On the Impact of Clear Channel Assessment on MAC Performance

Iyappan Ramachandran, Sumit Roy
Department of EE, University of Washington, Seattle, WA 98105
Email: {iyappan, roy}@ee.washington.edu

***Abstract*— Clear Channel Assessment (CCA) is an essential ingredient in wireless networks employing channel sensing as part of their medium access mechanism. While CCA itself is implemented at the PHY layer, the primary impact of its performance/complexity is on MAC metrics like throughput and energy efficiency; this cross-layer dependency makes it necessary to enhance MAC protocol performance evaluation by considering the specifics of CCA implementation that are naturally link-dependant. We perform such a cross-layer evaluation of the impact of CCA on MAC performance for the specific case of IEEE 802.15.4 standard for WPANs and derive some heuristics to choose the type of CCA and its parameters based on traffic and channel conditions to realize improved MAC performance.**

I. INTRODUCTION

Several WLAN and WPAN standards use Carrier Sense Multiple Access (CSMA) as their *de-facto* medium access control protocol. CSMA works by making the nodes sense the channel for ongoing transmissions and letting them begin their own transmission only if the channel is found to be idle [1]. Channel sensing, referred to as *clear channel assessment* (CCA), is a PHY layer activity and is an essential ingredient of CSMA-based MAC protocols.

In narrowband wireless networks, CCA at any node is accomplished by detecting the presence of energy in the vicinity of the carrier by using a *non-coherent* energy detector. This works well because the signal power is concentrated in a narrow band around the carrier and considerably exceeds the noise floor (Fig. 1(a)). Hence in narrowband systems, CCA, carrier sensing (CS) and energy detection (ED) are all synonymous. Design of CSMA protocols and their analysis have been conducted largely for this class of wireless networks.

Many of current wireless networks are *wideband* by comparison (e.g. the channel bandwidth in IEEE 802.11 is 20 MHz); 'carrier sensing' (which is anyway a misnomer according to [2]) in such networks refers to *coherent detection* of signal presence, in contrast to the regular non-coherent integration of energy in the band of interest. While both CS and ED are mechanisms for CCA in wideband networks, there are significant differences between the two in terms of performance and complexity owing to the fact that the signal occupies a much wider bandwidth around the carrier and its power is not well above the noise floor (Fig. 1(b)).

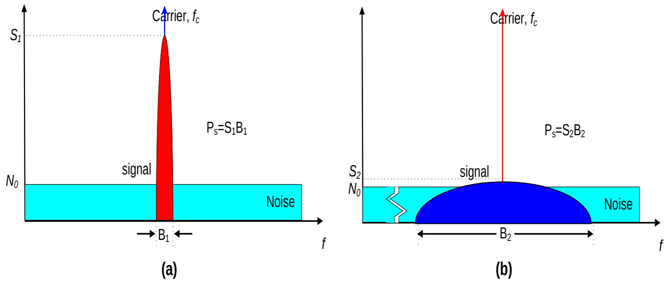

Fig. 1. Power spectra of (a) narrowband and (b) wideband signals with noise spectral density for the same signal power, P_S

Due to such differences, the choice of the wideband CCA method has considerable impact on MAC performance metrics such as throughput and energy efficiency. Often, the throughput and energy efficiency objectives are conflicting and achieving reasonable tradeoffs between the two requires a careful choice of the CCA method and its parameters. This cross-layer dependency has not been sufficiently explored in the literature with the exception of a few works [3], [4], [5]. There exists a need for enhanced cross-layer MAC protocol design by optimizing the underlying PHY CCA mechanism.

In this work, we take the particular case of a wireless personal area network using IEEE 802.15.4 and use it to thoroughly describe the effect of the PHY CCA on MAC performance. We also illustrate how an appropriate CCA method may be chosen and its parameters tuned based on traffic and channel conditions to realize optimized MAC performance and highlight the need for cross-layer considerations in the analysis and design of CCA and MAC.

