Research Article

Clear Channel Assessment in Integrated Medical Environments

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Complementary WLAN and WPAN technologies as well as other wireless technologies will play a fundamental role in the medical environments to support ubiquitous healthcare delivery. This paper investigates clear channel assessment (CCA) and its impact on the coexistence of WLAN (IEEE 802.11 high rate direct sequence spread spectrum (HR/DSSS) PHY) and WPAN (IEEE 802.15.4b) in the 2.4 GHz industrial, scientific, and medical (ISM) band. We derived closed-form expressions of both energy-based CCA and feature-based CCA. We qualified unequal sensing abilities between them and termed this inequality asymmetric CCA, which is different from the traditional "hidden node" or "exposed node" issues in the homogeneous network. The energy-based CCA was considered in the considered integrated medical environment because the 2.4 GHz ISM band is too crowded to apply feature-based CCA. The WPAN is oversensitive to the 802.11 HR/DSSS signals and the WLAN is insensitive to the 802.15.4b signals. Choosing an optimal CCA threshold requires some prior knowledge of the underlying signals. In the integrated medical environment we considered here, energy-based CCA can effectively avoid possible packet collisions when they are close within the "heterogeneous exclusive CCA range" (HECR). However, when they are separated beyond the HECR, WPAN can still sense the 802.11 HR/DSSS signals, but WLAN loses its sense to the 802.15.4b signals. The asymmetric CCA leads to WPAN traffic in a position secondary to WLAN traffic.

1. INTRODUCTION

Advances in biotechnologies and micro/nano-technologies, information and communication technologies enable revolutionary pervasive healthcare delivery in hospital, small clinic, residential care center, and home [1–3]. Integration of heterogeneous wireless technologies is required for revolutionary healthcare delivery in hospital, small clinic, residential care center, and home. Wireless connectivity to Internet, including wireless local area networks (WLANs) and wireless personal area networks (WPANs), provides the infrastructure and the mobility support for ubiquitous patient monitoring, recording, and reporting systems in the medical environment.

The medical environment is a diverse workspace, which encompasses everything from the patient admission process, to examination, diagnosis, therapy, and management of all these procedures. Some medical sensing applications, such as real-time waveform delivery, alarm notification, and remote control have very strict requirements in terms of accuracy and latency but usually have low data rate. The office-oriented applications, such as Internet access and the download of medical image and video, are bandwidth hungry and can recover from packet loss by using upper-layer protocols. There is a desire to use IEEE version of WLAN and WPAN technologies in the unlicensed industrial, scientific, and medical (ISM) bands as a common communication infrastructure [2, 3]. The former is typically used for office-oriented applications and patient connection to the outside world, while the latter is usually used for wearable sensors around patient to collect vital information [2–5]. They are becoming more and more popular in hospitals and homes.

The use of complementary heterogeneous WLANs and WPANs in ISM band in the integrated medical environment brings into picture coexistence, interference, and spectrum utilization issues. The coexistence of wireless technologies in the shared ISM band has been a hot topic [5–8]. Adaptive frequency hopping was proposed for Bluetooth devices to avoid interference from WLAN [6]. A model for analyzing the effect of 802.15.4 on 802.11b performance was provided by

Howitt and Gutierrez [7]. The degradation of WLAN performance is small given that the WPAN activity is low. However, the high-duty cycle of WLAN traffic can drastically affect the WPAN performance [5]. A distributed adaptation strategy for WPAN devices based on *Q-learning* has been proposed to minimize the impact of the 802.11b interference [8]. However, the spatial reuse issue in the heterogeneous networks environment has not drawn much attention. Some research has shown that the spatial reuse and aggregate throughput in the homogeneous WLAN mesh network is closely related to physical channel sensing. Channel sense is more generally known as clear channel assessment (CCA) in the IEEE wireless standards. Yang and Vaidya showed that the aggregate throughput can suffer significant loss with an inappropriate choice of carrier sense threshold [9]. Zhu et al. reported that a tunable sensing threshold can effectively leverage the spatial reuse of WLAN [10]. Zhai and Fang found that the optimal carrier sensing threshold of WLAN for one-hop flows does not work for multihop flows [11]. Ramachandran and Roy showed that there is a cross-layer dependence between CCA and system performance [12]. However, to the best of our knowledge, the impact of CCA has not been studied in the heterogeneous networks environment. Simulators widely used for performance evaluation, like NS-2 and OPNET, do not contain detailed physical (PHY) layer module like carrier sense. For the lack of carrier sensing knowledge between WPAN and WLAN, Golmie et al. simply simulated two channel sensing cases: the WPAN can only detect packets of its own type and the WPAN can also detect WLAN's transmission, in their coexistence study for medical applications [5].

