New Energy Efficient Clear Channel Assessment for Wireless Network

Soo Young Shin[1], Iyappan Ramachandran[2] and Sumit Roy[3]
[1]School of Electronic Engineering, Kumoh Institute of Technology
Gumi, Gyeongbuk, 730-701- Korea
[e-mail: wdragon@kumoh.ac.kr]
[2] Signal Analysis Division, Agilent Technologies
Everett, WA, 98205, USA
[3] School of Electrical Engineering, University of Washington
Seattle, WA 98195, USA
[e-mail: sroy@u.washington.edu]
*Corresponding author: Soo Young Shin

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Abstract

In this paper, a new clear channel assessment (CCA) method: cascaded-CCA, is proposed. The primary motivation for the proposed approach is to integrate the respective advantages of two standard CCA mechanisms, energy detect and preamble detect, to arrive at a new dual threshold CCA family that can provide greater flexibility towards tuning MAC performance. Cascaded-CCA integrates energy efficiency of the energy detector (ED) and the reliability of the preamble detector (PD). The probability of detection/false alarm and power consumption of cascaded-CCA in the CCA modules of IEEE 802.11b are analyzed and compared with ED and PD as an example. The performance of cascaded-CCA is explored via MATLAB simulations that implement the CCA modules and medium access control (MAC) protocol for IEEE 802.11 and IEEE 802.15.4. Simulation results showed that cascaded-CCA improves the energy efficiency significantly compared to ED-only or PD-only CCA. In addition, ED, PD, and cascaded CCA are applied to a cognitive network scenario to validate the effectiveness of the proposed cascaded-CCA.

Keywords: cascaded-CCA, energy detection, preamble detection, MAC performance, IEEE 802.11, IEEE 802.15.4, cognitive network

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1. Introduction

The integration of wireless communication technology with a multitude of portable devices (notebooks, PDAs, and smart phones) have generated a lot of interest in creating ad-hoc networks using low-cost, short-range radios without any static infrastructure such as base stations or access points. In such ad hoc networks, each node acts as a potential router to create an end-to-end path between two nodes that are not in direct radio range of each other. Among the many medium access control (MAC) protocol layer designs for wireless ad hoc networks [1][2][3], several prominent ones - notably 802.11 (WLAN) and 802.15.4 (WPAN) - utilize carrier sensing to determine the channel state.

Also, the continuing emergence of multiple wireless standards many in the unlicensed bands - has led to spectral congestion on one hand, whereas licensed bands with an identified primary service, often suffer from spectrum under-utilization. This motivates a new communication paradigm to exploit spectrum opportunistically via Cognitive Radio (CR) technologies. Many of the MAC protocols employ a listen-before-talk or carrier sense multiple access (CSMA) component. In all such cases, sensing the channel status accurately and expeditiously is the fundamental design challenge for CR [4][5][6].

In CSMA, network terminals seeking to transmit first sense the channel state and initiate access only if it determines that no other transmission is underway [7].There are several core flavors of channel sensing - notably energy and preamble detection - that are collectively known by the general term: Clear Channel Assessment (CCA). While on one hand, CSMA allows for graceful network scaling with increasing number of nodes, it also places significant energy burden on the nodes. For instance, IEEE 802.11 [8], which has been successfully modeled using p-persistent CSMA [9], requires that the nodes sense the channel continually even when not actively contending for the channel. This leads to considerable idle energy consumption, an important factor in the shortening of node lifetimes in energy-constrained sensor-net type devices [10].

Even in networks that do not require continuous channel sensing, one is forced to run CCA for extended periods of time for increased reliability. For instance, IEEE 802.15.4 [11], which has been modeled using non-persistent CSMA [12], allows nodes to sense for channel activity only when ready for packet transmission and stay idle at other times. However, such non-persistent channel sensing implies the use of energy efficient but less reliable CCA methods like energy detection (ED) for on-the-fly detection. A more reliable but power-hungry alternative like preamble detection (PD) requires the node to constantly run CCA so to catch the preamble as and when it occurs on air.

Thus, there is a need to devise channel sensing methods that will enable more fine-grained tuning of the tradeoff between energy consumption and throughput. It has been shown in [12][13] that from a MAC performance perspective, ED is a good choice as the CCA method at low traffic rates and PD at high rates. Thus CCA approaches that enable smooth transition between the two to achieve optimal MAC performance at all traffic rates, are also desirable.

In this paper, we develop cascaded-CCA that attempts to address both of the aforementioned goals. It has a low-power and less reliable ED running continually. On detection of channel activity, the ED triggers a more reliable and power-hungry preamble detector. The front-end ED significantly reduces idle energy consumption, while the back-end PD provides a high degree of reliability. By varying the parameters of the front-end, one gets the ability to smoothly trade-off energy consumption for reliability. By analysis, we calculate (a) receiver operational characteristics (ROCs) of Cascaded-CCA, (b) appropriate ED/PD threshold values for a given probability of false alarm and probability of detection, (c) energy efficiency of Cascaded-CCA. We also illustrate how the cascaded-CCA method can be used to optimize MAC performance at all traffic rates by exploring its impact on MAC performance of IEEE 802.11 and IEEE 802.15.4.

The paper is organized as follows. The structures of typical CCA methods - ED and PD - are described in the next section. Chapter 3 introduces the architecture of cascaded-CCA. In Chapter 4, false alarm/detection probability and power consumption of cascaded-CCA of IEEE 802.11b under AWGN(Additive White Gaussian Noise) are analyzed. In Chapter 5 and 6, we illustrate how the cascaded-CCA method can be applied in IEEE 802.11 and IEEE 802.15.4 protocols, respectively and tuned for optimum MAC performance. In Chapter 7, we investigate the performance of ED, PD, cascaded-CCA in cognitive radio network. We draw our conclusions in Chapter 8.

2. Structures of ED and PD

The purpose of CCA is to detect the presence of ongoing transmissions reliably so as to enable the sensing node to decide whether to proceed with channel access.

2.1 Energy Detection

Energy detection has been the traditional approach to narrowband CCA. It is based on estimating the signal energy around the carrier frequency, which is indicative of signal presence. Signal transmission can be detected via a non-coherent energy detect (ED) operation (integrating the square of the received signal or extracting signal envelope over a suitable period) with sufficient reliability. ED is a robust, universal mechanism that can be deployed in all systems without requiring any knowledge of the type of underlying modulation scheme employed. However, ED is inherently less reliable at low signal-to-noise ratios.

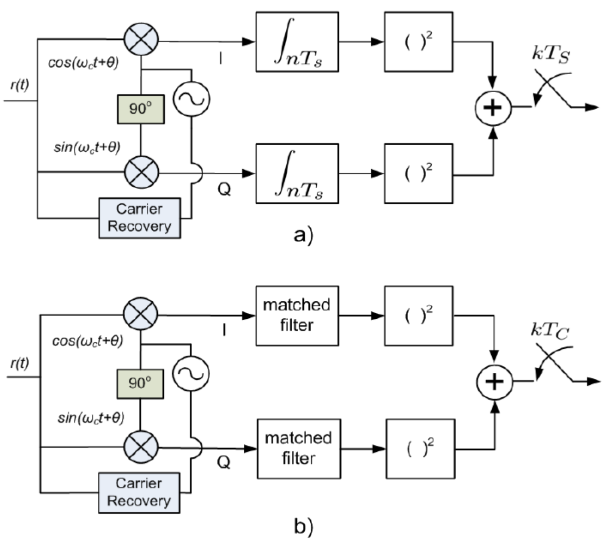


Fig. 1. Structure of (a) energy detector and (b) preamble detector

2.2 Preamble Detection

For coherent detection of wideband signals, the sensing node has to attain time synchronism with the ongoing transmission. In packet-based systems, the process of acquiring time synchronism is aided by the transmission of a preamble in front of every packet, typically consisting of repetitions of a sequence of known symbols. The receiver performs a correlation of the known sequence with the received signal with varying time offsets. At the offset corresponding to time synchronism, the correlation is high due to the processing gain resulting from the repetition of the known symbols. This high correlation is both indicative of signal presence and provides an estimate of time offset. This carrier-sense based CCA using correlation of the known preamble with the received signal is called preamble detection (PD).