The paper is organized as follows. In Section II, we describe the system under consideration. Section III contains the analytical derivation of the performance of the CCA modules and Section IV describes the impact of CCA on MAC performance. We make our some final remarks and conclude the paper in Section V.

II. SYSTEM DESCRIPTION

IEEE 802.15.4 [6] is a low-cost, low-power, low-rate PHY-MAC standard for WPANs intended for applications such as wireless sensor networks, inventory control, home automation, etc. The standard defines three physical layers, of which only one - for the 2.4 GHz band - resides in a globally allocated

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band. It provides a data rate of 250 kbps by using one of 16 pseudo-orthogonal PN codes of length 32 chips to represent 4 bits of information. The MAC layer supports both star and peer-to-peer topologies and can operate in beacon-enabled or non-beacon-enabled mode. In the former, a coordinator transmits regular beacons and imposes a superframe structure consisting of an active period that is divided in to a contention-access period (CAP) and a contention-free period (CFP), and an inactive period. Medium access in the CAP is slotted-CSMA based.

When the MAC layer receives a packet to transmit it instructs the PHY to do CCA in two consecutive slots. If the channel is found to be idle in both these slots, the node goes ahead with its transmission. Otherwise, the node attempts CCA again after a random backoff, which it repeats a certain number of times before reporting an access failure to the upper layer.

The standard specifies that the CCA duration shall be 8 symbol periods or 128 μs and that it can be done either by means of energy detection or carrier sensing, which is defined as the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. Other than that, there is considerable freedom in choosing an appropriate CCA method and its parameters to suit the requirements of the application under consideration. The CCA methods vary greatly in their ability to detect signal presence reliably and in their power consumption. Consequently, the particular choice of the CCA method has a considerable impact on the performance of MAC layer metrics such as throughput and energy efficiency. Often, these metrics are contradictory and require careful optimization of CCA parameters to attain a reasonable tradeoff.

To illustrate this trade off, in the next section we describe three possible implementations of the CCA module: an energy detector and two variations of carrier sensing. Our system model consists of an IEEE 802.15.4 PAN with star topology operating in the beacon-enabled mode with the superframe consisting only of the CAP. Since our intention is to study the impact of CCA, we consider an up-link only scenario; the nodes are typically in sleep mode and wake up occasionally to transmit their packets or to receive regular beacons from the coordinator. In other words, the responsibility of CCA is confined to determining the nature of the channel to facilitate its own transmission and not to detect the arrival of an incoming packet.

A. *Structures of CCA modules*

The three CCA structures we consider are (1) energy detector, that looks for received power above threshold without regard for the nature of the signal, (2) preamble detector, that indicates channel busy only on detecting an 802.15.4 preamble and (3) decorrelation-based detector, that looks for certain spreading characteristics of an 802.15.4 signal and not just the preamble. These three modules will provide us with a sufficiently large parameter space to tune for optimum MAC performance under varying channel and traffic conditions.

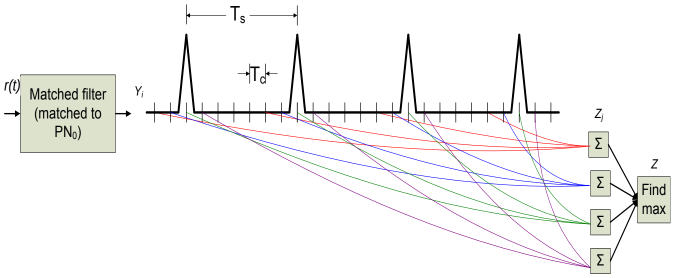

Fig. 2. Illustration of CCA using Preamble Detection

1) Energy Detector: The energy detector is a simple non-coherent module, that simply integrates the square of the received signal if implemented in analog domain and sums squares of its samples if implemented digitally. In particular, the energy detector consists of a quadrature receiver with x_{I_i} and x_{Q_i} representing the samples of the signals on the I and the Q branches respectively. It works by comparing the decision variable, $Y = \sum_{i=1}^{N}(x_{I_i}^2 + x_{Q_i}^2)$ to a threshold Υ, where $N = 8 \times 32$ is the length of 8 symbol durations assuming chip rate sampling.