In this paper, we studied the CCA issue in the integrated medical environments for ubiquitous healthcare applications. We used IEEE 802.15.4b standard and 802.11 high rate direct sequence spread spectrum (HR/DSSS) PHY of 802.11-2007 standard as examples. The remainder of the paper is organized as follows. Section 2 briefly reviews the two selected WLAN and WPAN technologies. Section 3 contains a description for various CCA methods. In Section 4, we present a mathematical analysis of energy-based CCA and feature-based CCA in the heterogeneous networks. Section 5 focuses on energy-based CCA and the impact of asymmetric CCA in the integrated medical environments. Section 6 finally concludes the paper.

2. SYSTEMS OVERVIEW

We consider the IEEE 802.15.4b and 802.11 HR/DSSS as examples of WPAN and WLAN wireless technologies in the integrated medical environments [2, 3, 5]. The former is likely a good candidate technology for low-rate medical sensors [2, 3]. Both of them operate in the unlicensed 2.4 GHz ISM band.

2.1. IEEE 802.11

Different IEEE 802.11 PHYs share a common medium access control (MAC) sublayer, which operates by default in distributed coordination function (DCF) mode based on carrier sense multiple access/collision avoidance (CSMA/CA) pro-

TABLE 1: WLAN and WPAN parameters.

Parameters	802.15.4b	802.11 HR/DSSS
Transmission power (dBm)	0	16
Channel bandwidth (MHz)	2	22
Background noise (dBm)*	−94.9	−84.6
Data rate (Mbps)	0.25	11

*We assumed −174 dBm/MHz thermal noise, 8 dB implementation losses, and 8 dB radio noise figure.

tocol [13]. In order to reduce the probability of two devices colliding when they cannot physically sense each other, DCF uses virtual carrier sense to announce the time and duration of future data exchange. The first popular IEEE HR/DSSS WLAN has data rate up to 11 Mbps using complementary code keying (CCK). The symbol spread employs 11-chip Barker code. There are three nonoverlapped channels, each occupying 22 MHz. The standard specifies a CCA window within 15 micro seconds. The CCA can be either energy-based, or feature-based, or a combination of both.

2.2. IEEE 802.15.4b

IEEE 802.15.4-2006 is a revision of the first IEEE standard for a simple, low-cost communication network that allows wireless connectivity in applications with limited power requirements [14]. The main objectives are ease of installation, reliable data transfer, short-range operation, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol. The standard defines two different channel accesses using CSMA/CA mechanism. Beacon-enabled networks use a slotted version of CSMA-CA, where the backoff slots are aligned with the start of the beacon transmission. The backoff slots are aligned to the piconet coordinator. Each transmission and CCA operation starts at a slot boundary. Nonbeacon-enabled networks use an unslotted CSMA-CA mechanism. Each transmission will wait for a random period.

The PHY layer describes three different frequency bands. There are 16 nonoverlapped channels where each has 2 MHz bandwidth and 5 MHz separation spacing in 2.4 GHz. There are only four 802.15.4b channels fall in the guard bands between 802.11 HR/DSSS channels. Each channel can provide 250 kbps by using one of 16 psuedorandom-noise (PN) codes of length 32 chips to represent four bits of information. The CCA of 802.15.4b is the same as that of 802.11 HR/DSSS, except that the CCA time is 8 symbol durations, which is 128 micro seconds.

Table 1 lists the system parameters of WLAN and WPAN considered in this paper.

3. METHODS OF CLEAR CHANNEL ASSESSMENT

Several IEEE WLAN and WPAN standards use CSMA-CA as *de facto* MAC protocols. The concept of CCA was first proposed as an enhancement ALOHA. CCA is a physical layer activity and is an essential element of the CSMA protocol.

The CCA provides two important services:

(i) detecting an incoming packet,
(ii) ensuring a free channel before transmission.

The CCA module processes received radio signals in a suitable time termed CCA window. The CCA processing can be either energy detection or sense of specific features of signal over the channel. It then reports channel state, either busy or idle, by comparing the detection with a threshold.

3.1. Energy-based CCA

Energy-based CCA integrates signal strength from radio front end during the CCA window. It then compares this signal strength with the noise floor, which is the signal strength of background noise, to make a decision. The energy-based CCA can be performed in both time domain and frequency domain.

The main advantages of energy-based CCA are its simplicity, generality, and low power consumption. The CCA module can be a simple noncoherent module. Since no signal specific feature is used, it is a universal mechanism that can be deployed in all systems. No knowledge of the underlying signal is needed. The signal power is immediately available after the CCA module is turned on. Unlike the feature-based CCA, there is no need for waiting time for the specific features of the underlying signal. The downside of energy-based CCA is that it is prone to false detection and works poorly in low SNR since the processing gain inherent in the detected signal cannot be used. Besides, it cannot distinguish the unintentional radio emission (e.g., microwave oven) from the intentional radio signal for communication since all the signal structures are lost.