2.3 ED-PD Comparison

ED is quite unreliable in detecting the presence of wideband signals, whose power levels are not much above the noise floor. However, it requires very little power to keep ED running, one reason for which is its symbol rate sampling, $1/T_S$. PD is quite reliable as it takes advantage of the processing gain inherent in the preamble. Its power consumption however may be exorbitant. Note that the PD requires a much higher sampling rate than $1/T_S$; it may be the chip rate in spread spectrum systems like 802.11b or the FFT rate in OFDM systems like 802.11a. We denote the sampling rate requirement of PD as $1/T_c$. Although the network examples considered in this paper are of spread-spectrum type, the methods developed are applicable to all wideband networks.

3. Structure of cascaded-CCA

Cascaded-CCA signifies, architecturally, a concatenation of ED and PD as follows. The ED block is always on, integrates the received RF signal over several symbol durations, and produces an output at symbol rate. If the integrated output exceeds the ED threshold Γ_{ED}, the ED triggers the PD to turn on. Once the PD is turned on, the receiver performs a correlation of the received signal with the known spreading sequence and continues to integrate the output over the available number of symbols. If the output exceeds the threshold for the PD, Γ_{PD} at the end of the preamble duration, the cascaded-CCA finally determines that the signal is present and sets the flag to BUSY; if not, it returns to observing the channel state via ED. **Fig. 2** shows a state diagram of cascaded-CCA operation with p_d^{ED} and p_{fa}^{ED} being the probabilities of detection and false alarm of the ED stage and p_d^{PD} and p_{fa}^{PD}, that of the PD stage.

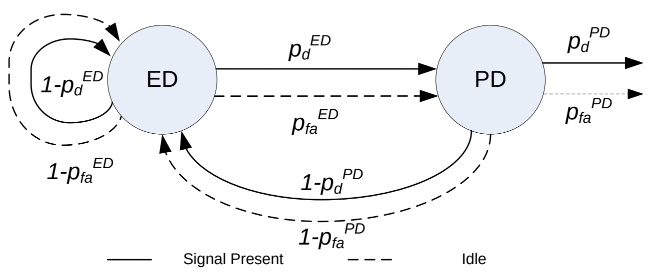
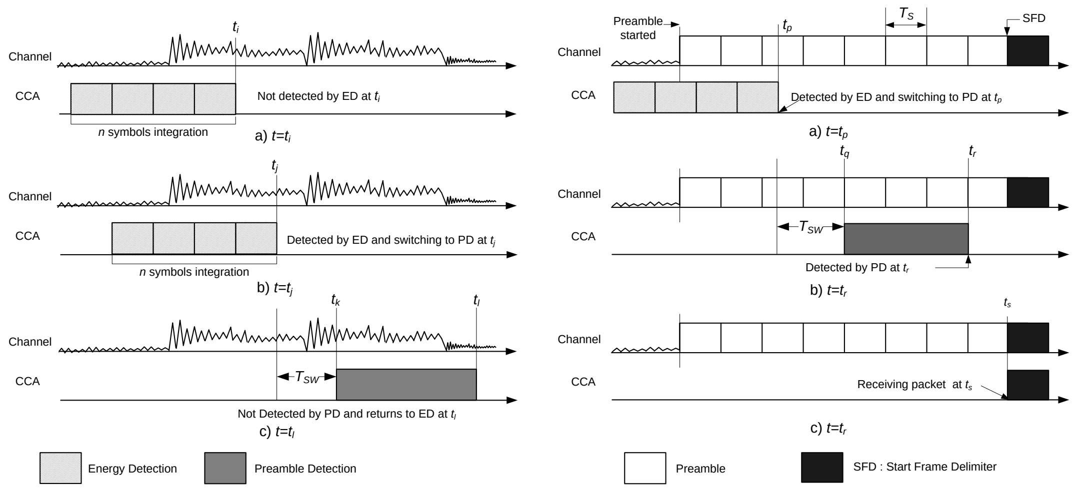


Fig. 2. State digram of cascaded-CCA



(a) When the channel is idle (a) When the channel is busy

Fig. 3. Operation of cascaded-CCA

Fig. 3 shows an example of the operation of cascaded-CCA when the channel is idle/busy. Here, ED threshold is not crossed at t_i as shown in **Fig. 3 (a) a)**. ED will continue to integrate over an n symbol sliding window, with output sampled at symbol rate. The ED threshold may be crossed with probability p_{fa}^{ED} at t_j as in **Fig. 3 (a) b)**. At this point, ED triggers a PD module, which takes T_{SW} for switching from ED to PD. And PD starts sampling the received signal at rate $1/T_c$ and correlates it over symbol duration with the known preamble template.

The PD output is then compared to a threshold Γ_{PD}. If at any point within N symbol durations, where N is the number of preamble symbols, PD threshold is crossed, the CCA module will declare the channel BUSY by setting the flag. Otherwise, PD returns control back to ED at t_k as shown in **Fig. 3 (a) c)**.

This happens with probability p_{fa}^{PD}. The overall false alarm probability is $p_{fa}^{ov} = p_{fa}^{ED} p_{fa}^{PD}$. Note that p_{fa}^{ov} cannot be larger than p_{fa}^{ED}.

Fig. 3 (b) shows an example operation of cascaded-CCA when the channel is busy. Note that in general, the integration boundary of the ED is not aligned with the symbol boundary. When an actual packet arrives, the ED threshold crossing happens k symbols into the packet at t_p, which is a random variable as shown in **Fig. 3 (b) a)**. Now, the PD has (N-k-w) remaining symbols to correlate over and make a final decision about signal presence. Here, w symbols represent the time required for the switching from ED to PD, i.e., T_{SW} shown in **Fig. 3**.

The preamble is said to be missed if the signal presence is not detected within these N symbols. In our example, the PD threshold Γ_{PD} is exceeded at t_q of **Fig. 3 (b) b)**. Then, the channel flag is set to BUSY and the receiver prepares to decode the subsequent packet payload starting with the start frame delimiter as in **Fig. 3 (b) c)**.

By keeping an ED running continually instead of PD, cascaded-CCA significantly reduces idle energy consumption. This is particularly attractive when traffic is expected to be sporadic. Secondly, varying the ED threshold provides the ability to smoothly tradeoff energy consumption for CCA reliability. A higher ED false alarm rate will trigger PD more often unnecessarily, but it gives a higher detection probability leading to better throughput. Conversely, one might get better energy efficiency by setting a low ED false alarm rate, but this will bring down the throughput due to a correspondingly reduced ED detection probability.

In the next chapter, we analyze detection/false alarm probability and power consumption of cascaded-CCA in IEEE 802.11b as an example

4. Probability of False Alarm/Detection and Power Consumption Analysis of cascaded-CCA in IEEE 802.11

4.1 Probability of False Alarm

Fig. 4 shows an operation of Cascaded-CCA in IEEE 802.11b when the channel is busy, which will be used for analysis. In IEEE 802.11b, the slot and the preamble duration are defined as $T_s(=20T)$ and $T_{PA}(=7\ T_s)$, where $T(=1\mu s)$ is a symbol duration. Since the IEEE 802.11b also exploits direct sequence spread spectrum, a symbol consist of n_c (= 11) chips. According to IEEE 802.11b standard, CCA must determine the channel state within N_S (=15) symbols. All those parameters are listed in **Table 1**.