The main advantage of the energy detector is its simplicity. Equally important is the fact that it need not be kept running constantly and can be turned on just when the MAC layer requests the PHY for a CCA, allowing the radio to sleep for extended periods. The downside is that since the ED does not take advantage of the processing gain inherent in 802.15.4 signals, it sees a low SNR, causing it to have low reliability.

2) Preamble Detector: All IEEE 802.15.4 packets contain a preamble consisting of 8 repetitions of the PN code PN_0 corresponding to symbol 0. This characteristic may be used to detect presence of 802.15.4 packets, resulting in a carrier sensing method called preamble detection (PD). In order to detect the preamble, it is required that the receiver acquire code synchronization with the received packet. A preamble detector consists of a quadrature receiver containing a digital matched filter each in the I and the Q branches matched to PN_0, whose outputs are represented by Y_{I_i} and Y_{Q_i} respectively. The preamble detector adds 8 Y_i's each separated by a symbol duration to get Z_j corresponding to an offset j, where $Y_i = Y_{I_i}^2 + Y_{Q_i}^2$, i.e. $Z_j = \sum_{i=1}^{8} Y_{32(i-1)+j}$. Z_j represents the correlation of the received signal over 8 symbol durations at a time offset of j. The decision variable Z is obtained by determining the maximum of Z_j over the 32 offsets, i.e. $Z = \max_{j=1..32} Z_j$. Preamble detection is depicted in Fig. 2.

Since preamble detection takes full advantage of the processing gain resulting from the use of spreading as well that from the repetition of known symbols in the preamble, it sees a much higher signal-to-noise ratio than energy detection. Consequently, it detects signal presence very reliably. However, the matched filters used for preamble detection have to operate at chip rate (or faster) owing to the lack of code synchronization and hence are quite power hungry. The biggest disadvantage of preamble detection is the requirement that it be constantly

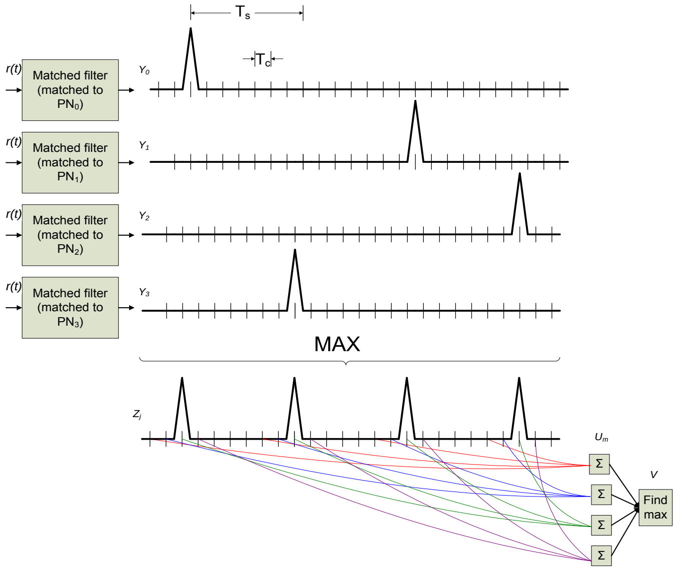

Fig. 3. Illustration of Decorrelation-based CCA

running; when the PHY is requested to do a CCA within 8 symbol durations, it does not have the liberty to do a preamble detection since the channel may be occupied with a packet whose preamble has elapsed at the time of CCA request.

