Asymmetric carrier sense in heterogeneous medical networks environment

Bin Zhen, Huan-Bang Li, Shinsuke Hara† and Ryuji Kohno††
National Institute of Information and Communications Technology, 3-4, Hikarino-oka, Yokosuka, 239-0847, Japan
†Osaka City University, 3-3-138 Sugimoto, Osaka, 530-0001 Japan
††Yokohama National University, 79-5 Tokiwadai, Yokohama, 240-8501, Japan

Summary: Complementary WLAN and WPAN technologies, as well as other wireless technologies will play a fundamental role to support ubiquitous healthcare delivery. This chapter investigates energy based clear channel assessment (CCA) of IEEE WLAN (802.11b) and WPAN (802.15.4b) system when they coexist in a close space. We derive closed-form expressions of energy based, qualify the asymmetric CCA in both AWGN channel and fading channels, and show the impact of noise uncertainty on CCA operation. In the heterogeneous medical networks environment, WPAN is oversensitive to the 802.11b signals and WLAN is insensitive to the 802.15.4b signals. The asymmetric CCA issue in heterogeneous networks is different from the traditional "hidden node" or "exposed node" issues in homogeneous network. Energy based CCA can effectively avoid possible packet collisions when they are close within the "heterogeneous exclusive CCA range". However, beyond this range, WPAN can still sense 802.11b signals, but WLAN lose its sense to 802.15.4b signals. This leads to WPAN traffic in a position secondary to the WLAN traffic. A two-band CCA scheme, with an additional CCA detector in auxiliary channel, is proposed to combat the asymmetric CCA issue in the heterogeneous networks.

1. Introduction

Integration of heterogeneous wireless technologies is required to for revolutionary healthcare delivery in hospital, small clinic, residential care center, and home [1-4]. 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. The concept of "wireless hospital" combines all medical, diagnostic and clinical data together whenever needed through wireless integration [4]. There is desire to use IEEE version of wireless local area networks (WLAN) and wireless personal area networks (WPAN) technologies in the unlicensed industrial, scientific and medical (ISM) bands as a common communication infrastructure [2, 3]. The WLAN technology is typically used for office oriented applications and patient connection to the outside world, while the WPAN technology is usually used for wearable sensors around patients to collect vital information for ubiquitous healthcare service [2-6].

The use of complementary heterogeneous WLANs and WPANs in the shared ISM band results in coexistence, interference and spectrum utilization issues. The coexistence of wireless technologies in ISM band has been a hot topic [6-9]. Adaptive frequency hopping was proposed for Bluetooth devices to avoid interference from WLAN [7]. A model for analyzing the effect of 802.15.4 on 802.11b performance was provided by Howitt and Gutierrez [8]. 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 [6]. A distributed adaptation strategy for WPAN based on Q-learning has been proposed to minimize the impact of interference from 802.11b [9]. However, the spatial reuse issue in the heterogeneous networks has not drawn much attention. Some researches have shown that the spatial reuse and aggregate throughput in the homogeneous WLAN mesh network is closely related to physical channel sensing. Yang and Vaidya showed that the aggregate throughput can suffer significant loss with an inappropriate choice of carrier sense threshold [10]. Ma *et al*, by means of Markov chain model, evaluated how carrier sense threshold affects the throughput and packet collision [11]. Zhai and Fang found that the optimal carrier sensing threshold for one-hop flows does not work for multihop flows [12]. Zhu *et al* reported that a tunable sensing threshold can effectively leverage the spatial reuse and demonstrated it through testbed measurement [13, 14]. In [15], Zhu *et al* proposed a heuristic algorithm to adaptively tune the threshold of carrier sense to enhance throughput per user. Jamieson found carrier sense can be inefficient at low data rate when capture effect is most prevalent [16]. Ramachandran and Roy showed cross-layer dependence between carrier sense and system performance [17]. Simulators widely used for performance evaluation, like NS-2 and OPNET, do not contain detailed physical layer module like carrier sense. For the lack of carrier sensing knowledge between WPAN and WLAN, Golmie *et al* simply simulated two carrier 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 [6].

In this chapter we study the coexistence issue in the heterogeneous medical networks environment from carrier sensing point. The remainder of the chapter is organized as follows. Section II briefly reviews various carrier sense methods and the considered WLAN and WPAN systems. In section III, a mathematical analysis of energy based carrier sense in both AWGN channel and fading channel is presented. Section IV describes the impact of asymmetric carrier sense in heterogeneous networks environment and presents a two-band carrier sense to combat the asymmetry. Section V finally concludes the chapter.

2. Review of systems and clear channel assessment

A. Wireless medical sensor networks

Wireless medical sensor networks can be considered as a special part of general wireless sensor networks (WSN), which are mainly implemented by low-rate WPAN technologies. As compared in Table I, both share some common features which include limited resources (e.g. computation power, memory, battery, bandwidth), low/modest duty cycle, energy efficiency, plug-and-play, diverse coexistence environments, and heterogeneous device ability. But we can also find significant differences between them in the sensor device, dependability, networking, traffic pattern and channel.