3.2. Feature-based CCA

Feature-based CCA looks for the known features, for example, the modulation and spreading characteristics, of the signal over the channel [12–14]. Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, or cyclic prefixes, which result in built-in periodicity. The periodicity exhibited in statistics, mean and autocorrelation, is typically introduced intentionally in signal format to facilitate receiving. For example, in frequency-hopping (FH) systems, only the frame preamble contains a known sequential-hopping pattern. In the direct-sequence (DS) spread spectrum systems, frame preamble consists of repetition of a psuedorandom-noise (PN) code. The cyclic prefix is a duplication of the end of the orthogonal frequency division multiplexing (OFDM) symbol in the guard interval to combat multipath delay spread. These signals are characterized as cyclostationary. This periodicity can then be used to detect signal of a particular modulation type.

CCA based on features in preamble can be implemented by sequential summary of matched filter after synchronization. It can take full advantage of the processing gain resulting from spread spectrum and repetition in the preamble. Thus an SNR much higher than that for energy-based CCA is obtained. However, the frame preamble is not always available even when the channel is busy. The CCA module must be constantly running until the end of CCA window when the channel is free or the targeting preamble features are found in a busy channel. The FH PHY of 802.11 conducts CCA by looking for a preamble pattern of frame within the maximum duration of frame [13]. A long CCA time, unfortunately, provides low throughput and burns large amount of energy, which is a major constraint for some sensor devices.

An alternative method is to detect features in the data portion of frame. A parallel structure must be included in the CCA module since no synchronization information is available [12]. For FH systems, the CCA must look for all possible channels; for DS systems, the CCA must look for all possible slots. Although a shot CCA time can be achieved, the parallel structure put enormous burden on device in terms of complexity and power consumption in order to drive them at chip rate.

CCA to detect cyclostationary signals exploits a sliding correlation in either the time or the frequency domain depending on the underlying signal. The noise and interference exhibit no correlation. The processing and recognition of cyclostationary signals require a strong signal processing capacity. A large amount of resources are therefore needed in the CCA module.

Feature-based CCA performs far better than the energy-based CCA. However, a prior knowledge of the signal characteristic is necessary. Also, the CCA module would need a dedicated detector for every potential coexistence signal class. If the priori knowledge of the detected signal is not available for any reason, feature-based CCA degenerates into energy-based CCA which does not rely on features of a specific signal type.

4. ANALYSIS OF CLEAR CHANNEL ASSESSMENT

We analyze the abilities of energy-based CCA in the mixed WLAN and WPAN environment in this section.

In mathematics, CCA is a test of the following two hypotheses:

$$H_0 : y[n] = w[n] \quad \text{signal absent,}$$
$$H_1 : y[n] = x[n] + w[n] \quad \text{signal present,} \tag{1}$$

where $x[n]$ is the targeted signal; $w[n]$ is the white Gaussian noise with variance σ^2; and $n = 1, \ldots, N$ is the sample index in total N-independent samples in the CCA window. Under common detection performance criteria, for example, Neyman-Pearson (NP) criteria, likelihood ratio yields the optimal hypothesis testing solution. The CCA metric is compared to a threshold Γ to make a decision. CCA performance is characterized by a resulting pair of detection and false alarm possibilities (P_d and P_{fa}) which are associated with the particular threshold Γ.

4.1. Energy-based CCA

For simplicity, we assume that the energy-based CCA is realized by a simple noncoherent module that integrates the square of the received signal and sums its samples in analog

or digital domain. In particular, the energy detection consists of a quadrature receiver with y_I and y_Q representing samples of signals on the I (in-phase) and Q (quadrature) branches, respectively. The energy-based CCA metric can be given by

$$Y = \sum_{n=1}^{N} \left(|y_I[n]|^2 + |y_Q[n]|^2 \right), \qquad (2)$$

where N is the number of independent samples in the CCA window. In an additive white Gaussian noise (AWGN) channel, each $|y_I[n]|$ and $|y_Q[n]|$ have a normal distribution with mean μ and variance σ^2 and Y can be evaluated as generalized chi-square function $Y \sim \chi^2(\lambda, 2N)$, where $2N$ is the degrees of freedom and $\lambda = 2N\sigma^2(1 + \mu^2/\sigma^2)$. Under the H_0 hypothesis in the absence of signal, each normal distribution has $\mu = 0$. Thus, Y has a χ^2 distribution. Under the H_1 hypothesis in the presence of signal with an SNR $= \mu^2/\sigma^2$, Y has a noncentral χ^2 distribution. We have mean and variance as follows [15]:

$$H_0 : \mu_0 = 2N\sigma^2, \quad \sigma_0^2 = 4N\sigma^4,$$
$$H_1 : \mu_1 = 2N(\mu^2 + \sigma^2), \quad \sigma_1^2 = 4N(2\mu^2 + \sigma^4). \qquad (3)$$

When N is large, using central limit theory, the energy-based CCA metric in (1) can be approximated as Gaussian random process. Then P_d and P_{fa} can be expressed in terms of the Q function [15]:

$$P_d = Q\left(\frac{\Gamma - 2N(1 + \text{SNR})}{\sqrt{4N(1 + 2\text{SNR})}}\right), \qquad P_{fa} = Q\left(\frac{\Gamma - 2N}{\sqrt{4N}}\right). \quad (4)$$