3) Decorrelation-based CCA: A third alternative is to do a coherent signal detection without relying on the preamble, a method we call decorrelation-based CCA. Each symbol in a 802.15.4 packet is transmitted using one of 16 known PN codes. Decorrelation-based CCA works by using 16 quadrature receivers, the i^{th} one of which contains two matched filters matched to PN$_i$. At each sampling instant k, the module forms $Y_{ik} = Y_{I_{ik}}^2 + Y_{Q_{ik}}^2$ and $Z_k = \max_{i=1..16} Y_{ik}$ over the 16 correlators. Then 8 Z_k's each separated by a symbol duration are added to form new variables $U_m = \sum_{i=1}^{8} Y_{32(i-1)+j}$ for 32 code offsets, $m = 1..32$. Finally, the decision variable V is formed by finding the maximum of U_m over the 32 offsets, i.e. $V = U_m$. This procedure is shown pictorially in Fig. 3.

Decorrelation-based CCA uses all of the 16 pairs of matched filters for signal detection; although this does not add extra complexity as the correlators are already present in the receiver, they put an enormous burden on the receiver in terms of the power consumption as each of the matched filters has to operate at chip rate to attain code synchronization. The upside is that the CCA method takes advantage of the processing gain due to spreading and more importantly, it is capable of signal detection anywhere in the packet and not just the preamble and therefore does not have to be kept constantly running unlike the preamble detector.

III. PERFORMANCE OF THE CCA MODULES

There are two primary performance metrics of the CCA modules: P_D-P_{FA} and power consumption. The probability of detection P_D and false alarm P_{FA} are the probabilities that the receiver detects a busy channel correctly to be busy and an idle channel incorrectly to be busy, respectively. There is an inherent tradeoff between these two probabilities which can be realized by varying the detection threshold Υ.

A. Detection and false alarm probabilities

1) Energy Detector: In an AWGN channel in the absence of a signal, each x_{I_i} and x_{Q_i} has a normal distribution with zero mean and variance σ^2. Thus, $Y = \sum_{i=1}^{N}(x_{I_i}^2 + x_{Q_i}^2)$ has a central chi-square distribution with $2N$ degrees of freedom, with $N = 8 \times 32$. The probability of false alarm is then

$$P_{FA}^{ED} = 1 - F_{\chi}\left(\frac{\Upsilon}{\sigma^2}, 2N\right) \tag{1}$$

where $F_{\chi}(x, v)$ is the cdf of a standard chi-square random variable with v degrees of freedom. In the presence of a signal with an $E_c N_0$ ratio of $\gamma = a^2/\sigma^2$, Y has a non-central chi-square distribution with a non-centrality parameter of $s^2 = Na^2$. Therefore the probability of detection is given by

$$P_D^{ED} = Q_N\left(\frac{s}{\sigma}, \frac{\sqrt{\Upsilon}}{\sigma}\right) = Q_N\left(\sqrt{N\gamma}, \sqrt{\frac{\Upsilon}{\sigma^2}}\right) \tag{2}$$

$Q_m(\cdot, \cdot)$ is the generalized Marcum-Q function of order m.

2) Preamble Detector: In the absence of a signal, the outputs of the matched filters on the I and Q branches, Y_{I_j} and Y_{Q_j} are zero-mean Gaussian random variables with a variance of $32\sigma^2$. $Y_i = Y_{I_i}^2 + Y_{Q_i}^2$, is thus chi-square distributed with 2 degrees of freedom and Z_j has a central chi-square distribution with 16 degrees of freedom. The decision variable, $Z = \max_{j=1..32} Z_j$ determines the probability of false alarm.

$$P_{FA}^{PD} = 1 - F_Z\left(\frac{\Upsilon}{32\sigma^2}\right) = 1 - \left(F_{\chi}\left(\frac{\Upsilon}{32\sigma^2}, 16\right)\right)^{32} \tag{3}$$

In the presence of a signal with an $E_c N_0$ ratio of $\gamma = a^2/\sigma^2$, at the correct offset Z_j has a non-central chi-square distribution with non-centrality parameter $s^2 = 8 \times (32a)^2$, while at other offsets it has a central chi-square distribution. Therefore the probability of detection is given by

$$P_D^{PD} == 1 - Q_8'\left(\sqrt{N\gamma}, \frac{\sqrt{\Upsilon}}{\sqrt{32}\sigma}\right) F_{\chi}\left(\frac{\Upsilon}{32\sigma^2}, 16\right)^{31} \tag{4}$$

where $Q_m'(a, b) = 1 - Q_m(a, b)$.

