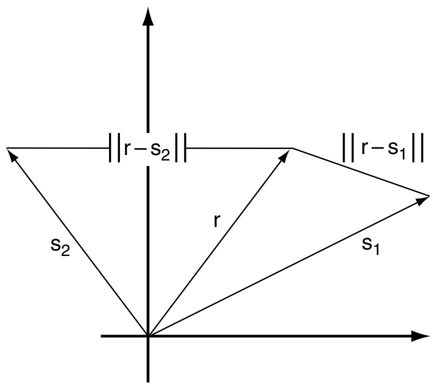

Fig. 2.2. Detection at receiver.