The energy-based CCA can meet any desired P_d and P_{fa} simultaneously if the number of samples in the CCA window N is unlimited. Given a limited N, the CCA ability is obviously determined by the SNR of the signal. There is an inherent tradeoff between P_d and P_{fa}. We define the CCA error floor at the optimal threshold, which can be found by equating $1 - P_d$ and P_{fa}. Using (4), we obtain the CCA error floor

$$P_{\text{CCA\_ef}} = Q\left(\sqrt{N}\frac{\text{SNR}}{1 + \sqrt{1 + 2\text{SNR}}}\right). \qquad (5)$$

Note that the error floor depends on the number of symbol chips and the SNR. When $SNR \ll 1$, then (5) is approximated as

$$P_{\text{CCA\_ef}} = Q\left(\sqrt{N}\frac{\text{SNR}}{2}\right). \qquad (6)$$

A linear decrease in SNR requires a quadratic increase in N to maintain the same error floor.

4.2. Feature-based CCA

The feature-based CCA can also be implemented by quadrature receiver containing a matched filter each in the I and the

Q branches. The feature-based CCA metric can then be given by

$$Y = \sum_{n=1}^{N} \left(y_I[n] + y_Q[n] \right)$$
$$= \sum_{n=1}^{N} \left(\text{Re}(y[n]x^*[n]) + \text{Im}(y[n]x^*[n]) \right), \qquad (7)$$

where $y_I[n]$ and $y_Q[n]$ representing samples of signals on the I and the Q branches, respectively. We have mean and variance as follows [15]:

$$H_0 : \mu_0 = 0, \quad \sigma_0^2 = 2N\mu^2\sigma^2,$$
$$H_1 : \mu_1 = 2N\mu^2, \quad \sigma_1^2 = 2N\mu^2\sigma^2. \qquad (8)$$

Based on similar argument as before, the feature-based CCA metric in (8) can be approximated as Gaussian random process. Then P_d and P_{fa} can be expressed in terms of the Q function again [15]:

$$P_d = Q\left(\frac{\Gamma - 2N\sqrt{\text{SNR}}}{\sqrt{2N}}\right), \qquad P_{fa} = Q\left(\frac{\Gamma}{\sqrt{2N}}\right). \quad (9)$$

Using (9), we obtain the error floor of feature-based CCA at the optimal threshold by equating $1 - P_d$ and P_{fa}:

$$P_{\text{CCA\_ef}} = Q\left(\sqrt{\frac{N}{2}\text{SNR}}\right). \qquad (10)$$

In other words, a linear reduction in SNR requires only a linear increase in N to maintain the same error floor.