Table 1. Paramters of IEEE 802.11b

Parameter	Definition	Value
n_c	Number of chips per symbol	11
T	Symbol duration	1 μs
T_s	Slot duration	20 μs
T_{PA}	Preamble duration	140 μs
N_S	Number of symbols for CCA	15

ED runs continuously and integrates the received RF signal during n symbols duration as shown in **Fig. 4**. When an actual packet arrives, Γ_{ED} crossing happens kn symbols into the preamble, where k = 1,2,…, $\lfloor N_S / n \rfloor$. It is assumed that T_{SW} (=*w symbol duration*) are required for the switching from ED to PD. Now, the PD has N_S-kn-w remaining symbols to correlate over and make a final decision by comparing correlated output with Γ_{PD}. The preamble is said to have been missed if the signal presence is not detected within N_S symbols.

Since IEEE 802.11b is slot-based CSMA/CA, we assumed that the front-end ED will start at each slot boundary for simplicity. In an AWGN channel with the absence of a signal, each in-phase and quadrature, r_{I_i} and r_{Q_i}, has a normal distribution with zero mean and variance σ^2 (= 1). Thus, the integrated output of ED of the x-th trial, $Y_{ED} = \Sigma_{i=1}^{n \cdot n_c} (r_{I_i}^2 + r_{Q_i}^2)$ has a central chi-square distribution with $2n \cdot n_c$ degrees of freedom.

Then, the probability of false alarm of ED is

$$p_{fa}^{ED} = Pr\{Y_{ED} > \Gamma_{ED}\} = 1 - F_\chi(\frac{\Gamma_{ED}}{\sigma^2}, 2n \cdot n_c), \tag{1}$$

where $F_{\chi}(x,v)$ is the cumulative distribution function (CDF) of a standard chi-square random variable with ν degrees of freedom [14].

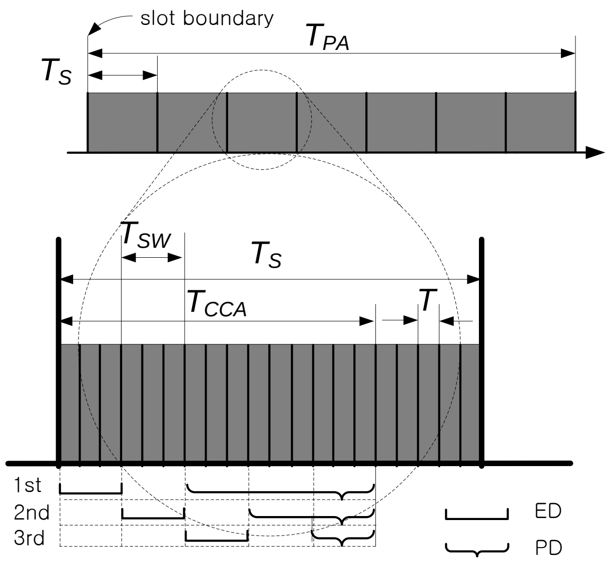


Fig. 4. Operation of cascaded CCA in IEEE 802.11 (n= 3 symbols)

By simple induction, we can express the probability of false alarm at *k*-th integration as

$$p_{fa,k}^{ED} = \left(1 - p_{fa}^{ED}\right)^{k-1} p_{fa}^{ED}. \tag{2}$$

Once Γ_{ED} is crossed at *k*-th trial, PD takes a role for a final decision with N_S-*kn*-*w* symbols where *w* represents the time required for switching from ED to PD. Then, Y_{PD}, the correlated output of PD, has a central chi-square distribution with 2 degree of freedom with a variance of $(N_S\text{-}kn\text{-}w)\cdot n_c$. Therefore, the probability of false alarm by PD at *k*-th trial could be obtained as [14]

$$p_{fa,k}^{PD} = Pr\{Y_{PD}^{k} > \Gamma_{PD}\} = 1 - F_{\chi}\left(\frac{\Gamma_{PD}}{\left(\sqrt{(N_S - kn - w)\cdot n_c}\right)^2}, 2\right). \tag{3}$$

From above equations, the overall probability of false alarm in Cascaded-CCA could be expressed as

$$p_{fa}^{ov} = \sum_{j=1}^{\lfloor N_S/n \rfloor} p_{fa,j}^{ED} p_{fa,j}^{PD}. \tag{4}$$

4.2 Probability of Detection

In an AWGN channel with the presence of a signal with E_c/N_0 ratio of $\gamma = a^2/\sigma^2$, the integrated output of ED of the x th trial, $Z_{ED} = \Sigma_{i=1}^{n \cdot n_c}(r_{I_i}^2 + r_{Q_i}^2)$ has a non-central chi-square distribution with a noncentrality parameter of $s^2 = Na^2$, where $N = n \cdot n_c$.

Then, the probability of detection by the *k*-th ED trial front-end ED is given by

$$p_d^{ED} = Pr\{Z_{ED} > \Gamma_{ED}\} = p_D = Q_N\left(\frac{s}{\sigma}, \frac{\Gamma_{ED}}{\sigma}\right) = Q_N\left(\sqrt{N\gamma}, \frac{\sqrt{\Gamma_{ED}}}{\sigma}\right), \quad (5)$$

where $Q_m(\cdot,\cdot)$ is the generalized Marcum-Q function with order of m [14].

With the same logic as in the probability of false alarm, the probability of detection at *k*-th trial could be expressed as

$$p_{d,x}^{ED} = \left(1 - p_d^{ED}\right)^{k-1} p_d^{ED}. \quad (6)$$

The correlated output of the PD, Z_{PD} at *k*-th trial has a non-central chi-square distribution with 2 degree of freedom. The non-centrality parameter is $s^2 = (N_S - kn - w) \cdot n_c (a)^2$ and the variance is $(N_S - kn - w) \cdot n_c$ based on [14].

$$p_d^{PD} = Pr\{Z_{PD} > \Gamma_{PD}\} = Q_1\left(\sqrt{(N_S - kn - w)?n_c\gamma}, \sqrt{\frac{\Gamma_{PD}}{(N_S - kn - w)n_c}}\right). \quad (7)$$

From Eq. (3.2) and (3.2), the overall probability of detection in Cascaded-CCA could be expressed as

$$p_d^{ov} = \sum_{l=1}^{\lfloor N_S/n \rfloor} p_{d,l}^{ED} p_{d,l}^{PD}. \quad (8)$$

p_{fa}^{ov} and p_d^{ov} of all CCA methods- ED, PD and Cascaded-CCA (CA) - can be shown using Receiver Operating Curves (ROCs) as in **Fig. 5(a)**, obtained by varying the thresholds, Γ_{ED} and Γ_{PD} under AWGN channel with $E_b / N_o = 7$ dB. For Cascaded-CCA, the p_{fa}^{ED} ,probability of false alarm of front-end ED, are varied from 10% to 90%.

For a given p_{fa}^{ov}, PD has the best $p_d^{ov} \approx 1$ due to the correlation gain of known preamble symbols. Because ED measures only the signal power level, it consequently suffers the worst p_d^{ov}. As expected, Cascaded-CCA provides intermediate performance. As p_{fa}^{ED} increases, the post-end PD is turned more frequently. This will consume more energy but increase the detection probability, p_d^{ov}, due to the correlation property of PD.