Firstly medical sensors consider safety, quality and reliability as top priority, while general WSN are cost sensitive for market reason. The safety to human/animal body is therefore the first factor taken into considered. Thus medical sensors must be conscious of specific absorption ratio (SAR) to protect human tissue. Wearable IEEE WPAN devices are suggested to be separated at least 30cm distance from human body. Safe to human is the top priority of medical sensors. The radio emission should be as weak as possible. And medical sensors should be lightweight and small to achieve non-invasive and unobtrusive monitor. This limits the available resource which includes memory, battery power and computation ability in the medical sensors. The requirement is more stringent than the general WSN.

Secondly the medical sensor networks have more frequency bands to select than general WSN, which usually work in ISM band. Although the specific medical bands are less noisy, they are narrow band and conditional license. For example, the wireless medical telemetry service (WMTS) band can only be used in the licensed hospital and clinic, but not at home. On the contrary, the wideband ubiquitous ISM is somehow noisy since the frequency band should be shared with other systems.

Thirdly, the traffic pattern in medical sensor networks is featured by periodical real time data (e.g. EEG and ECG) and some top priority burst data (e.g. alarm and alert) [17]. In contrast, general WSN typically consider versatile traffic. The medical information, especially the alarm notification, have very strict requirement in terms of Quality-of-Service (QoS) since they are life critical. The transmission of vital signal has a life or dead meaning. This means more stringent QoS requirement than general WSN.

Fourthly, security of data is traditionally utmost important. Patient data needs to be protected in all stages of data acquiring, data transmission and data storage. It therefore importance to secure data at physical layer and MAC lay. However, security is not free, extensive sources are needed to secure data at the link layer. In the resource limited WSN, security becomes an overhead of existing network QoS. Because both of them are paramount in the healthcare service, the balance of security and QoS is a new issue. The general WSN do not require strict QoS and security simultaneously.

Fifthly, to improve reliability, general WSN tend to distribute redundant sensors as backup for sensing, transmission and forwarding. In contrast, there is little redundancy in medical WSN for medical reasons. For example, vital signals, like EEG (Electroencephalography) and ECG (Electrocardiogram), are location dependent and can only be measured by deterministic location. Therefore it is difficult to allocate redundant sensors in the limited area. Especially, it makes no sense to allocate sensors outside of the interest/effect area.

In summary, the lack of redundancy, priority traffic, dominant periodical data and balance of guaranteed QoS and security in versatile coexistence environment challenge the reliability design of wireless medical sensor networks.

	Medical wireless sensor networks	General wireless sensor networks
Common features	Limited resources: battery, computation, memory, energy efficiency Diversity coexistence environment low/modest data rate, low/modest duty cycle Dynamic network scale, plug-and-play, heterogeneous devices ability, dense distribution	
Sensor/ actuator	Single-function device Fast relative movement in small range device lifetime, days, <10 years (implant sensor) Safe (low SAR) and quality first	Multi-function device Rare or slow movement in large range network lifetime and device lifetime, months, <10 years Cost sensitive
Dependability	Reliability (first), guaranteed QoS Strongly security (except emergency)	expected QoS, redundancy-based reliability Required security
Networking	Small scale star network No redundancy in device Deterministic node distribution	Large scale hierarchical network redundant distribution Random node distribution
Traffic	Periodical RT (dominant), burst (priority) Uni-directional traffic M:1 communication	Burst (dominant), periodical Uni-directional or bi-directional traffic M:1 or point-point communication
channel	Specific medical channel, ISM band Body surface or through body	ISM band Obstacle is unknown

Table 1. Comparison between wireless medical sensor network and general wireless sensor networks

B. Systems overview

We consider IEEE 802.15.4b and 802.11b as examples for the ubiquitous medical services [2, 3, 6]. The former is a good candidate technology for low data rate and low cost medical sensors. Both systems operate in the unlicensed 2.4GHz ISM band, and both are based on carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Carrier sense is more generally known as clear channel assessment (CCA) in the standards. The physical CCA can be either energy based, or feature based, or a combination of two. As shown in Fig. 1, there are only 4 WPAN channels locate in the guard bands of WLAN. Table II lists the parameters of both systems [18, 19]. The bit error rate (BER) of WLAN systems with AWGN channel is give by [18]

$$BER_{11b} = \frac{128}{255} \times \sum_{l=1}^{6} M1_l \times \sqrt{Q(M2_l \times SNR)}\,, \tag{1}$$

where *SNR* is the signal-to-noise ratio, *Q(.)* is Gaussian Q-function, *M1=[24 16 174 16 24 1]*, and *M2=[4 6 8 10 24 16]*. The BER of WPAN systems is given by [19]

$$BER_{15.4b} = \frac{8}{15} \times \frac{1}{16} \times \sum_{k=2}^{16} -1^k \binom{16}{k} e^{20SNR(1/k-1))}\,. \tag{2}$$

The radio path loss for indoor channels in the working frequency band is given by

$$\begin{cases} pl = 40.2 + 20\log_{10} d & d \le 8 \\ pl = 58.5 + 33\log_{10}(d/8) & d > 8 \end{cases}, \tag{3}$$

where d is separation distance between transmitter and receiver.