4.3. Asymmetric CCA

Energy-based CCA and feature-based CCA are supported by both IEEE 802.15.4b and 802.11 HR/DSSS standards. Table 2 lists the numbers of signal chips in the CCA window as defined by the standards [12, 13]. Figure 1 shows the CCA error floor in the coexistence scenario as per (5), (9), and Table 2. As expected, feature-based CCA provides better detection than energy-based CCA. However, for both of them, the error floors decrease with increment in signal chips in the CCA window. Given the CCA windows defined in the standards, CCA abilities, for example, sensitivity and range, to determine the channel state (busy or idle), are different, this is termed asymmetric CCA. Under the same SNR conditions, the lowest error floor is when WPAN is used to sense the 802.11 HR/DSSS signal; the highest error floor is when WLAN is used to sense the 802.15.4b signal. For energy-based CCA, the performance difference between these two scenarios is nearly 10 dB. For feature-based CCA, as shown in Figure 1(b), the difference is 32 dB. The CCA asymmetry can be attributed to differences in underlying signals over channel (power, symbol rate, and background noise) and CCA operation (CCA window and CCA mechanisms). In physics, a higher data rate and a longer CCA window mean that more signal pulses or features in baseband can be collected in the
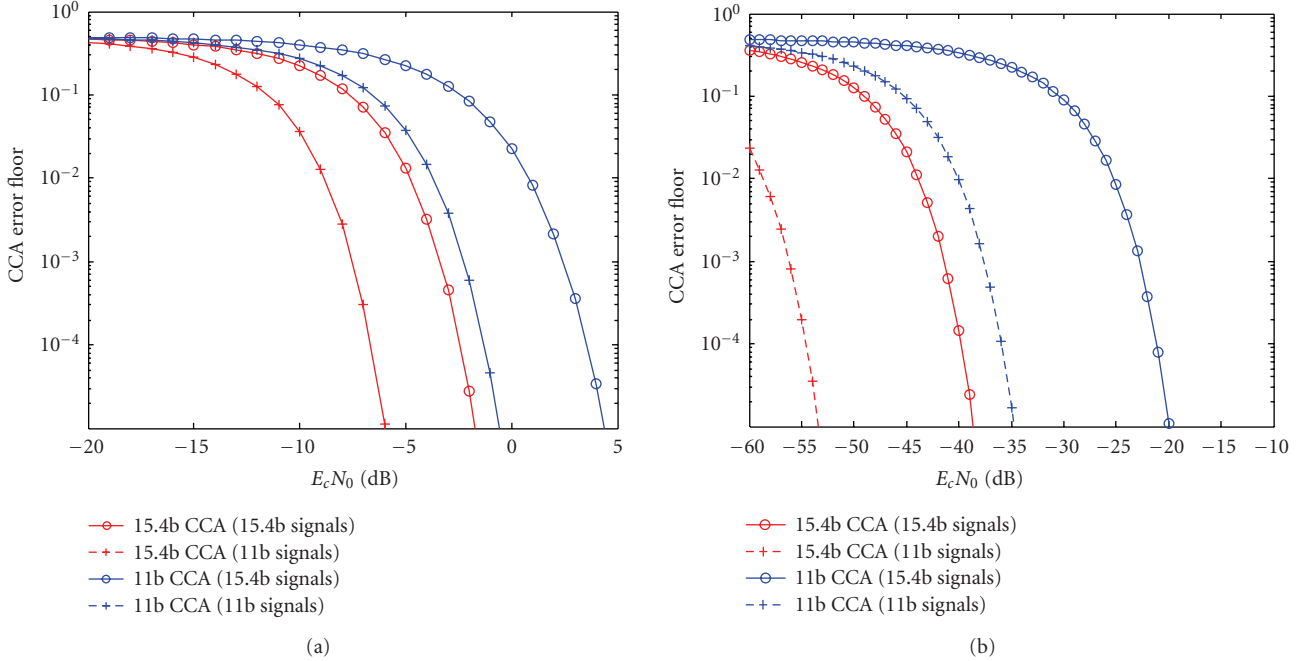
FIGURE 1: (a) Error floor of energy-based CCA and (b) feature-based CCA in integrated medical environments (the IEEE 802.11-2007 HR/DSSS PHY was originally known as 802.11b. We remained the same title in the figure legend due to the limited space).

CCA operation. Better CCA performance is, thus, a natural result. In the integrated medical environment, asymmetric CCA is further reinforced by other factors:

(i) difference in transmission powers which is usually stronger for WLAN,

(ii) difference in channel bandwidth which are 22 MHz and 2 MHz for the WLAN and WPAN, respectively.

For both WPAN and WLAN, the performances to detect the signal of its own type are similar. There is no big difference in the numbers of symbols in the CCA window between them.

Table 3 compares the communication performance with both CCA performances when a probability of error of 1‰ was achieved. As expected, the CCA range is larger than the communication range. For energy-based WPAN, sensing the 802.11 HR/DSSS signals has 4 dB greater link margin compared to sensing the signals of its own type due to the larger number of symbols in the CCA window. In contrast, energy-based WLAN requires a 4.8 dB higher SNR to sense the 802.15.4b signals because of the fewer symbols in the CCA window.

5. ENERGY-BASED CCA IN MEDICAL ENVIRONMENTS

5.1. Energy-based CCA in medical environments

Because of the global availability and relatively large bandwidth, the unlicensed 2.4 GHz ISM band is fast becoming the frequency band of choice for an increasingly wide range of applications. These include WLAN (802.11, 802.11 HR/DSSS, 802.11 extension rate PHY using or-

TABLE 2: Number of signal chips, N, in the CCA window.

Device	Sensed signal	
	CCA signals (802.15.4b)	CCA signals (802.11 HR/DSSS)
802.15.4b	32*8	128*11
802.11 HR/DSSS	15*2	15*11

TABLE 3: SNRs (dB) to achieve 1‰ communication BER and CCA error floors.

Signal		Device	
		802.15.4b	802.11 HR/DSSS
Communication		−0.8	5.6
802.15.4b	Energy-based	−3.2	2.6
	Feature-based	−41	−22
802.11 HR/DSSS	Energy-based	−7.2	−2.2
	Feature-based	−55	−37

thogonal frequency division multiplexing, and 802.11n), WPAN (Bluetooth, 802.15.3, 802.15.4-2003, 802.15.4-2006, and 802.15.4a), passive radio frequency identification and so on. Significantly, electric surgical knife, magnetic resonance imaging (MRI), heat treatment machines, and microwave ovens also use this frequency band. They are expected to be collocated in the integrated medical environments.

We applied energy-based CCA to 802.15.4b and 802.11 HR/DSSS in the medical environments. There are several reasons for this. First, there have been nearly 10 wireless technologies with different modulations, band plans, and

transmission powers in the 2.4 GHz ISM bands, and there could be more in the future. A device is unlikely to have all these types of knowledge. Secondly, feature-based CCAs are usually complex and power hungry [12]. Medical sensors based on 802.15.4b, however, are low-complexity, low-cost, and battery-powered devices. It would be impractical to specify some features in such kind of device. Thirdly, energy-based CCA can still help us understand the impact of CCA on system performance.