As illustrated in **Fig. 5(a)**, for Cascaded-CCA, the front-end ED determines the starting point of ROC and the back-end PD increases p_d^{ov} for a given p_{fa}^{ov}.

From Eq. (1), Γ_{ED} could be obtained for a given p_{fa}^{ED} as

$$\Gamma_{ED} = F_\chi^{-1}\left(\left(1 - p_{fa}^{ED}\right)^{(1/(N_S/n))}, 2n \cdot n_c\right). \quad (9)$$

If p_d^{ED} is given, Γ_{ED} can be obtained from inverse function of the generalized Marcum-Q function. The inverse function can be solved by numerical methods.

4.3 Power Consumption

In Cascaded-CCA, the channel is detected by ED at first and the PD is turned on when ED output is larger than Γ_{ED}. Hence, the power consumption of Cascaded-CCA in the absence and presence of signal, $P_C^{CCA,ab}$ and $P_C^{CCA,pr}$, could be expressed as

$$P^{CCA,ab} = \left(1 - p_{FA}^{ov}\right) P_C^{ED} + \sum_{j=1}^{\lfloor N_S/n \rfloor} p_{FA^{ED}}^{j} \, p_{FA^{PD}}^{j} \left\{ jnP_C^{ED} + wP_C^{SW} + \left(N_S - jn - w\right) P_C^{PD} \right\}, \quad (10)$$

and

$$P^{CCA,pr} = \left(1 - p_{D}^{ov}\right) P_C^{ED} + \sum_{j=1}^{\lfloor N_S/n \rfloor} p_{D^{ED}}^{j} \, p_{D^{PD}}^{j} \left\{ jnP_C^{ED} + wP_C^{SW} + \left(N_S - jn - w\right) P_C^{PD} \right\}, \quad (11)$$

where j = 1, 2, · · ·, $\lfloor N_S / n \rfloor$. In both equations, the first term represents that only ED runs without turning on PD and the second term represents the operation of Cascaded-CCA, i.e., front-end ED, switching from ED to PD, and post-end PD.

The parameters of the radio were obtained from [15] , which has idle, transmit and receive states with respective power consumptions of $P_{idle}=0.83W$, $P_{tx}=1.4W$, and $P_{rx}=1W$. An extra CCA state has been introduced to capture the differences in power consumptions among different CCA methods. Accurate models for power consumption of the CCA modules are not available. We therefore resort to certain heuristic arguments to arrive at reasonable numbers for the power consumption. For example, since the energy detector is a rather simple module, but still requires the ADCs to be operational, we estimate its power consumption to be a fraction, say quarter of the power consumption in receive state, $P_C^{ED} = P_{rx}/4$. A PD has a matched filter running at chip rate, but the other blocks such as demodulation, etc. are absent. We therefore estimate its power consumption to be the same as that in receive state $P_C^{PD} = P_{rx}$ [16]. Although the switching from ED to PD consumes considerable power, there is no accurate model for that. Hence, we assumed the switching from ED to PD consumes P_C^{SW} (= P_{RX}), which takes w symbol times. The power consumptions of each state in IEEE 802.11b are shown in **Table 2**.

Table 2. Power Consumption of IEEE 802.11b

Parameter	Definition	Value
P_{idle}	Power consumption of idle state	0.83W
P_{tx}	Power consumption of tx state	1.4 W
P_{rx}	Power consumption of rx state	1 W
P_C^{ED}	Power consumption of energy detection	0.25 W
P_C^{PD}	Power consumption of preamble detection	1 W
P_C^{SW}	Power consumption of switching from ED to PD	1 W

Fig. 5 (b) illustrates the power consumption of all CCA methods when the channel is busy. the power consumptions of ED and PD are constants regardless of the probabilities of detection probabilities. Note that the power consumption of Cascaded-CCA shows intermediate values between ED and PD.

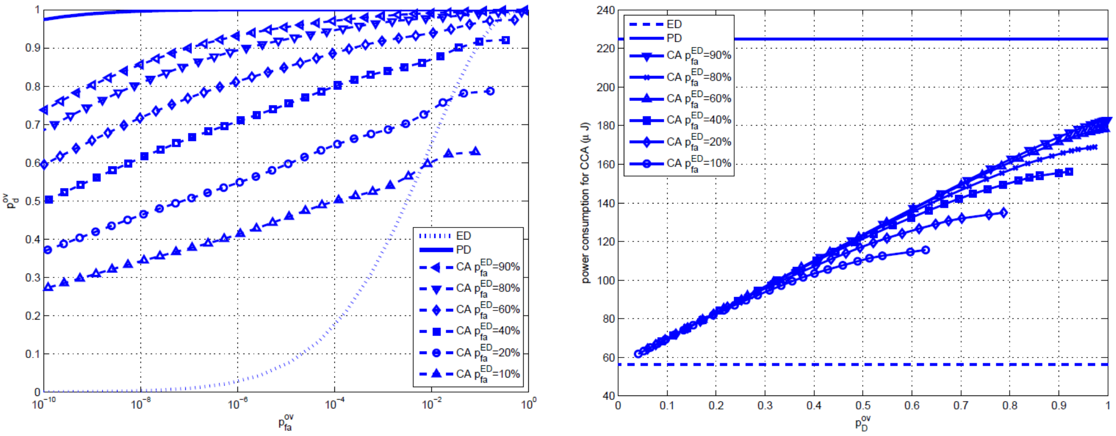


Fig. 5. Analytic results of different CCA in IEEE 802.11

The same analysis can be applied to IEEE 802.15.4. However, it is omitted in this paper.

5. Application to IEEE 802.11b

ED, PD and cascaded-CCA were implemented into the CCA module of IEEE 802.11. Although pure ED is not appropriate to IEEE 802.11 as every node needs to monitor the channel continually to accept packets that is destined to it, ED is implemented for the purpose of comparison. For simplicity, the switching time from ED to PD is assumed to take 3 symbols time of IEEE 802.11 in our analysis.

p_d^{ov} and p_{fa}^{ov} of all CCA methods can be shown using a Receiver Operating Curve (ROC) as in **Fig. 6**, obtained by varying the thresholds, Γ_{ED} and Γ_{PD}. An AWGN channel with a signal-to-noise ratio (SNR) of 7 dB has been used. Also both analytic and simulation results are compared to validate the analysis.