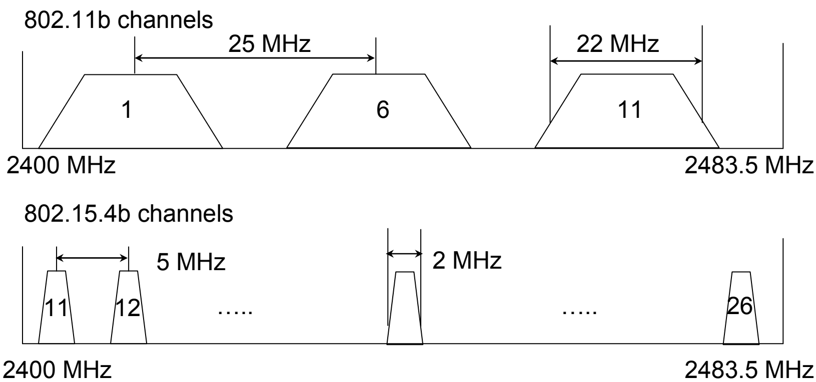

Fig. 1. Channel plan for IEEE 802.11b and 802.15.4b in 2.4GHz ISM band

Parameters	802.15.4b	802.11b
Transmission power (dBm)	**0**	**16**
Channel bandwidth (MHz)	**2**	**22**
Adjacent channel separation (MHz)[1]	**5**	**25**
Background noise (dBm) [2]	**-94.9**	**-84.6**
Spread code (chips)	**32/4 bits**	**11**
Data rate (Mbps)	**0.25**	**11**
CCA window (μs)	**120**	**15**

Table 2. System parameters of IEEE WLAN and WPAN

C. Clear channel assessment

Several IEEE WLAN and WPAN standards adopt CSMA protocol for channel access. CCA is a physical layer activity and is an essential element of the CSMA protocol. The concept of CCA was first proposed as an enhancement to the ALOHA protocol. The CCA detects an incoming packet and ensure a free medium before transmission. The CCA module processes received radio signals in a suitable time duration termed CCA window. It then reports the medium state, either busy or idle, by comparing the detection with a threshold.

The energy based CCA integrates signal strength from radio front end during the CCA window. The feature based CCA looks for the known features, *e.g.* the modulation and spreading characteristics, of the signal over the channel. Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, or cyclic prefixes, which result in built-in periodicity. This periodicity can be used to detect signal of a particular modulation type.

The feature based CCA performs far better than the energy based CCA. However, a prior knowledge of the signal characteristic is necessary. And the CCA module would need a dedicated detector for every potential coexistence signal class. The main advantages of energy based CCA are its simplicity, generality, and low power consumption. It is a universal mechanism that can be deployed in all systems. Unlike feature based CCA, there is no need for waiting time for the specific features of the signal and synchronization [17]. The downside of energy based CCA is that it is prone to false detection.

We applied energy based CCA to 802.15.4b and 802.11b systems to deliver ubiquitous healthcare service in this heterogeneous networks environment. There are several reasons for this. First, there have been nearly 10 wireless technologies with different modulations, band plans, and transmission powers in the 2.4GHz ISM bands due to its global availability.

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[1] Distance between the central frequencies of non-overlapped adjacent channel.

[2] We assumed -174dBm/MHz thermal noise, 8dB implementation losses, and 8dB radio noise figure.

These include WLAN (802.11, 802.11b, 802.11g and 802.11n), WPAN (Bluetooth, 802.15.3, 802.15.4b, and chirp spread spectrum PHY of 802.15.4a), and passive radio frequency identification *etc*. Significantly, some medical equipments like electric surgical knife, magnetic resonance imaging (MRI), heat treatment machines, and microwave ovens also use this frequency band. Different from the communication device, the medical equipments emit radio signals unintentional. All the communication device and medical equipments are expected to be collocated in the integrated medical environments. Secondly, a medical sensor based on 802.15.4b is unlikely to have all the knowledge. And feature based CCA is usually complex and power-hungry due to the waiting time and synchronization [17].

3. Energy based clear channel assessment in heterogeneous networks

In mathematics, CCA is a test of two hypotheses:

$$\begin{cases} H_0 : y[n] = w[n] & \text{signal absent} \\ H_1 : y[n] = x[n] + w[n] & \text{signal present} \end{cases}, \quad (4)$$

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, *e.g.* 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 probabilities, (P_d and P_{fa}), which are associated with the particular threshold Γ.
For simplicity, we assume the energy based CCA is realized by a simple non-coherent 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. Figure 2 depicts a block diagram of energy based CCA.

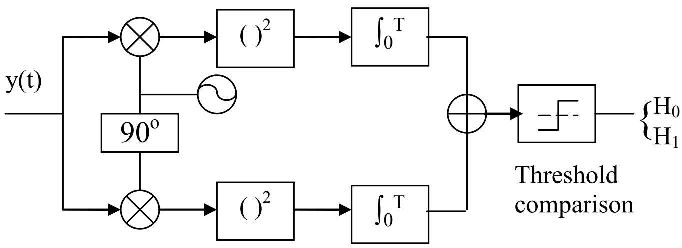


Fig. 2. Block diagram of energy based CCA detector

The energy based CCA metric can be given by

$$Y = \frac{1}{N}\sum_{n=1}^{N}\left(\left|y_I[n]\right|^2 + \left|y_Q[n]\right|^2\right), \quad (5)$$

where N is the number of independent samples in the CCA window. In an AWGN channel, each $|y_I[n]|$ and $|y_Q[n]|$ has 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 $\lambda = \sigma^2 + \mu^2$. Under the H_0 hypothesis, each normal distribution has $\mu=0$. Thus, Y has a χ^2 distribution. Under the H_1 hypothesis in the present of signal with an signal-to-noise ratio (SNR) $\gamma = \frac{\mu^2}{\sigma^2}$, Y has a non-central χ^2 distribution. We have mean and variance as follows [20, 21]

$$\begin{cases} H_0: & \mu_0 = \sigma^2, \quad \sigma_0{}^2 = \dfrac{2}{N}\sigma^4 \\ H_1: & \mu_1 = \mu^2 + \sigma^2, \quad \sigma_1{}^2 = \dfrac{2}{N}(2\mu^2 + \sigma^4) \end{cases} . \tag{6}$$

When N is large, using central limit theory, the energy based CCA metric in Eq. (4) can be approximated as Gaussian random process. Then P_d and P_{fa} can be expressed in terms of Gaussian Q-function

$$P_d = Q\left(\frac{\frac{\Gamma}{\sigma^2} - (1+\gamma)}{\sqrt{\frac{2}{N}(1+2\gamma)}}\right), \quad P_{fa} = Q\left(\frac{\frac{\Gamma}{\sigma^2} - 1}{\sqrt{\frac{2}{N}}}\right), \tag{7}$$

where Γ is the decision threshold. Eq. (7) clearly shows that the decision threshold is related with noise level. If the noise is completely known, eliminating Γ in Eq. (7) gives

$$N = 2\left(\frac{Q^{-1}(P_{fa}) - Q^{-1}(P_d)\sqrt{1+2\gamma}}{\gamma}\right)^2, \tag{8}$$

where $Q^{-1}()$ is inverse Gaussian Q-function. The energy based CCA can meet any desired P_d and P_{fa} simultaneously by increasing the number of samples in the CCA window N. Given a limited N, the CCA ability is obviously determined by the SNR of the signal and noise variance σ^2. 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 Eq. (7), we obtain the CCA error floor

$$P_{CCA\_ef} = Q\left(\sqrt{N}\,\frac{\gamma}{1+\sqrt{1+2\gamma}}\right). \tag{9}$$

Note that the error floor depends on the number of symbol chips and the SNR. When SNR<<1, Eq. (9) can be approximated as

$$P_{CCA\_ef} = Q\left(\sqrt{N}\,\frac{\gamma}{2}\right). \tag{10}$$

A linear decrease in *SNR* requires a quadratic increase in *N* to maintain the same error floor.
A. Asymmetric energy based CCA
Table III lists the numbers of signal chips in the CCA windows of IEEE WLAN and WPAN. Figure 3 shows the CCA error floor in the heterogeneous networks environment when the noise is known. Per Eq. (9), the error floors decrease with increment in signal chips in the CCA window. Given the defined CCA windows, the CCA abilities, *e.g.* sensitivity and range, to determine the channel state are different, this is termed asymmetric CCA. Under the same SNR conditions, the lowest error floor is where WPAN is used to sense 802.11b signals; the highest error floor is where WLAN is used to sense 802.15.4b signals. The performance difference is nearly 10dB.
The CCA asymmetry can be attributed to differences in the underlying signals over channel (power, symbol rate and background noise) and CCA window. In physics, a higher data rate and a longer CCA window means more signal pulses in baseband can be collected. Better CCA performance is a natural result. Asymmetric CCA can be further reinforced by other factors. For example, the difference in transmission powers which is usually stronger for WLAN, and the difference in channel bandwidth, which are 22MHz and 2MHz 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 not big difference in the numbers of symbols in the CCA window.
Table IV compares communication with CCA when both have an error probability of 1‰ with AWGN channel. As expected, the CCA range is larger than the communication range. For WPAN, sensing 802.11b signals has 4dB greater link margin compared to sensing the signals of its own type. In contrast, for WLAN sensing 802.15.4b signals requires a 4.8dB higher SNR.
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 homogeneous network. In the homogeneous network, two devices belong to the same system are reciprocal in ability to sense each other (we do not consider the minor difference due to implementation.). However, in the heterogeneous networks, the sensing abilities of different systems are unequal and depend on the underlying signals over channel and the separation distances. As shown in Fig. 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.

Device \ Sensed signals	802.15.4b signals	802.11b signals
802.15.4b	32*8	120*11
802.11b	15*2	15*11

Table 3. Number of signal chips in the CCA window

Signal \ Devices	802.15.4b	802.11b
Communication	-0.8	5.6
802.15.4b CCA	-3.2	2.6
802.11b CCA	-7.2	-2.2

Table 4. SNRs (dB) to achieve 1‰ communication BER and CCA error floors in AWGN channel

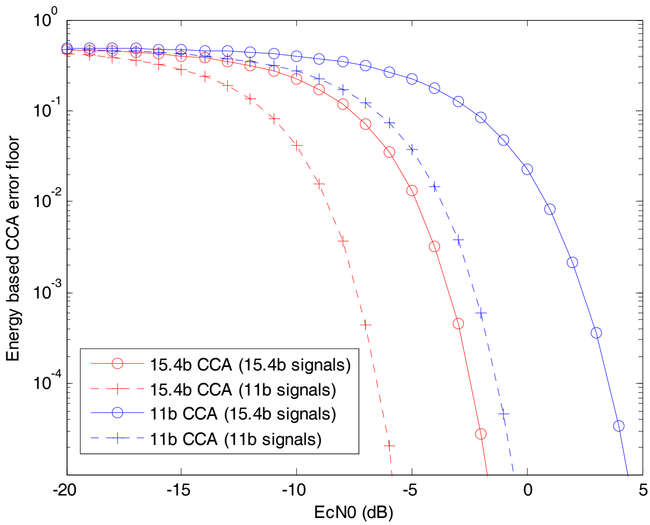


Fig. 3. Error floor of energy based CCA with AWGN channel in heterogeneous networks

Usually, NP criteria is adopted in CCA because a miss detection of a busy channel is riskier than a false alarm of a free channel. Eq. (7) can be re-written as

$$P_d = Q\left(\frac{Q^{-1}(P_{fa}) - \sqrt{2N}\gamma}{\sqrt{1+2\gamma}}\right). \tag{11}$$

As expected, P_f is independent of γ since there is no signal under H_0. When the channel is varying due to fading and shadowing, Eq. (12) gives a CCA performance conditioned on the instantaneous SNR. The average CCA performance can be derived by averaging Eq. (11) over fading statistics

$$\overline{P_d} = \int_0^\infty Q\left(\frac{Q^{-1}(P_{fa}) - \sqrt{2N}\gamma}{\sqrt{1+2\gamma}}\right) f(\gamma)d\gamma, \tag{12}$$

where $f(\gamma)$ is the probability of distribution function (PDF) of SNR under fading.

The medium-scale variance of SNR can be characterized by log-normal distribution [22]. The log-normal shadowing is usually described in-term of its dB-spread, σ_{dB}, which is related to σ by

$$\sigma = \sigma_{dB} \ln(10)/10. \tag{13}$$

Under Rayleigh fading, the SNR γ has an exponential PDF

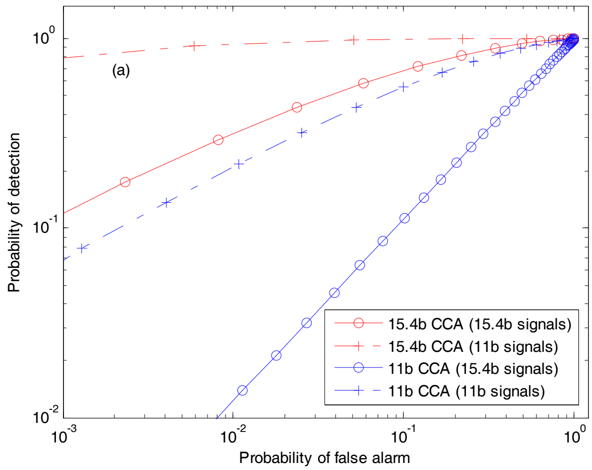
$$f(\gamma) = \frac{1}{\overline{\gamma}} \exp(\frac{\gamma}{\overline{\gamma}}) \quad \gamma \geq 0, \tag{14}$$