5.2. *Asymmetric energy-based CCA*

Usually, NP criteria are adopted in CCA because a miss detection of a busy channel is riskier than a false alarm of a free channel. But the CCA threshold Γ is optimized for its own type of signals, not for other signals. The "nonoptimized" Γ may result in CCA that is insensitive or oversensitive to other signals in the heterogeneous networks environment. In extreme case, an opposite channel state could be obtained. This is unidirectional sensing in the same configuration, where device A can sense the activities of device B, but not vice versa. The receiver operating characteristics (ROCs) of energy-based CCA were plotted in **Figure 2**, in which we set SNR by -9.5 dB. (The selected SNR corresponds the doubled distances to achieve BER of 0.1% for WPAN [14].) The SNR was measured by the signal type of its own. As mentioned above, for WPAN sensing, the 802.11 HR/DSSS signal offers the best detection. The WLAN's sensing of the 802.15.4b signal, in contrast, is prone to fail at such a low SNR. A particular reason for the worse performance is the mismatch of channel bandwidths. When WLAN applies a 22 MHz bandpass filter to 2 MHz WPAN signals, an additional 10.4 dB background noise is introduced.

Look at (5), in both the H_0 and H_1 hypotheses, the energy distribution is related to N. This means that the CCA threshold is related to the targeted signals. **Figure 3** depicts the distribution of collected energy over a free channel by the WLAN and WPAN devices based on different underlying signal assumptions. The x-axis is the threshold normalized by noise power density. When WLAN senses channel per data rate of WLAN, the collected channel energy is small due to a short integration time. However, more collections can be obtained during the CCA window. When WLAN senses channel per the data rate of WPAN, stronger channel energy with fewer samples is obtained due to a long integration time. The different energy distributions shown in **Figure 3** indicate that the optimal CCA threshold is quite dependent on the type of underlying signal. Prior knowledge is, therefore, needed to determine the optimal CCA threshold.

Asymmetric CCA makes channel sensing insensitive or oversensitive to other signals in the mixed WLAN and WPAN environment. The asymmetric CCA in the heterogeneous networks is different from the traditional "hidden node" or "exposed node" issues in the CSMA protocol in the homogeneous network. In the homogeneous network, two devices belong to the same system are reciprocal in ability to sense each other. In other words, the two devices can or cannot sense each other in the same configuration. Although the CCA abilities in homogeneous network may be different due
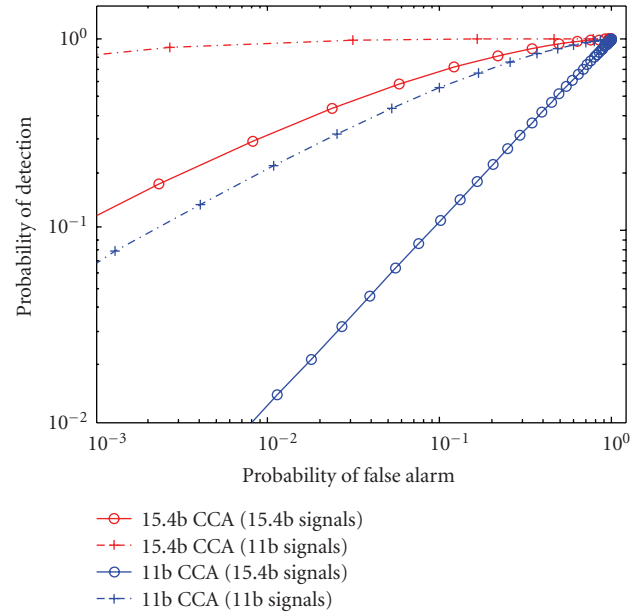

FIGURE 2: ROC of energy-based CCA in integrated medical environment (SNR = -9.5 dB measured by WPAN).
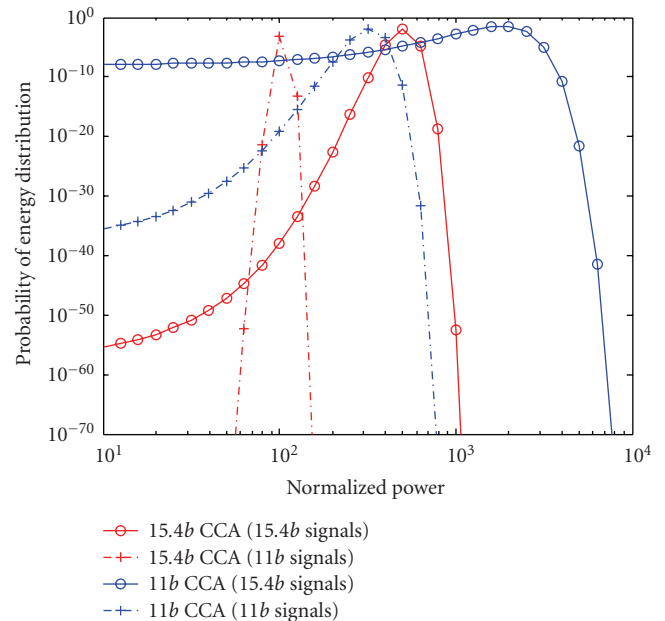