3) Decorrelation CCA: In the absence of a signal, the outputs of the i^{th} matched filters at the k^{th} sample $Y_{I_{ik}}$ and $Y_{Q_{ik}}$ are zero-mean Gaussian with variance $\varsigma^2 = 32\sigma^2$. $Y_{ik} = Y_{I_{ik}}^2 + Y_{Q_{ik}}^2$, is chi-square distributed with 2 degrees of freedom. Now, $Z_k = \max_{k=1..16} Y_{ik}$ has the following cdf

$$F_{Z_k}(z_k) = F_{Y_{ik}}(z_k)^{16} = \left(1 - \exp\left(\frac{-x}{2\varsigma^2}\right)\right)^{16} \tag{5}$$

and its characteristic function is given by

$$\psi_{Z_k}(j\nu) = \prod_{l=0}^{15} \frac{(l+1)}{l + 1 - 2j\nu \times 32\sigma^2} \tag{6}$$

The distribution of U_m, obtained as the sum of 8 mutually independent Z_k's, is $f_{U_m}(u_m) = \mathfrak{F}_{u_m}^{-1}\left[\psi_{Z_k}(j\nu)^8\right]$, where $\mathfrak{F}_{u_m}^{-1}$ denotes the inverse Fourier transform. Now, the decision

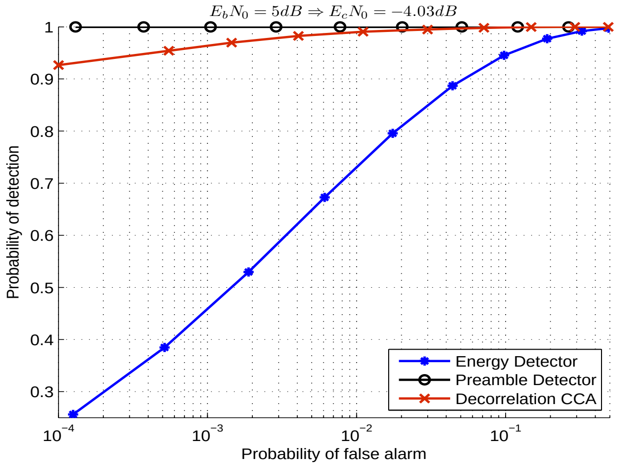

Fig. 4. Receiver operating characteristics of ED, PD and decorrelation based CCA in IEEE 802.15.4 at post-detection SNR=5dB

variable $V = \max_{m=1..32} U_m$ has the cdf $F_V(v) = F_{U_m}(v)^{32}$ and the probability of false alarm is then

$$P_{FA}^{decor} = 1 - F_V(\Upsilon) = 1 - F_{U_m}(\Upsilon)^{32} \tag{7}$$

In the presence of a signal with an E_cN_0 ratio of $\gamma = a^2/\sigma^2$, at the correct offset, one of the Y_{ik}'s has a non-central chi-square distribution with two degrees of freedom and non-centrality parameter of $s^2 = (32a)^2$ and the others are central chi-square distributed, while at other offsets all Y_{ik}'s have a central chi-square distribution. Therefore at the correct offset, Z_k has cdf

$$F_{Z_k}(z_k) = \left(1 - Q\left(\sqrt{32\gamma}, \frac{\sqrt{z_k}}{\varsigma}\right)\right)\left(1 - \exp\left(-\frac{z_k}{2\varsigma^2}\right)\right)^{15} \tag{8}$$

while at other offsets, its cdf is the same as (5). The distribution of U_m is again $g_{U_m}(u_m) = \mathfrak{F}_{u_m}^{-1}\left[\psi_{Z_k}(j\nu)^8\right]$, where $\psi_{Z_k}(j\nu)$ is the characteristic function of Z_k, which is that of (8) for the correct offset and (6) for other offsets. The detection probability is then given by

$$P_D^{decor} = 1 - G_{U_m}(\Upsilon)F_{U_m}(\Upsilon)^{31} \tag{9}$$

where $F_{U_m}(\Upsilon)$ is obtained from (6).