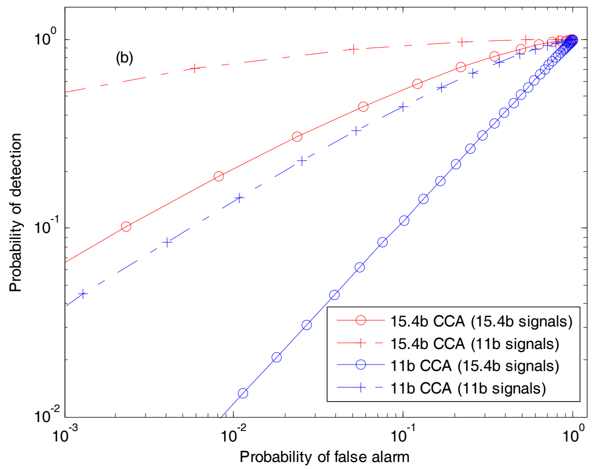
where $\overline{\gamma}$ denotes to average SNR. If the SNR follows a Rician distribution, the PDF of γ becomes

$$f(\gamma) = \frac{K+1}{\overline{\gamma}} \exp(-K - \frac{(K+1)\gamma}{\overline{\gamma}}) I_0(2\sqrt{\frac{K(K+1)\gamma}{\overline{\gamma}}}) \quad \gamma \geq 0, \tag{15}$$

where K is the Rician factor and $I_0(.)$ is the modified Bessel function with order zero. Because it is difficult to have close-form expressions of Eq. (12) over fading channels, we evaluated them numerically in this chapter.

Figure 4 plots ROCs of energy based CCA over AWGN, log-normal shadowing, Rayleigh fading, and Rician fading channels. The asymmetric CCA abilities of WPAN and WLAN remain the same in fading channels. WLAN systems are insensitive to WPAN signals, while WPAN systems are oversensitive to WLAN signals. Comparing with the AWGN curves, we observe that channel fading degrades the performance of energy based CCA, and the degradations are closely related with the CCA parameters and SNR. In other words, meeting the desired performance demands a longer CCA window. Especially Rayleigh fading and Rician fading degrade the CCA performance of all systems significantly.


(a)
Probability of detection
Probability of false alarm
10^{0}
10^{-1}
10^{-2}
10^{-3}
15.4b CCA (15.4b signals)
15.4b CCA (11b signals)
11b CCA (15.4b signals)
11b CCA (11b signals)


(b)
Probability of detection
Probability of false alarm
10^{0}
10^{-1}
10^{-2}
10^{-3}
15.4b CCA (15.4b signals)
15.4b CCA (11b signals)
11b CCA (15.4b signals)
11b CCA (11b signals)

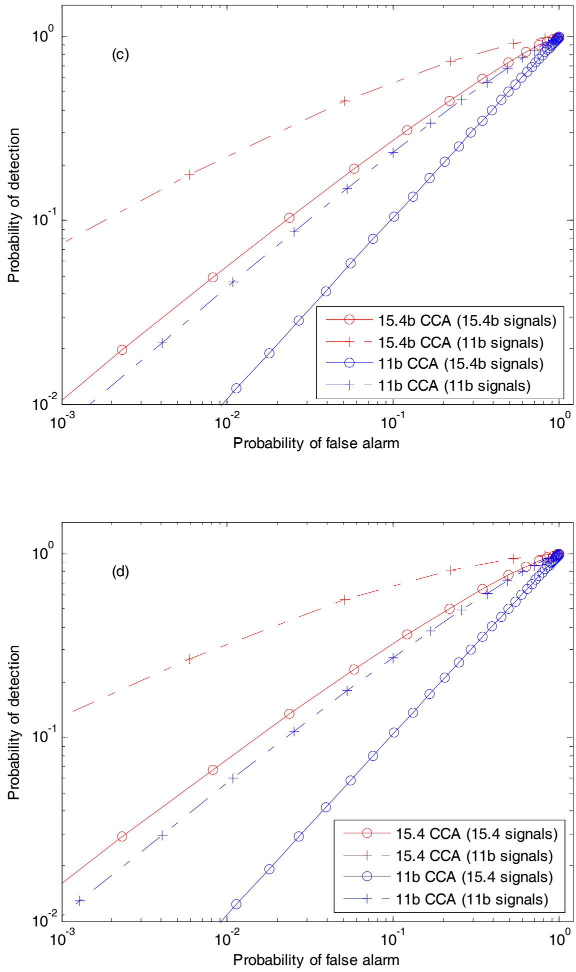


Fig. 4. ROC of energy based CCA in the case of SNR=-9.5 dB measured by WPAN over a) AWGN channel; b) log-normal shadowing (σ_{dB}= 6dB) channel; (c) Rayleigh fading channel, and d) Rician fading (K=1.5) channel.

B. Noise uncertainty

NP criteria requires a desired P_{fa} to determine the decision threshold. We can re-write Eq. (7) to have

$$\Gamma = \sigma^2 (1 + Q^{-1}(P_{fa})\sqrt{\frac{2}{N}}) , \tag{16}$$

which shows the desired threshold should proportional to the noise energy. In practical, the noise power cannot be estimated accurately because of noise uncertainty [23].

The background noise power fluctuates from time to time due to changes of environment and mobility of device. Another source of uncertainty is the error in quantization which us usually implemented by A/D convertor. Assume the noise estimation is expressed as

$$\hat{\sigma}^2 = k\sigma^2, \quad k \geq 0. \tag{17}$$

When $0 < k < 1$, the noise is underestimated; when $k > 1$, it is overestimated. The Γ biases to the desired value due to error in noise estimation. An overestimation of noise decreases P_{fa} at expense of boosting P_d. It is *vice versa* for an underestimation of noise level. We can obtain the total CCA error by $1\text{-}P_d+P_{fa}$ using Eq. (7). Figure 5 shows the impact of noise uncertainty with 3 dB error. We used an 802.15.4 device to sense the 802.15.4 signals. The x-axis is the true SNR condition of CCA. As expected, both overestimation and underestimation deteriorate the CCA performance because of an un-optimal threshold. As shown in Fig. 5 and other numeric results, the performance loss of energy based CCA can be approximated as $\begin{cases} 10*\lg(k) & 0 < k \leq 1 \\ -10*\lg(k) & k > 1 \end{cases}$ in both cases when SNR is high. In practical, we are usually more interested in noise underestimation. In order to guarantee the P_{fa} the Γ is purposely biased. This increases the probability of miss detection of CCA and therefore the probability of packet collision. In other words, the noise level estimation of free channel also plays an important role in the CCA operation.

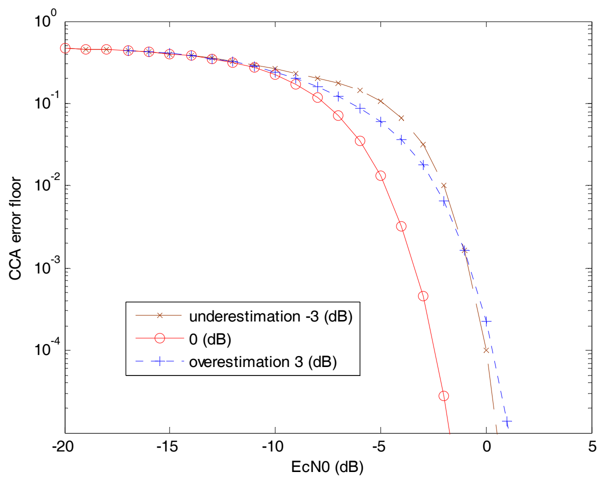


Fig. 5. Total error of energy based CCA with AWGN channel in the case of a 3dB noise uncertainty

4. Two-band clear channel assessment

A. Impact of asymmetric CCA in heterogeneous networks

Table V lists the required minimum SNRs and their corresponding distances to achieve reliable energy based CCA (P_{FA}<1% and P_D>90%) over AWGN channel. The corresponding distances were computed using Eq. 1 to Eq. 3 and the parameters listed in Table I. For WPAN, the sensing of 802.11b signals is reliable at an SNR as low as -9.25dB. This SNR is 9.65dB lower than the critical SNR which is the least SNR to achieve BER<0.1‰ for communication. 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 9.75dB, which is 3.15dB more than the critical SNR for communication. The CCA range is 42 meters shorter than the communication range. In the fading channels, all distances decreases depending on the fading condition.

We can define a "heterogeneous exclusive CCA range" (HECR), in which systems in the heterogeneous environment can reliably sense the activities of each other. In the considered scenario, the HECR is the maximum distance that WLAN can sense 802.15.4b signals. Given the system parameters and assumptions, the HECR for IEEE WLAN and WPAN is 25m in AWGN channel. 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. For WPAN systems, the CCA range of WLAN signals is more than twice as long as the communication range. And 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.[3] 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. For WLAN systems, the CCA range of WPAN signals is about a quarter of the communication range. Packet collision may occur when WLAN traffic occurs immediately after the WPAN traffic.

	802.11b CCA		802.15.4b CCA	
	WPAN signals	**WLAN signals**	**WPAN signals**	**WLAN signals**
SNR (dB)	**9.75**	**-4.5**	**-6**	**-9.25**
Distance (m)	**25**	**200**	**155**	**280**

Table 5. Minimum SNRs (dB) and corresponding distances (m) to achieve CCA (P_{FA} <1%, P_D>90%) with AWGN channel

[3] The keep-out range denotes to the minimum separation which WPAN and WLAN do not interfere each other.

Although the HECR of 25 meters is not sufficient for outdoor applications, it seems to be good enough for most indoor applications. Typical bedside medical applications define by IEEE 1073 are within this range [24]. This is different from those of most coexistence studies in which it is usually assumed that WLAN cannot sense the activities of WPAN [6, 8, 9]. The HECR over fading channels is expected to be shorter than 25 meters depending on the fading parameters. But the asymmetric CCA issue still exists. 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 over-protected, while the WPAN is vulnerable.

B. Two-band clear channel assessment

The asymmetric CCA issue in heterogeneous medical networks environment must be solved. It is needed to recognize the signal source, WPAN signals or WLAN signals, when the medium is busy. When the channel is occupied by WLAN signals, an 802.15.4b device should increase its CCA threshold to lower the CCA sensitivity. On the other hands, when the channel is busy in WPAN signals, an 802.11b device should lower its CCA threshold to heighten the CCA sensitivity.

Figure 6 illustrates the mechanism of a two-band CCA. The 22 MHz WLAN channel depicted in dash-dotted line and the 2 MHz WPAN channel depicted in dotted line overlap each other. There are about 3 MHz space between adjacent WPAN channels, which are inside the WLAN channel. As shown in red-solid line in Fig. 7, we termed it auxiliary channel in this chapter. We added a new energy based CCA detector in the auxiliary channel to provide additional information. For example, the auxiliary CCA detector can be the same as the 802.15.4b CCA detector except that the working frequency is tuned to the auxiliary channel. For both WLAN systems and WPAN systems, there are two energy based CCA detectors tuned in its original channel and in the auxiliary channel, respectively. The two detectors have the same ability to conduct carrier sensing given the same configuration. Besides, there is a little increase in the complexity of device and the power consumption of CCA.

The two-band CCA in the WPAN/WLAN device conduct channel sensing simultaneously. When the channel is free, both CCA detectors indicate a free channel. Table VI lists the output states of the two-band CCA detector when the channel is busy. The channel state indications are the same in both systems. When the channel is occupied by WLAN signals, both CCA detectors indicate a busy channel. In contrast, when the channel is occupied by WPAN signals, the auxiliary CCA detector indicates a free channel. Therefore, the signal source can be easily distinguished.

In the two-band CCA, the performance of every energy detector can be analyzed as in Section III. The total performance can be expected as the AND of the two CCA detector.

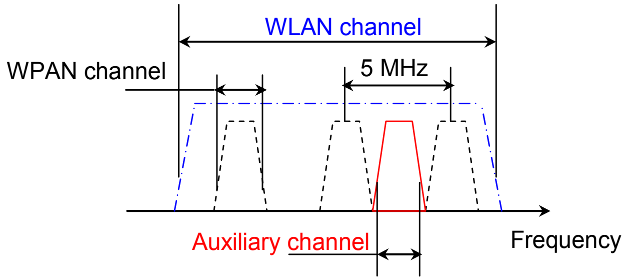


Fig. 6. Mechanism of two-band clear channel assessment

	802.11b		802.15.4b	
	CCA_{ch_11b}	CCA_{ch_aux}	$CCA_{ch\_15.4b}$	CCA_{ch_aux}
WPAN signals	√	×	√	×
WLAN signals	√	√	√	√

Table 6. Output states of the two-band CCA detector when the channel is busy

5. Conclusion

In this chapter, we have investigated the coexistence issue in the heterogeneous medical networks environment for ubiquitous health services from network access point. The energy based CCA was considered because the 2.4GHz ISM band is too crowded to apply feature based CCA for simple medical sensors.

Using central limit theorem, we have derived closed-form expressions for energy based CCA. We have shown and qualified impact of noise uncertainty on CCA and the asymmetric CCA in AWGN channel and fading channels. In the considered heterogeneous medical networks environment for ubiquitous healthcare purposes, WPAN is oversensitive to 802.11b signals and WLAN is insensitive to 802.15.4b 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. However, when they are farther apart, WLAN lose its sense to 802.15.4b signals. The asymmetric CCA puts WPAN traffic in a secondary position in the heterogeneous networks. We have proposed a two-band energy-based CCA with an additional CCA detector tuned in the auxiliary channel to combat the asymmetric CCA issue.

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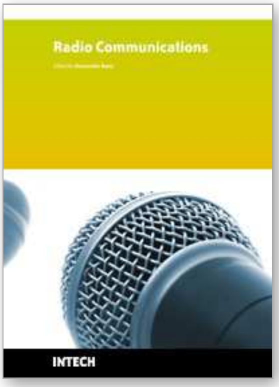

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In the last decades the restless evolution of information and communication technologies (ICT) brought to a deep transformation of our habits. The growth of the Internet and the advances in hardware and software implementations modified our way to communicate and to share information. In this book, an overview of the major issues faced today by researchers in the field of radio communications is given through 35 high quality chapters written by specialists working in universities and research centers all over the world. Various aspects will be deeply discussed: channel modeling, beamforming, multiple antennas, cooperative networks, opportunistic scheduling, advanced admission control, handover management, systems performance assessment, routing issues in mobility conditions, localization, web security. Advanced techniques for the radio resource management will be discussed both in single and multiple radio technologies; either in infrastructure, mesh or ad hoc networks.