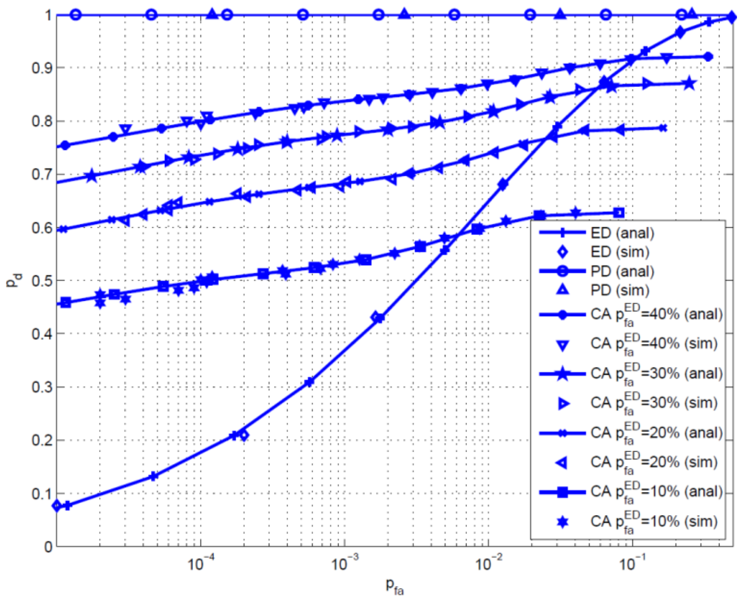
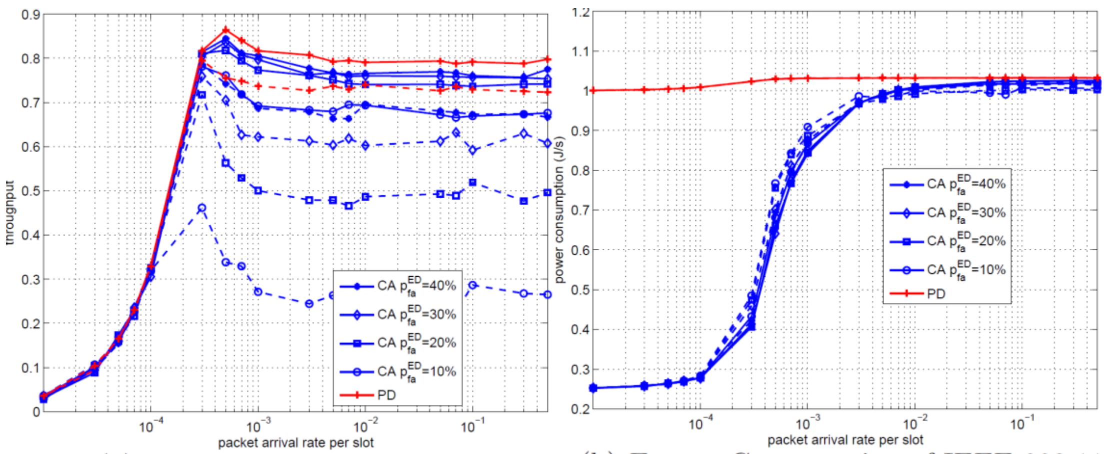


Fig. 6. ROCs of IEEE 802.11b : both analytic and simulation results

PD has the best p_d, p_{fa} as it takes full advantage of the coherent correlation gain of known preamble symbols. For the cascaded-CCA, four different false-alarm probabilities of the front-end ED, p_{fa}^{ED} =40%, 30%, 20%, and 10% are used. For obtaining the p_{fa}^{ED}, analytic approach described in Section 4 is used. The integration duration of the front-end ED is set to 3 symbols time. To determine the impact of the CCA performance, we ran a full 802.11 MAC simulator using different CCA methods. For our simulations, M=15 nodes are connected with each other in ad hoc manner and each node generates packets of 500 bytes long (about 224 slot durations), with Poisson arrivals. The power consumption of each state in IEEE 802.11b was already assumed in Section 4 as summarized in **Table 2**.

For our simulations, we have used an overall CCA false alarm probability of 5%. Appropriate thresholds for ED, PD, CA are obtained using analytic method in Chapter 4. Both AWGN and Rayleigh fading with a SNR of 7 dB are taken into consideration for obtaining the performances of IEEE 802.11b.



(a) Throughput of IEEE 802.11 (b) Energy Consumption of IEEE 802.11

Fig. 7. Throughput and power consumption of IEEE 802.11 using different CCA methods

Fig. 7 shows throughput and power consumption, of IEEE 802.11 using different CCA methods against the packet arrival rate per slot, λ under AWGN (solid line) and Rayleigh fading (dashed line). Throughput of IEEE 802.11b based on PD is the highest because PD provides the best p_{fa} for a given p_d. Due to its poorer p_{fa}, cascaded-CCA has a correspondingly poorer throughput performance. Throughput of IEEE 802.11 with both PD and cascased-CCA under Rayleigh fading shows poorer performances because of channel fading.

Although both PD and cascaded-CCA monitor the channel till a preamble is detected, cascaded-CCA consumes much less energy compared to PD because of the underlying energy efficiency of the front-end ED for small λ. As λ increases, the PD portion of cascaded-CCA is triggered more frequently and the energy consumption of cascaded-CCA approaches that of PD. Note that the energy consumption of the cascaded-CCA increases abruptly around $\lambda = 10^{-3}$ as the node consumes more energy due to the packet transmissions. Note that in AWGN and Rayleigh fading, both PD and cascaded-CCA shows similar energy consumptions.

Fig. 8 shows the metric which is defined as number of bytes that a node can successfully transmit per unit energy (Joule), Kbyte/J for different λ under both AWGN (solid line) and Rayleigh fading (dashed line).

Due to the energy saving of the ED and the reliability of the PD, the proposed cascaded-CCA could improve the energy efficiency without great loss of throughput at packet error rates less than 10^{-3}. However, if λ increases, PD overtakes cascaded-CCA in both throughput and power efficiency. So, if the packet arrival rate is small (for example, $\lambda < 10^{-3}$ in AWGN and $\lambda < 8 \cdot 10^{-3}$ in Rayleigh fading) cascaded CCA is the preferred approach for channel detection instead of PD.

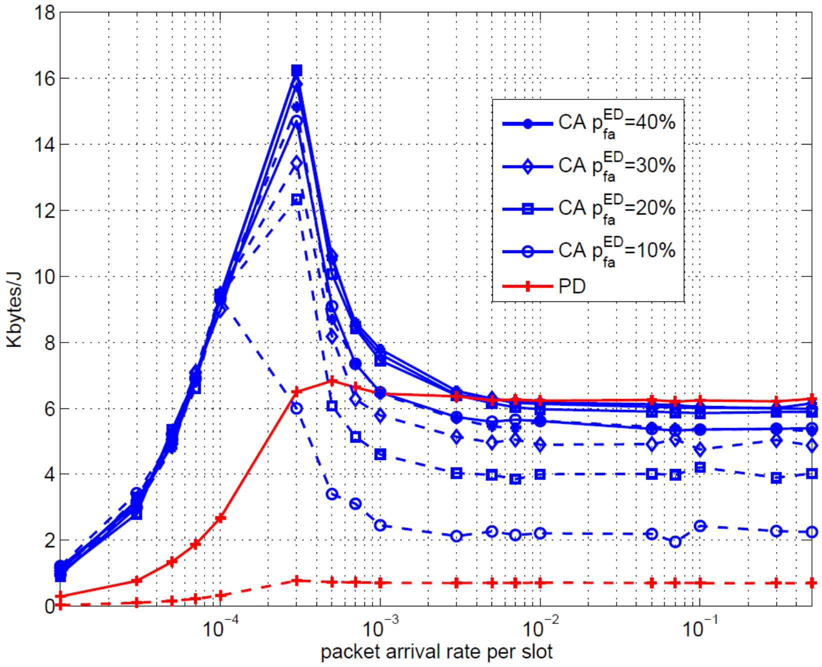


Fig. 8. Kbytes/J of IEEE 802.11 using different CCA methods

6. Application to IEEE 802.15.4

ED, PD and cascaded-CCA were implemented in IEEE 802.15.4. Unlike IEEE 802.11, pure ED can be used in IEEE 802.15.4 because there is no need to sense the channel continually. According to IEEE 802.15.4, CCA must determine the channel state within 8 symbol durations (128us corresponding to one symbol duration of 16us). Each symbol in IEEE 802.15.4 is spread using 32 chips. A backoff slot duration of IEEE 802.15.4 is 20 symbol durations, i.e., 320us. For simplicity, the switching time between the ED and the PD is assumed to take 2 symbols time of IEEE 802.15.4 in our analysis.