4) Receiver Operating Curves: For each of the CCA methods, the receiver operating characteristic showing the P_D and P_{FA} values obtained by varying the receiver threshold Υ are shown in Fig. 4 for a post-detection E_bN_0 ratio of 5 dB which translates to a pre-detection E_cN_0 ratio of -4.03 dB. It is clear from the figure that preamble detection based CCA offers the best P_D owing to the fact that it takes full advantage of the processing gain resulting from the repetition of known symbols in the preamble. The energy detector measures only the signal power level without looking for any known structures and consequently suffers the worst P_D among the three CCA methods. In fact, at $P_{FA} = 10^{-3}$, P_D is below 0.5. Decorrelation based CCA, on the other hand, takes partial advantage of the processing gain resulting from spreading and has an intermediate performance.

B. *Power consumption*

Accurate models for power consumption of the CCA modules are not available; neither are representative numbers revealed in data sheets. We therefore resort to certain heuristic arguments to arrive at reasonable numbers for the power consumption of the three CCA modules. 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 half of the power consumption in receive state. A preamble detector has two matched filters 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. Thirdly, since the decorrelation-based CCA requires multiple matched filters to be operational simultaneously, its power consumption is estimated to be a few times, say twice that in receive state. The power consumption of a CCA module combined with the duration of time that it is kept on determines its energy consumption, which is a more relevant metric as we will see in Section IV.

The three methods of CCA presented in the previous subsections provide us with ways to trade off performance for power consumption and thus explore the possibility of choosing the right mix of these parameters to realize improved MAC performance based on traffic and channel conditions.

IV. IMPACT OF CCA ON MAC PERFORMANCE

False alarm that occurs with probability P_{FA}, prevents an otherwise possible transmission and thus causes underutilization of the channel. On the other hand, missed detection that occurs with probability $1 - P_D$ causes a node to transmit when a different transmission is underway thus causing a collision. Both these factors detrimentally affect the channel throughput defined as the fraction of time that the channel is occupied with successful transmissions. Therefore, it is imperative that these probabilities be kept low.

The effect of CCA on MAC energy consumption is not as straightforward. There is usually a tradeoff between the P_D-P_{FA} performance of a CCA module and its energy consumption. While the energy detector causes energy to be wasted due to its poor P_D-P_{FA} performance, the CCA itself is low power and added to the fact that it need not be kept always on, it has very little energy overhead. Preamble detector represents the other extreme in that although it is near perfect in its P_D-P_{FA} performance, it puts an enormous energy burden on the node. In order to simultaneously capture the effect of CCA on throughput and energy consumption, we use as our performance metric *bytes-per-Joule capacity* defined as the number of bytes successfully transmitted by a node at the expense of one Joule of energy.

We have in our previous work [7] analyzed the performance of IEEE 802.15.4 MAC without carrier sense imperfections. In order to evaluate the effect of CCA imperfections, we ran a full 802.15.4 simulator with each of the three CCA methods. For our simulations we used M=12 nodes connected to a coordinator in a star topology and each generating packets of size N=10 backoff slots at a Poisson rate for the coordinator.

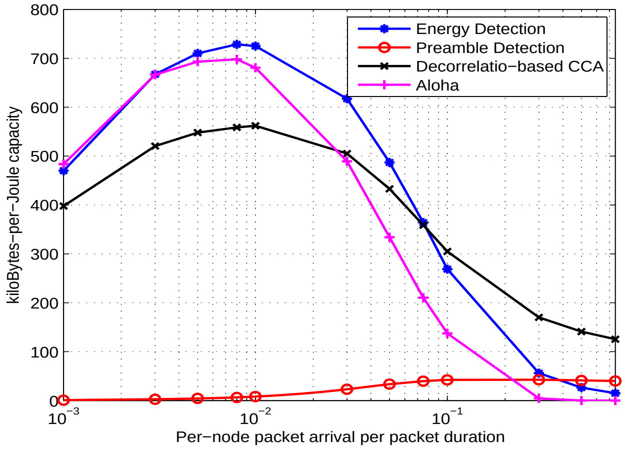

Fig. 5. Bytes-per-Joule capacity of IEEE 802.15.4 MAC versus packet arrival rates for different CCA methods at SNR=5dB and $P_{FA} = 10^{-3}$

A superframe of length 0.9988s has been considered, the whole of which is active and contains only the CAP. The parameters of the radio used for simulations were obtained from Chipcon 802.15.4 radio CC2400 [8], which has four energy states, transmit, receive, idle and sleep with respective power consumptions of P_{tx}, P_{rx}, P_{idle} and P_{sleep}. We introduced an extra state, the CCA state with a power consumption of P_{cca}, to capture the difference in power consumptions among the CCA methods and estimated its value to be $P_{rx}/2$, P_{rx} and $2P_{rx}$ for the energy detector, preamble detector and decorrelation-based CCA respectively.

The results of our simulations are shown in Fig. 5 in which the bytes-per-Joule capacity is plotted against the packet arrival rate at a post-detection E_bN_0 of 5 dB for the three CCA modules with the decision threshold adjusted for $P_{FA} = 10^{-3}$. The plot shows that the energy detector outperforms the other CCA methods at low packet arrival rates. At these rates, the energy consumption of the CCA module has a more telling effect on the metric than P_D. Preamble detection, in spite of its favorable P_D, is bogged down by its excessive energy consumption arising from its requirement to stay constantly on and thus suffers very poor performance at low rates.

At moderate traffic rates, both P_D and the CCA energy consumption are equally important for MAC performance and consequently, decorrelation-based CCA that has moderate P_D and energy consumption proves to be a good choice. At high packet rates the figure shows that preamble detection overtakes energy detection and at rates close to saturation (not shown in figure), preamble detection would offer the best performance among the three CCA methods. At these rates, the smaller P_D values of energy detection causes collisions that severely bring down its performance. The performance of slotted-Aloha protocol is also shown in the figure for comparison purposes. It is important to note that CSMA offers better performance than Aloha only if the CCA method and its parameters are chosen carefully based on the channel and traffic conditions.

Based on the above observation, a simple heuristic for the choice of the CCA method may be derived: choose energy detection for very sparse traffic, preamble detection for near-saturation traffic and decorrelation-based CCA when the network is moderately loaded. A similar heuristic to tune the decision threshold of the chosen CCA module may be to favor lower false alarm at low traffic rates and higher probability of detection at higher rates. By making the PHY layer CCA parameters adaptive to network traffic rates, cross-layer design can improve MAC performance significantly.

One may similarly derive a SNR-dependent heuristic to favor ED at large SNRs and PD at very small SNRs. More specific directives for parameter tuning would require more detailed analysis/modeling of MAC performance in terms of SNR, threshold and packet arrival rate.

V. CONCLUSIONS

We have shown, with the example of IEEE 802.15.4, the inter-dependency that exists between PHY CCA and MAC performance. We have evaluated MAC performance in terms of an upper layer parameter namely, the packet arrival rate and PHY layer parameters such as signal-to-noise ratio, carrier sense threshold and CCA power consumption. This analysis paves the way for a truly cross-layer protocol design that is cognizant of and adaptive to varying traffic conditions and channel noise levels.

A similar evaluation would prove particularly useful for ultra-wideband networks such as IEEE 802.15.4a in which the impact of CCA would be much more pronounced. ED is virtually impossible owing to the ultra-low signal power levels and PD takes a very long time due to the need for code acquisition. In such cases, one has to choose between decorrelation-based CCA and plain Aloha. An intelligent cross-layer design of MAC and CCA would result in significantly improved performance. In fact, the IEEE 802.15.4a working group is currently deliberating this issue of CCA for the UWB PHY.

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