FIGURE 3: Collected power distributions of energy-based CCA over a free channel per different underlying signals.

to implementation strategies, we do not consider the issue in this paper. However, there is more than one system in the heterogeneous networks. The sensing abilities of two devices from different systems are unequal and depend on the underlying signals over channel and the separation distances. As shown in **Figure 3**, WLAN signals are well sensed by both of them, but WPAN signals could be ignored by the WLAN systems when they are separated by enough space in which the SNR is lower than a certain threshold. CCA asymmetry

TABLE 4: Minimum SNRs (dB) and corresponding distances (m) to achieve CCA ($P_{FA} < 1\%$, $P_D > 90\%$).

	802.11 HR/DSSS CCA		802.15.4b CCA	
	WPAN signals	WLAN signals	WPAN signals	WLAN signals
SNR (dB)	9.75	−4.5	−6	−9.25
Corresponding distance (m)	25	200	155	280

places WPAN traffic in a secondary position and provides a preferential treatment to WLAN traffic. The WLAN traffic is well protected, but WPAN traffic can sometimes be corrupted by the WLAN system due to miss detection of a busy channel.

5.3. *Impact of asymmetric energy-based CCA*

Table 4 lists the required minimum SNRs and their corresponding distances to achieve reliable energy-based CCA ($P_{FA} < 1\%$ and $P_D > 90\%$). The corresponding distances were computed using (1)–(3) and the parameters listed in Table 1. For WPAN, the sensing of 802.11 HR/DSSS signals is reliable at an SNR as low as −9.25 dB. This SNR is 9.65 dB lower than the critical SNR for communication. (The critical SNR for communication is the least SNR to achieve BER < 0.01%.) The CCA range is 180 meters longer than the communication range. In contrast, sensing 802.15.4b signal by WLAN requires a high SNR up to 9.75 dB, which is 3.15 dB more than the critical SNR for communication. The CCA range is 42 meters shorter than the communication range.

Figure 4 qualitatively compares the communication range and CCA ranges in the integrated medical environment. We can define "heterogeneous exclusive CCA range (HECR)" in which different systems in the heterogeneous environment can reliably sense the activities of each other. In the scenario considered in this paper, the HECR is the maximum distance that the 802.11 HR/DSSS system can sense 802.15.4b signals. Given the system parameters and assumptions, the HECR for the IEEE version of WLAN and WPAN is 25 m. Peaceful and fair coexistence between them can be expected when they are located within the HECR. However, it becomes different when they are separated beyond the HECR. When WPAN conducts energy-based CCA, the CCA range of WLAN signals is more than twice as long as the communication range. Also, it is longer than the CCA range of its own signal type. That is, the WPAN is oversensitive to the WLAN signals. It can even sense a WLAN packet that is outside of the keep-out range of receiver in the worst case. (The keep-out range denotes to the minimum separation which WPAN and WLAN do not interfere each other.) Although the oversensitive CCA avoids the "hidden node" issue, it suffers from the "exposed node" issue. This results in poor spatial reuse of frequency channels and low aggregation throughput since WPAN sometimes unnecessarily withdraw packet before transmission. As simulated in [11], the threshold optimized to maximize aggregate throughput is higher than the optimal threshold for a single hop. When WLAN conducts energy-based CCA, the CCA range of WPAN signals is about a quarter of the communication range. That is,
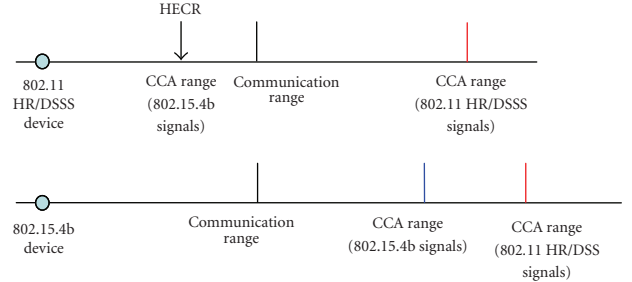

FIGURE 4: Communication range and energy-based CCA ranges in integrated medical environment.

the WLAN is insensitive to the activities of WPAN beyond the HECR. Because the WLAN loses its sensing to WPAN activities, packet collision may occur when WLAN traffic occurs later than the WPAN traffic.