ROCs of the different CCA methods for IEEE 802.15.4 are shown in **Fig. 9** for 5 dB SNR in AWGN channel. For a given p_{fa}, PD has the best p_d because of the coherent correlation gain. Cascaded-CCA with p_{fa}^{ED} =40%, 30%, 20%, and 10% with the 2 symbols integration duration of the front-end ED are shown. Also, for obtaining the p_{fa}^{ED}, analytic approach described in Section 4 is used. Appropriate thresholds for ED, PD, CA are obtained using analytic method in Chapter 4. Cascaded-CCA provides intermediate performance. ED measures only the signal power level without looking for any known structures and consequently suffers the worst p_d among the three CCA methods. Also both analytic and simulation results are compared to validate the analysis.

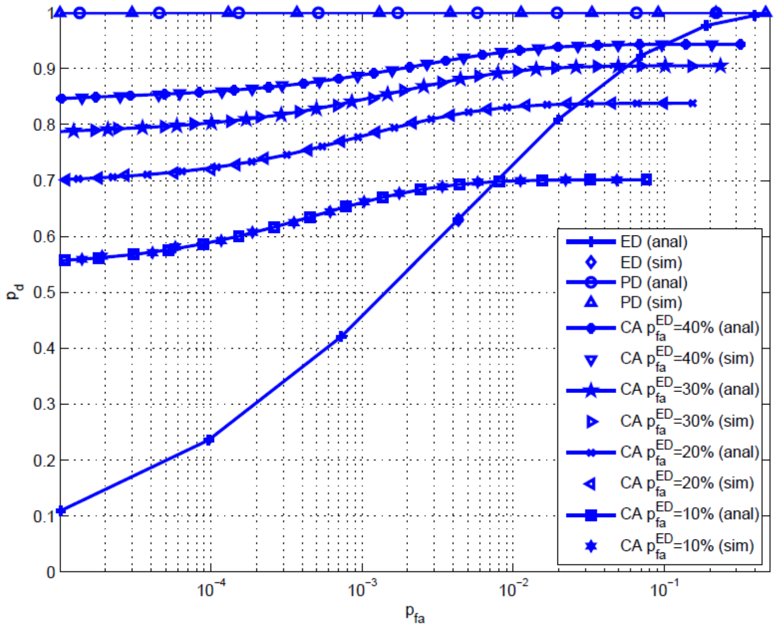


Fig. 9. ROCs of IEEE 802.15.4 : both analytic and simulation results

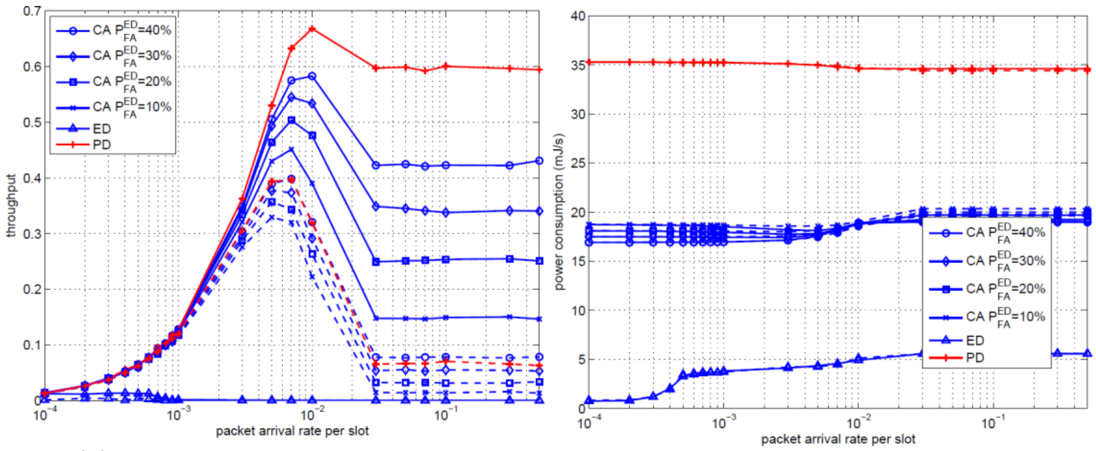
To determine the impact of the CCA performance, an 802.15.4 MAC simulator using each of the CCA methods was implemented. A star topology with M=10 end devices connected to an IEEE 802.15.4 coordinator is used. Each end device generates packets of size L=13 backoff slots at a Poisson rate to the coordinator. Both AWGN and Rayleigh fading with a SNR of 5 dB are considered for channel model.

The packet reception in the coordinator is also assumed to be error-free. The parameters of the radio used for simulations were obtained from [17], which has idle, transmit and receive states with respective power consumptions of P_{idle}=712 μW, P_{tx}=31.32 mW, and P_{rx}=35.28 mW. The CCA power consumptions of ED and PD are set to P_{rx} /4 and P_{rx}. For the cascaded-CCA, the CCA power consumptions of the ED and PD are set to $P_C^{ED}=P_{rx}/4$ and $P_C^{PD}=P_{rx}$ based on the same heuristics. As the same in IEEE 802.11, we assumed that the power required for switching from ED to PD, P_C^{SW} , is equal to P_{rx}. All the power consumptions of IEEE 802.15.4 are listed in **Table 3**.

Table 3. Power Consumption of IEEE 802.15.4

Parameter	Definition	Value
P_{idle}	Power consumption of idle state	712 μW
P_{tx}	Power consumption of tx state	31.32 mW
P_{rx}	Power consumption of rx state	35.28 mW
P_C^{ED}	Power consumption of energy detection	7.83 mW
P_C^{PD}	Power consumption of preamble detection	31.32 mW
P_C^{SW}	Power consumption of switching from ED to PD	31.32 mW

Here again, p_{fa}^{ov} is also set to 5%. While there are two consecutive CCAs in IEEE 802.15.4, the preamble length is 8 symbol durations that is smaller than one backoff slot time. Hence, there is only one chance to detect the preamble at the first CCA and an end device cannot enter the idle state if the preamble is lost at the first CCA. For the ED, the channel is sensed only when there is a packet to be transmitted. Otherwise, the ED remains at the idle state.



(a) Throughput of IEEE 802.15.4 (b) Energy Consumption of IEEE 802.15.4

Fig. 10. Throughput and power consumption of IEEE 802.15.4 using different CCA

Fig. 10 shows throughput and power consumption of IEEE 802.15.4 using different CCA methods with varying λ under AWGN (solid line) and Rayleigh fading (dashed line). According to p_d for a given p_{fa}, PD and ED show the best and the worst performance respectively while cascaded-CCA has intermediate throughput in both AWGN and Rayleigh fading. The large value of p_{fa}^{ED} means that the front-end ED stage triggers the subsequent PD more frequently. Due to the correlation property of PD, the channel will be detected more precisely and the throughput is improved comparing to the ED only. This leads higher p_{fa}^{ov} in the cascaded CCA. Under Rayleigh fading channel, performances of all PD, ED, and cascaded-CCA decreases because of channel fading.

In both AWGN and Rayleigh fading, ED consumes the smallest energy because it remains in the idle state except when there is a packet to be transmitted. The other PD and cascaded-CCA should monitor the channel continuously until there is a preamble. However, cascaded-CCA consumes less energy compared to PD because of the energy efficiency of the front-end ED.