Although the HECR of 25 meters is not sufficient for outdoor applications, it seems to be good enough for most indoor medical applications. Typical bedside medical applications defined by ISO/IEEE 11073 are within this range [16]. This finding is different from those of most coexistence studies in which it is usually assumed that WLAN cannot sense the activities of WPAN [5, 7, 8]. Putting the oversensitive and insensitive CCAs together results in an unfair share of channel between WLAN and WPAN when they are separated beyond HECR. There is a preferential treatment of WLAN traffic. The WLAN is overprotected, while the WPAN is vulnerable.

6. CONCLUSION

In this paper, we have investigated the carrier sensing issue in integrated medical environments. The energy-based CCA was considered because the 2.4 GHz ISM band is too crowded to apply feature-based CCA for simple sensor devices. We studied the hybrid of 802.11 HR/DSSS and 802.15.4b as examples.

Using central limit theorem, we have derived closed-form expressions of both energy-based and feature-based CCA. We have shown and qualified the asymmetric CCA. The asymmetric CCA is different from the traditional "hidden node" or "exposed node" issues in the CSMA protocol in the homogeneous network. In the considered integrated medical environments, WPAN is oversensitive to 802.11 HR/DSSS signals and WLAN is insensitive to 802.15.4b signals. The optimal CCA thresholds require some prior knowledge of the underlying signals. When WPAN and WLAN are located within the HERC, energy-based CCA can effectively avoid

possible packet collisions. The HERC is sufficient for most indoor medical applications. This is different from most coexistence studies. However, when they are farther apart, WPAN can still sense 802.11 HR/DSSS signals, and WLAN loses its sense to 802.15.4b signals.

Although energy-based CCA enables peaceful coexistence of WLAN and WPAN within HERC, the asymmetric CCA puts WPAN traffic in a secondary position in the integrated medical environments. The WPAN may lose chance for successful transmission. Future work will focus on removing or mitigating the oversensitivity of CCA.

REFERENCES

[1] R. S. H. Istepanian, E. Jovano, and Y. T. Zhang, "Guest editorial introduction to the special section on M-Health: beyond seamless mobility and global wireless healthcare connectivity," *IEEE Transactions on Information Technology in Biomedicine*, vol. 8, no. 4, pp. 405–414, 2004.

[2] A. Soomro and D. Cavalcanti, "Opportunities and challenges in using WPAN and WLAN technologies in medical environments," *IEEE Communications Magazine*, vol. 45, no. 2, pp. 114–122, 2007.

[3] D. Cypher, N. Chevrollier, N. Montavont, and N. Golmie, "Prevailing over wires in healthcare environments: benefits and challenges," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 56–63, 2006.

[4] A. Lymberis, "Smart wearable systems for personalised health management: current R&D and future challenges," in *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology (EMBS '03)*, vol. 4, pp. 3716–3719, Cancun, Mexico, September 2003.

[5] N. Golmie, D. Cypher, and O. Rebala, "Performance analysis of low rate wireless technologies for medical applications," *Computer Communications*, vol. 28, no. 10, pp. 1266–1275, 2005.

[6] N. Golmie, N. Chevrollier, and O. Rebala, "Bluetooth and WLAN coexistence: challenges and solutions," *IEEE Wireless Communications*, vol. 10, no. 6, pp. 22–29, 2003.

[7] I. Howitt and J. A. Gutierrez, "IEEE 802.15.4 low rate—wireless personal area network coexistence issues," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC '03)*, vol. 3, pp. 1481–1486, New Orleans, La, USA, March 2003.

[8] S. Pollin, M. Ergen, A. Dejonghe, et al., "Distributed cognitive coexistence of 802.15.4 with 802.11," in *Proceedings of the 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom '06)*, pp. 1–5, Mykonos Island, Greece, June 2006.

[9] X. Yang and N. Vaidya, "On physical carrier sensing in wireless ad hoc networks," in *Proceedings of the 24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '05)*, vol. 4, pp. 2525–2535, Miami, Fla, USA, March 2005.

[10] J. Zhu, X. Guo, L. L. Yang, and W. S. Conner, "Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing," in *Proceedings of IEEE International Conference on Communications (ICC '04)*, vol. 7, pp. 4004–4011, Paris, France, June 2004.

[11] H. Zhai and Y. Fang, "Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks," in *Proceedings of the 25th IEEE Conference on Computer Communications (INFOCOM '06)*, pp. 1–12, Barcelona, Spain, April 2006.

[12] I. Ramachandran and S. Roy, "On the impact of clear channel assessment on MAC performance," in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM '06)*, pp. 1–5, San Francisco, Calif, USA, November 2006.

[13] IEEE 802.11-2007 standard, "Wireless medium access control and physical layer specification for low rate wireless local area networks," 2007.

[14] IEEE 802.15.4b standard, "Wireless medium access control and physical layer specification for low rate wireless personal area networks," 2006.

[15] S. M. Kay, *Fundamentals of Statistical Signal Processing: Detection Theory*, Prentice-Hall PTR, Upper Saddle River, NJ, USA, 1998.

[16] IEEE P1073, "IEEE standard for medical device communications-overview and framework," 1996.