Fig. 11 shows the metric, Kbyte/J, for different λ. Although PD shows the best throughput, its energy efficiency is significantly lower than that of cascaded-CCA with 40% of p_{fa}^{ED}. This is because PD requires considerable amount of energy for continuous preamble detection. Although the throughput of ED is the worst, its energy efficiency very good for the low packet rates ($\lambda < 6 \times 10^{-4}$) as shown in **Fig. 11**. Because cascaded-CCA outperforms PD in energy consumption and ED in sensing reliability, it shows better energy efficiency for $\lambda > 6 \times 10^{-4}$. So to maximize the energy efficiency, if the packet arrival rate is small (for example, $\lambda < 6 \times 10^{-4}$, ED is the best choice while cascaded-CCA is the best for $\lambda > 6 \times 10^{-4}$. PD could be chosen to maximize the throughput when the power consumption is not a big issue. Under Rayleigh fading, energy efficiencies of all ED, PD, and cascaded-CCA are reduced due to decreased throughput. Note that ED shows the worst energy-efficiency at all times unlike under AWGN due to steep throughput decreasing. Cascaded-CCA outperforms the others under Rayleigh fading because of relatively higher throughput compared to ED and lower energy consumption compared to PD.

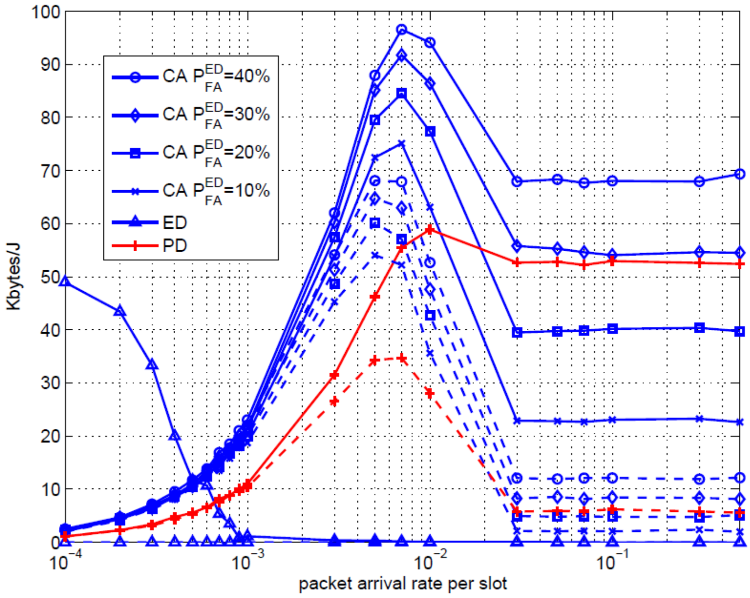


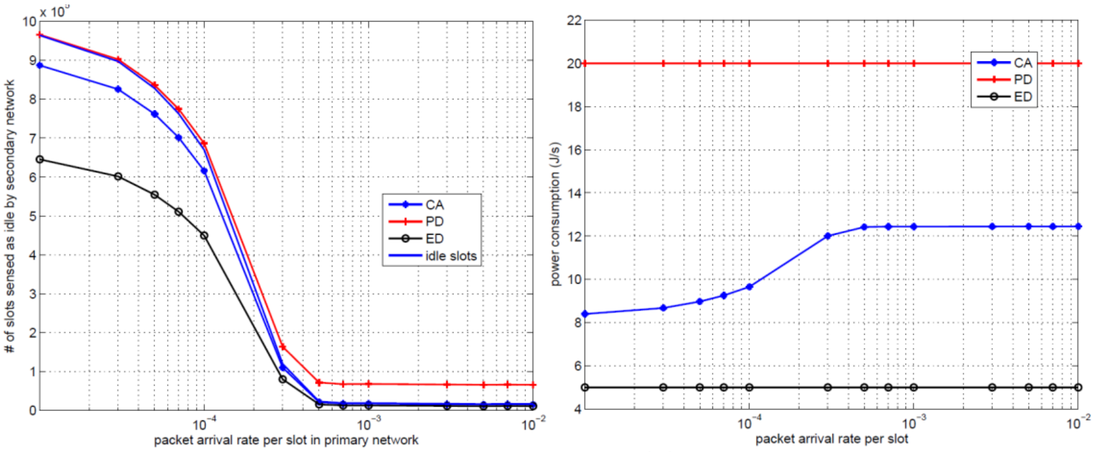
Fig. 11. Kbytes/J of IEEE 802.15.4 using different CCA methods

7. Application to Cognitive Radio Network

In this chapter, we investigate the performance of ED, PD, cascaded-CCA in cognitive radio network. It is assumed that there are one IEEE 802.11-type primary network and a secondary network which wants to use the channel licensed for the primary network. It is assumed that the primary network operates under the perfect channel sensing, i.e., without false alarm/missed-detection and the secondary network tries to check empty channel time (spectrum hole) which is not exploited by the primary network.

For our simulations, the primary network consists of M=15 nodes and each node generates packets of 500 bytes long (about 224 slot durations), with Poisson arrivals. Because our focus is searching the spectrum holes in the current channel, the secondary network consists of only one device which sees the channel activity of the primary network. In this simulation, AWGN channel model is assumed.

For ED, PD and cascaded-CCA, probabilities of detection are set to 95% so that the secondary network detects the primary channel activity accurately. **Fig. 12 (a)** shows the number of slots sensed as idle by the secondary network while the load of the primary network is changing. The legend 'idle slots' represents the actual number of idle slots in the primary network. PD shows the best results because of very low false alarm probability. However, the number of slots sensed as idle in PD is higher than that of 'idle slots' due to 5% of missed-detection probability, which will cause performance degradation of the primary network. The number of slots sensed as idle using ED shows the worst performance because higher detection probability in ED causes higher false alarm probability, which will tell idle slots as busy slots. Cascaded-CCA shows intermediate performance between PD and ED.



(a) # of slots sensed as idle

(b) Energy Consumptions in secondary network

Fig. 12. Number of slots sensed as idle and Energy consumption in the secondary network

Fig. 12 (b) shows the power consumption for detecting the idle slots in the secondary network while the load of the primary network is changing. As expected, ED consumes the smallest energy, PD consumes the largest, and the cascaded-CCA consumes less energy compared to PD because of the energy efficiency of the front-end ED.

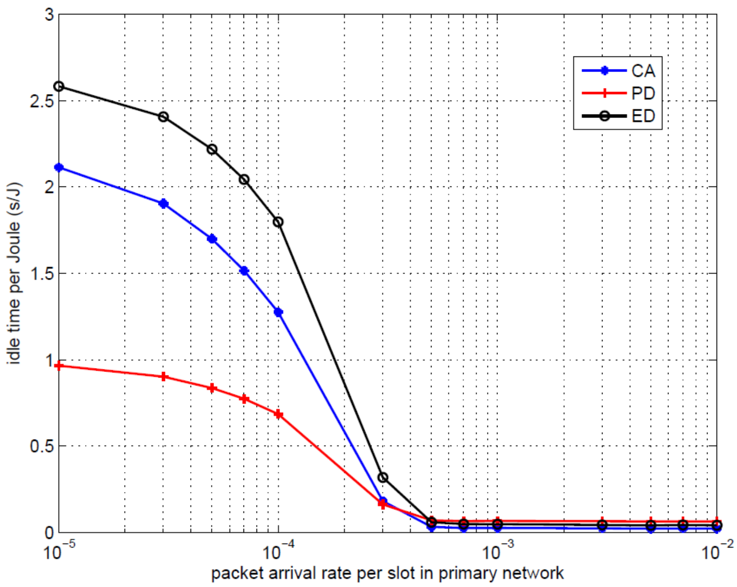


Fig. 13. Energy efficiency of the secondary network

Fig. 13 shows the energy efficiency of the secondary network in terms of (the number of slots sensed as idle)/(energy). ED shows the best performance because of the energy consumption even though the number of sensed idle slots is small. However, as shown in **Fig. 12 (a)**, performance of ED is worst because of inaccurate channel detection. PD shows the worst energy efficiency due to its highest energy consumption. Cascaded-CCA shows intermediate energy efficiency between PD and ED.

As shown in the figures, cascaded-CCA shows higher energy efficiency compared to PD and more accurate channel sensing compared to ED. Therefore, when a cognitive network requires low energy consumption and has low load such as wireless sensor network, ED will be the best choice. If a cognitive network requires high throughput, PD will be the best option. Cascaded-CCA could be chosen for a cognitive network which has middle to high load with some energy constraint such as mobile ad-hoc network.

8. Conclusion

In this paper, a new energy efficient and reliable clear channel assessment (CCA) method called cascaded-CCA is proposed, which combines the energy-efficiency of an energy detector (ED) and the reliability of a preamble detector (PD). In addition, receiver operational characteristics (ROCs) of cascaded-CCA, relationship among the probability of false alarm and the probability of detection, in IEEE 802.11b is analyzed mathematically and the analysis is validated via simulation. Also, the power consumptions of cascaded-CCA are also compared to both ED-only and PD-only CCA to prove the power efficiency of cascaded-CCA. To verify the efficiency of the proposed CCA method, cascaded-CCA is applied to IEEE 802.11, as a representative example of networks that require continuous channel sensing and IEEE 802.15.4, of those that do not require continuous sensing. The performances of cascaded-CCA are compared to the standard ED-only and PD-only CCA methods. For the network with continuous channel sensing such as IEEE 802.11, the proposed cascaded-CCA reduces idle energy consumption significantly. For networks without continuous channel sensing requirement such as IEEE 802.15.4, provides a means to smoothly trade-off energy consumption for throughput and vice-versa and choose the optimum combination for best MAC performance at all packet arrival rates. Performance of the cascaded-CCA is investigated in cognitive network scenario where IEEE 802.11-like primary network exists. The real implementation of the suggested cascaded-CCA is considered as future works.

References

[1] S. Kumar, V.S. Raghavan, J. Deng, "Medium Access Control Protocols for Ad hoc Wireless Networks: a Survey," *Ad-Hoc Networks (Elsevier)*, vol. 4, no. 3, pp. 326-358, May 2006. Article (CrossRef Link)

[2] C. Cormiob, K.R. Chowdhurya, "A Survey on MAC Protocols for Cognitive Radio Networks," *Ad-Hoc Networks (Elsevier)*, vol. 7, pp.1315-1329, 2009. Article (CrossRef Link)

[3] K. Mariam, J. Nihar, Ø. Geire, "Improving the Performance of Wireless Ad Hoc Networks Through MAC Layer Design", *IEEE Transactions on Wireless Communications*, vol. 10, no.1, pp. 240-252, 2011. Article (CrossRef Link)

[4] I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, "Next Generation / Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey," *Computer Networks*, vol. 50, pp. 2127-2159, Sep. 2006. Article (CrossRef Link)

[5] T. Yucek, H. Arslan, "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications," *IEEE Communications Surveys & Tutorials*, vol. 10, no. 1, pp. 116-130, 2009. Article (CrossRef Link)

[6] A. Sahai, N. Hoven, R. Tandra, "A Review on Spectrum Sensing for Cognitive Radio: Challenges and Solutions," *EURASIP Journal on Advances in Signal Processing*, 15 pages, 2010. Article (CrossRef Link)

[7] L. Kleinrock, F.A. Tobagi, "Packet Switching in Radio Channels: Part I-Carrier Sense Multiple-Access Modes and their Throughput-Delay Characteristics," *IEEE Transactions on Wireless Communications*, vol. 23, pp. 1400-1416, Dec.1975. Article (CrossRef Link)
[8] ANSI/IEEE Std. 802.11, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specification: Higher Speed Physical Layer Extension in the 2.4 GHz Band," Sep. 1999. Article (CrossRef Link)
[9] F. Cali, M. Conti, E. Gregori, "Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit," *IEEE/ACM Trans. Networking*, vol. 8, no. 6, pp. 785-799, Dec. 2000. Article (CrossRef Link)
[10] W. Ye, J. Heidemann, D. Estrin, "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks," *IEEE Trans. on Networking*, vol. 12, no. 3, pp. 493-506, June 2004. Article (CrossRef Link)
[11] IEEE Std. 802.15.4, "Part 15.4: Wireless Medium Access Control and Physical Layer Specifications for Low Rate Wireless Personal Area Networks," 2006. Article (CrossRef Link)
[12] I. Ramachandran, S. Roy, "On the Impact of Clear Channel Assessment on MAC Performance," *IEEE Globecom*, Dec. 2006. Article (CrossRef Link)
[13] K. Schwieger, A. Kumar, G. Fettweis, "On the Impact of the Physical Layer on Energy Consumption in Sensor Networks," in *Proc. of the Second European Workshop*, pp. 13-14, Jan. 2005. Article (CrossRef Link)
[14] J.G. Proakis, "Digital Communications," McGraw Hill, 2001.
[15] B. Chen, K. Jamieson, H. Balakrishnan, R. Morris, "Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks," in *Proc. of International Conference on Mobile Computing and Networking*, pp. 85-96, July 2001. Article (CrossRef Link)
[16] I. Ramachandran, S. Roy, "Clear Channel Assessment in Energy constrained Wideband Wireless Networks," *IEEE Wireless Communications Magazine*, pp. 70-78, June 2007. Article (CrossRef Link)
[17] B. Bougard, F. Catthoor, D. Daly, A. Chandrakasan, W. Dehaene, "Energy efficiency of the IEEE 802.15.4 Standard in Dense Wireless Microsensor Networks: Modeling and Improvement Perspectives," in *Proc. of IEEE DATE 2005*, pp. 196-201, Mar. 2005. Article (CrossRef Link)

Soo Young Shin was born in 1975. He received his B.S., M.S., and Ph. D degrees in Electrical Engineering and Computer Science from Seoul National University, Korea in 1999, 2001, and 2006, respectively. He was a visiting scholar in FUNLab at University of Washington, US, from July 2006 to June 2007. After 3 years working in WiMAX design lab. of Samsung Electronics, he was appointed as full-time lecturer in Kumoh National Institutue of Technology on September 2010. His research interests include wireless LAN, WPAN, WBAN, wireless mesh network, sensor networks, coexistence among wireless networks, cross-layer methodology, cognitive radio networks, and mobile wireless broadband networks.

Iyappan Ramachandran received a B. E. (Hons.) degree from Birla Institute of Technology and Science, Pilani, India, and M. S. and Ph.D. degrees from the University of Washington, Seattle, all in electrical engineering in 2000, 2004, and 2006, respectively. He is at present a research engineer in the Signal Analysis Division of Agilent Technologies. His research interests are in UWB systems, acquisition/synchronization issues of wideband systems, and PHY-MAC cross-layer optimization.

Sumit Roy received the B.Tech. degree from the Indian Institute of Technology, Kanpur, in 1983, and the M.S. and Ph.D. degrees from the University of California at Santa Barbara, all in electrical engineering, in 1985 and 1988, respectively, as well as an M.A. in statistics and applied probability in 1988. His previous academic appointments were at the Moore School of Electrical Engineering, University of Pennsylvania, and at the University of Texas, San Antonio. He is presently Professor of Electrical Engineering at the University of Washington where his research interests include analysis and design of communication systems and networks, with a topical emphasis on next-generation mobile and wireless networks. Dr. Roy's activities for the IEEE Communications Society include membership of several technical committees, and he presently serves as an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS.