CLEAR CHANNEL ASSESSMENT IN ENERGY-CONSTRAINED WIDEBAND WIRELESS NETWORKS

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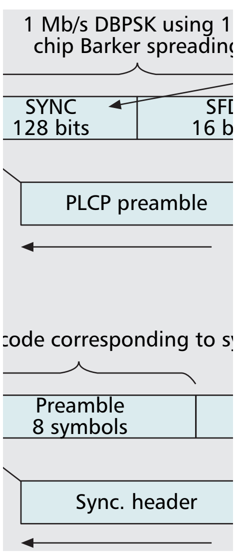


The authors provide a description of CCA methods for wideband wireless networks such as IEEE 802.11 and IEEE 802.15 followed by illustrations of their impact on the respective MAC protocols.

ABSTRACT

This is intended as a tutorial review of the clear channel assessment (CCA) component of typical data link layers in *wideband* wireless networks that employ some form of channel sensing as part of their medium access mechanism. While channel sensing — the core component within CCA module — is implemented at the physical layer, its primary impact is on MAC throughput and energy efficiency, and this impact has not yet been adequately highlighted in the existing literature. We provide a description of CCA methods for wideband wireless networks like IEEE 802.11 and IEEE 802.15 followed by illustrations of their impact on the respective MAC protocols. We also demonstrate the need for a cross-layer consideration of MAC and CCA to optimize the performance of CSMA protocols.

INTRODUCTION

Multiple access schemes have the important responsibility of allocating network resources fairly and efficiently among many users desiring access to a shared communication medium. Random access methods that operate in a distributed manner have been a staple of packet-switched systems for their simplicity. In order to improve efficiency of such schemes, the notion of carrier sense multiple aaccess (CSMA) was introduced [1]. In CSMA, a node with a packet to transmit *listens* for activity in the channel and begins its transmission only if it finds the channel to be idle; otherwise, it defers transmission to a later time. This characteristic of random access is sometimes referred to as *listen before talk* (LBT) or *detect and avoid* (DAA) and is considered a critical component of wireless medium access control (MAC) design toward meeting the challenge of network scalability (increasing aggregate throughput with user density).

CSMA was initially developed for wired LANs, wherein sensing the channel state is, relatively speaking, straightforward. The shared wired medium or bus suffers from low levels of thermal noise with little signal attenuation, implying that any transmission from a single node could be reliably detected by all other nodes; that is, all nodes are effectively in a single-hop neighborhood of each other (broadcast channel assumption). Furthermore, the event of multiple simultaneous transmissions (or collisions) on the channel can also be reliably detected by all nodes, by comparing the net measured power to a preset threshold. This collision detection (CD) mechanism allows the transmitting nodes to abandon their current transmissions and reattempt at a later time. This principle (CSMA/CD) formed the basis of the eminently successful wired Ethernet LAN standard (IEEE 802.3).

Application of CSMA in wireless networks faces fundamentally different challenges from their wired counterparts in several significant ways. First, signals between a source and destination pair undergo significant attenuation of received power in the medium dictated by the node separation. Consequently, not all nodes in the network can sense each other's transmission; in power constrained networks, this naturally leads to multihop operation. Second, the wireless medium is susceptible to interference and is hence inherently very noisy. Third, current wireless systems operate in a half-duplex manner (i.e., they cannot transmit and receive simultaneously), which effectively prevents collision detection.

Due to the above differences, some variants of CSMA methods have been devised to suit the wireless environment. For example, since wireless terminals do not have CD capability, 802.11 nodes employ collision avoidance by introducing random backoff for the terminals *before* beginning their transmissions (CSMA/CA). Similarly, use of reservation packets (request/clear to send, RTS/CTS) or *virtual carrier sensing* is also a popular method to alleviate the *hidden node* problem (inability of a node to hear some others' transmissions) [2]. Nevertheless, the design and analysis of CSMA-based MAC protocols for wireless networks have been done with the assumption that the underlying channel sensing activity for wireless networks is the same as wired networks. While this assumption is largely

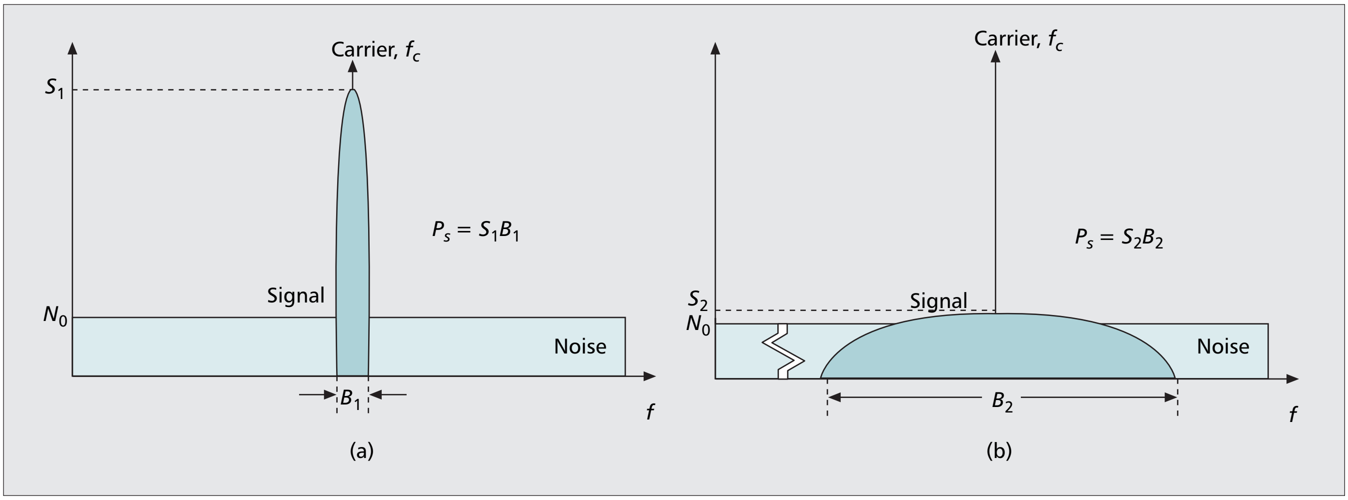


Figure 1. *Power spectra of: a) narrowband and b) wideband signals with noise spectral density for the same signal power,* P_S.

valid for narrowband wireless networks, it requires revisiting as wireless networks' bandwidth increase (as is occurring with each new generation of such networks).

Channel sensing in wideband wireless networks is a much more complex operation and suffers from several imperfections owing to the shared multi-access and strongly attenuating nature of the wireless channel. The wideband nature of signals itself makes reliable detection of transmissions difficult and necessitates use of complex and power-hungry channel sensing methods. Continuous channel sensing using such complex schemes drains significant battery resources and needs to be given serious consideration in wireless networks with power limited nodes. MAC protocols that do not take such crucial differences into account in their design tend to be sub-optimal. Similarly, analyses that do not consider the imperfections and overheads of channel sensing tend to lead to unrealistic predictions of MAC performance. It is thus necessary that wireless channel sensing methods be clearly understood, and their impacts on medium access protocols properly incorporated via suitable analytical and experimental [3] models.

Our focus in this article is to elucidate the various channel sensing options available for wideband wireless networks. Accordingly, we define clear channel assessment (CCA) as the generic label for the activity of channel sensing in this work.[1] Metrics for evaluating the performance of CCA methods are explained and their impact on MAC demonstrated. We illustrate the application of the CCA methods with a particular emphasis on IEEE 802.15.4 MAC for wireless personal area networks (WPANs). By highlighting the close interdependence between CCA and MAC, we bring out the need for a cross-layer approach to improve system performance.

[1] *The term "carrier sensing" is often used as being equivalent to CCA. Here, "carrier sensing" is specifically used to only imply a certain type of CCA in the context of wideband wireless networks.*

Methods of Clear Channel Assessment

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. A generic link layer CCA module uses a suitable time window of the received RF signal and produces a CCA BUSY/IDLE flag as a result of suitable algorithmic processing. We next delve into the link layer CCA methods in some detail.

CCA in Narrowband Systems: Energy Detection

In narrowband radio systems, the CCA operation can be performed by simply detecting the presence of energy at the carrier frequency, which is indicative of signal presence. Narrowband radio systems are characterized by a signal bandwidth-to-center frequency ratio (called the *fractional bandwidth*) typically less than 0.1 percent. In such systems, the bulk of the signal power is concentrated around the carrier frequency f_c. For a certain signal power P_S, the signal power spectral density S_1 is significantly higher than the noise floor N_0 as shown in Fig. 1a. Narrowband signal transmission can hence be detected via a non-coherent energy detection (ED) operation (integrating the square of the received signal or signal envelope over a suitable period) with sufficient reliability. It is important to note that 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 at the physical layer.

Energy Detection in Wideband Systems

Wideband systems, on the other hand, have fractional bandwidths of 1–5 percent and therefore for the same signal power P_S, the signal is spread much wider around the carrier frequency. The signal power spectral density is not significantly above the noise floor as shown in Fig. 1b. Ultra-wideband systems, which represent an extreme case of wideband systems, are characterized by fractional bandwidths of about 20 percent and

We reserve the term carrier sensing in the context of wideband networks to specifically indicate methods of coherent detection based on suitable signal properties to distinguish it from non-coherent energy detection. We denote general channel sensing as clear channel assessment and note that it may be done coherently using CS or non-coherently using ED.

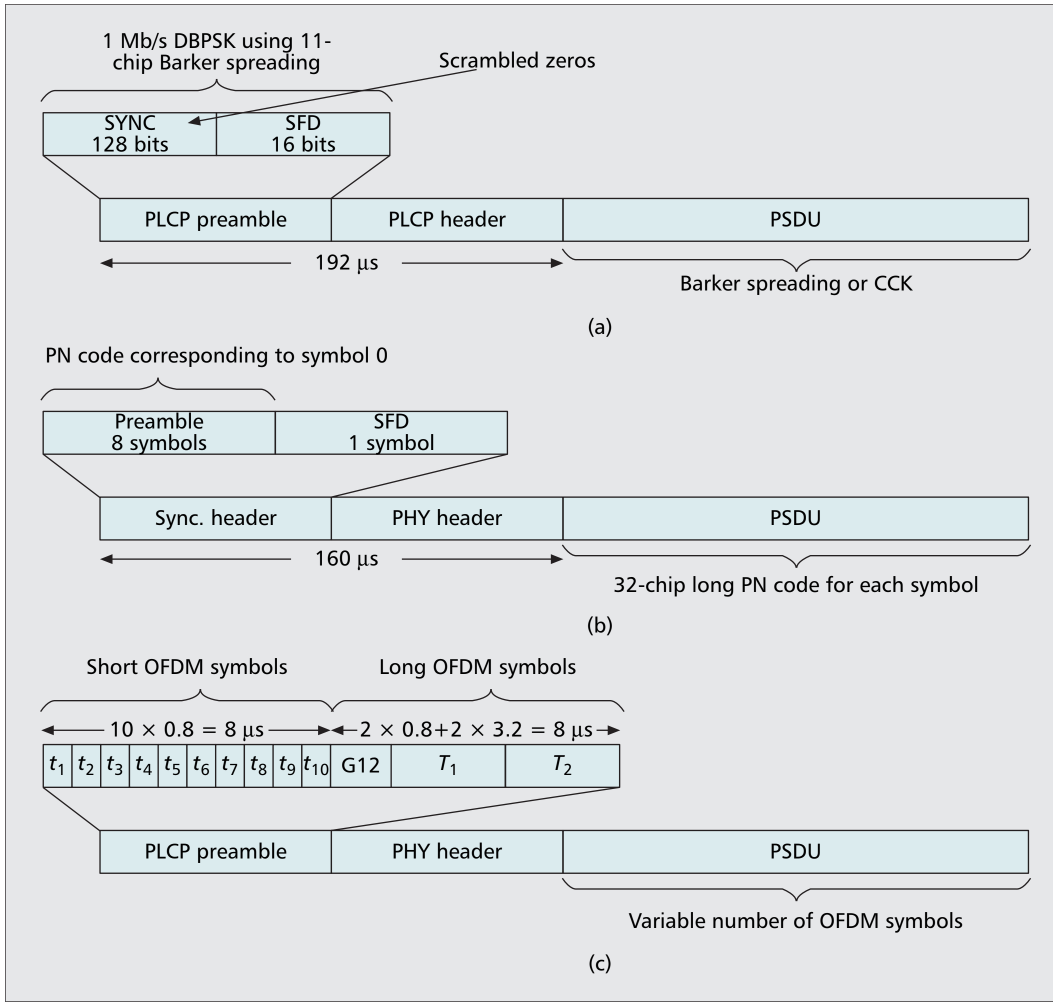


Figure 2. *Packet structures showing preambles of: a) IEEE 802.11b; b) IEEE 802.15.4; c) IEEE 802.11a.*

may have signal power levels well below the noise level. Wideband systems therefore must employ more reliable *coherent detection* methods to extract the wideband signal from noise at given (input) signal-to-noise ratio prior to demodulation. We thus reserve the term *carrier sensing* (CS) in the context of wideband networks to specifically indicate methods of coherent detection based on suitable signal properties to distinguish it from non-coherent energy detection. We denote general channel sensing as clear channel assessment (CCA) and note that it may be done coherently using CS or non-coherently using ED.

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 sequence is designed for a *near-ideal* autocorrelation property. 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 CS-based CCA using correlation of the known preamble with the received signal is called *preamble detection* (PD).

Preamble Structures in Current Systems — IEEE 802.11b [4] employs direct-sequence spread-spectrum (DS-SS) using a 11-chip Barker code for 1 and 2 Mb/s data rates. and complementary code keying (CCK) for 5.5 and 11 Mb/s. All 802.11b packets are preceded by a preamble consisting of 128 zeros, each spread using the 11-chip Barker code (Fig. 2a). For successful despreading/demodulation, the receiver performs code acquisition (time alignment of local pseudo noise [PN] code with that in the received signal) by running a filter matched to the PN code in the preamble and observing a peak indicating that the channel is busy.

IEEE 802.11a [5] uses orthogonal frequency-division multiplexing (OFDM) with the preamble in every packet consisting of 10 repetitions of a short OFDM symbol followed by two repetitions of a long OFDM symbol as shown in Fig. 2c. The receivers use the short OFDM symbols to acquire symbol timing by a time domain correlation of the received signal with the known time domain sequence of the short OFDM symbol, and thus detect signal presence.

IEEE 802.15.4 [6] uses one of 16 nearly orthogonal 32-chip long PN sequences to represent one of 16 symbols. All packets contain a preamble consisting of 8 repetitions of the PN code corresponding to the zero symbol (Fig. 2b). In all these systems, multiple repetitions of known symbol sequences in the preamble provide the receiver with sufficient processing gain for a more reliable decision about the presence of a signal. Non-coherent energy detection on the other hand does not take advantage of this processing gain and hence suffers from a poor signal-to-noise ratio leading to unreliable channel state decisions.

In summary, CCA in wideband systems is based either on CS/PD or by ED, with the former being more reliable. IEEE 802.11b standard specifies that the nodes be capable of doing CCA either by CS/PD or ED or a combination of both within 15 μs (15 repetitions of the Barker code). IEEE 802.15.4 nodes are also required to complete CCA using one of the three methods within 128 μs (8 symbol periods). IEEE 802.11a nodes, on the other hand, are required to employ *both* CS and ED methods to accomplish CCA within 4 μs (5 repetitions of the short OFDM symbol).

Energy Comparison: ED vs. PD

Although PD is capable of detecting signal presence with higher reliability, it has one primary disadvantage. A node seeking channel access undertakes CCA to determine channel state (busy/idle) at the instant when it becomes ready with a packet to transmit. However, when a node initiates CCA, the preamble of any ongoing transmission might already have elapsed and the channel may be occupied with the data payload. Thus, for PD based CCA, it is required that the CCA portion of the receiver be always on, so that any preamble on the air is detected immediately (channel busy). If the node becomes ready for its own packet transmission midway through an ongoing transmission, it can use the knowledge of the channel status from its already running CCA process to decide to defer its transmission.

Unfortunately, matched filters/correlators needed for PD are power hungry and running them continually would lead to significant energy drain. ED based CCA on the other hand, has a simple implementation and can be performed anywhere within a packet. Thus, although energy detection is less reliable, it is very amenable to an energy efficient implementation. The energy consumption — detection performance considerations of ED vs. PD is thus a fundamental tradeoff that must be considered in choice of CCA mechanism in (energy-constrained) wireless systems. Since energy efficiency is not a primary constraint in IEEE 802.11 standards, the 802.11 MAC has been designed such that nodes can receive packets destined for them at any time. They are therefore required to do CCA continually even if they do not have a packet to transmit, so as to ensure that packets destined for them are not missed.

Decorrelation-Based CCA

It would be desirable to combine the merits of PD and ED into a CCA scheme that can be done anywhere within a packet (not only the preamble), and that provides reliable detection without the attendant high energy consumption. Such a possibility exists in some wireless LAN (WLAN) and WPAN systems — *decorrelation based* CCA — that uses certain characteristic properties of the signal to detect presence anywhere in the packet more reliably than energy detection. This is particularly true for systems employing spread spectrum.

The main difference between the preamble and data portions of a packet is that the latter is modulated with unknown user data while the former consists of a sequence of known symbols. Symbol timing acquisition can still be achieved in the data portion of the packet and signal presence detected coherently if certain properties of the signal are exploited, a process called *blind acquisition*. The 2.4 GHz PHY of IEEE 802.15.4 for instance, uses one of 16 pseudo orthogonal PN codes of length 32 chips $\{PN_0, \ldots, PN_{15}\}$ to represent one of 16 symbols. Even without knowing the sequence of data symbols, the fact that these symbols are spread using a known fixed set of PN codes may be exploited to achieve code synchronization in principle by running 16 matched filters simultaneously, each matched to a different PN code. Similarly, in IEEE 802.11b, if the data rate employed is known to be 1 or 2 Mb/s, it may be possible to acquire symbol timing using a filter matched to the 11-chip Barker code. For 5.5 and 11 Mb/s, signal detection may be accomplished by running 16 or 256 correlators, respectively, simultaneously in the form of a fast Walsh transform. Even in the absence of knowledge about the data rate employed by the nodes in the system, CCA may be done by simultaneously running the Barker MF and Walsh transforms.

Admittedly, the lack of information about the modulating symbols would cause some loss in processing gain and a consequent drop in signal-to-noise ratio (SNR), resulting in a certain loss of reliability of CCA, but it is expected to still be more reliable than ED. Furthermroe, while running a multitude of correlators/matched filters for decorrelation-based CCA would mean enormous power consumption, these have to be on only for a short CCA duration due to its ability to perform CCA anywhere within the packet. The power consumption profile in this method is thus distinct from the constant drain for always-on preamble detection.

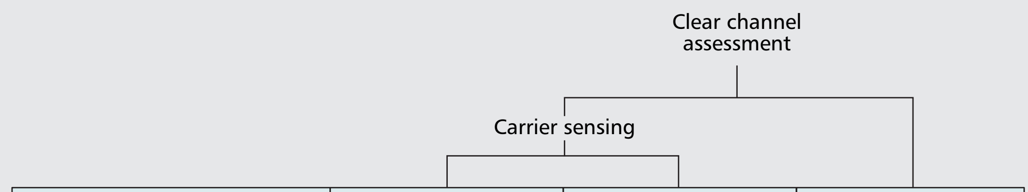
Thus, we categorize CCA as either using CS or ED; CS may further be classified as being PD-based or decorrelation-based. This categorization of CCA methods is depicted in Fig. 3, along with relative measures of their complexities and performances. The choice of the right CCA method for a particular application depends on its performance and impact on MAC, which we describe next.

Symbol timing acquisition can still be achieved in the data portion of the packet and signal presence detected coherently if certain properties of the signal are exploited, a process called blind acquisition.

CCA Performance Metrics and Impact on MAC Performance

All three CCA methods shown in Fig. 3 compare a test statistic to a suitably chosen threshold. That is, the output of the ED or CS module is

Throughput is a measure of how efficiently a multiple access protocol packs the channel and is defined as the fraction of time that the channel is used for successful transmissions. Channel idleness and collisions are the two factors that cause the throughput to drop.



	Preamble detection	Decorrelation based	Energy detection
Complexity/power consumption	Moderate	High	Low
Reliability	High	Moderate	Low
Position in packet	Preamble	Anywhere	Anywhere

Figure 3. *Flavors of clear channel assessment in wideband wireless networks with relative measures of complexity and performance.*

compared to a threshold, Γ_{th}, exceeding which results in the channel being declared busy; otherwise the channel is declared idle. The performance of a CCA method is characterized by two probabilities, those of correct detection, P_D and false alarm, P_{FA}. P_D and P_{FA} are the probabilities that a busy channel will be correctly detected as being busy and an idle channel will be incorrectly detected as being busy, respectively. The probabilities depend, among other things, on the SNR and the threshold. For a constant SNR, increasing the threshold decreases P_{FA} but decreases P_D (and vice versa), indicating a trade-off. For a constant threshold, however, increasing SNR simultaneously increases P_D and decreases P_{FA}.

P_D and P_{FA} have significant impact on MAC performance metrics. When the MAC layer gets a packet to transmit, it requests the PHY layer to perform a CCA. If the CCA indicates an idle channel, MAC directs the PHY to start transmitting the packet. If, on the other hand, a busy channel is indicated, MAC waits for a certain duration (called backoff) and requests another CCA. If a busy channel had been incorrectly detected by PHY as idle (with probability, $1 - P_D$), the ensuing transmission would cause a collision, thus destroying the node's own packet and any others on air (we ignore the capture effect for now). Similarly, if an idle channel had been incorrectly detected as being busy (with probability, P_{FA}), the node would postpone an otherwise possible transmission, and the channel would consequently go unutilized. Multiple access, as mentioned earlier, consists of efficiently and fairly packing the channel with transmissions. *Throughput* is a measure of how efficiently a multiple access protocol packs the channel and is defined as the fraction of time the channel is used for successful transmissions. Channel idleness and collisions are the two factors that cause the throughput to drop. P_{FA} and $(1 - P_D)$ cause channel idleness and collisions, respectively, thus detrimentally affecting MAC throughput.

In addition to P_D and P_{FA}, the effectiveness of a CCA method must also consider the power consumed in the process for energy constrained nodes. P_D, P_{FA}, and power consumption can be subsumed together in an alternate MAC performance metric, *energy efficiency* — the fraction of the total energy spent by a node on successful transmissions. Collisions caused by missed detection (which occurs with probability $(1 - P_D)$) result in energy being wasted in unsuccessful transmissions. False alarms that occur with probability P_{FA} cause MAC to back off unnecessarily and spend more energy in subsequent CCAs. The CCA mechanisms discussed in the previous section affect MAC energy efficiency to varying degrees because of their different power consumption characteristics and $P_D - P_{FA}$ performance. While the poor $P_D - P_{FA}$ performance of ED causes MAC energy efficiency to drop on one hand, its energy consumption causes very little overhead during CCA. Similarly, P_D would cause very little drop in MAC energy efficiency performance due to incorrect channel sensing, but causes significant energy to be spent in the CCA operation itself.

Clearly there is a trade-off between energy consumption and $P_D - P_{FA}$ performance in how it impacts MAC throughput and energy efficiency. The right balance between $P_D - P_{FA}$ performance and complexity has to be chosen with MAC layer performance in mind. In the next section we examine this trade-off by applying the three CCA methods to IEEE 802.15.4 MAC. For existing analysis of the effect of $P_D - P_{FA}$ on the throughput and energy efficiency performance of CSMA protocols, the reader is referred to [7–9].

An Illustration of CCA Methods in IEEE 802.15.4

IEEE 802.15.4 [6] is a low-data-rate PHY/MAC standard for low-cost low-power WPAN applications such as home automation, inventory control, and wireless sensor networks. The standard includes a PHY in the global industrial, scientific, and medical (ISM) 2.4 GHz band based on DS-SS, whereby 4 information bits are mapped to one of 16 nearly orthogonal 32-chip-long PN sequences. The IEEE 802.15.4 MAC supports star and peer-to-peer topologies with the network being beacon-enabled or non-beacon-enabled. In the former mode, communication is controlled by a coordinator that transmits regular beacons and defines a superframe. A superframe contains an active period for all communications, and an inactive period in which the nodes turn down their radios for power saving purposes. The active period in turn consists of a contention access period (CAP), in which channel access is based on slotted CSMA, and a contention-free period (CFP), in which the coordinator allots guaranteed time slots (GTSs) for nodes. Since the focus of our discussion is CCA for contention access, we concentrate exclusively on the CAP of the 802.15.4 superframe. For a detailed overview of the standard, please refer to [10].

CCA Implementation in IEEE 802.15.4

The 802.15.4 standard specifies that clear channel assessment may be performed using either energy detection or carrier sensing or a combination of the two. It further specifies that the CCA detection time is 8 symbol periods; that is, the PHY layer has to finish its CCA and report its findings to MAC within 128 μs. It is to be noted that a false alarm which prevents an otherwise possible transmission is detrimental to the node that commits it. On the other hand, missed detection that could potentially cause collisions is detrimental to the overall system performance. Therefore, most standards specify a minimum P_D to be met, but leave the choice of P_{FA} to the implementer. IEEE 802.15.4, however, imposes no requirements on either probability. This gives another degree of freedom to investigate possible trade-offs and determine the right $P_D - P_{FA}$ balance for the application under consideration.

We apply the three CCA methods — energy detection, preamble detection, and decorrelation detection — described earlier, and investigate the relative performance of each and its impact on MAC metrics.

• Energy detection consists of observing the channel for the CCA duration, squaring the received signal followed by integration if implemented in analog domain or summation in digital domain, and comparison to a suitable threshold to determine signal presence.

• Preamble detection uses a filter matched to the PN code corresponding to symbol zero; the output of the matched filter is summed over 8 symbol durations and the result compared to a threshold. Since the receiver does not have knowledge of the sampling instant, the input to the matched filter needs to be oversampled (by a factor of 4 or more), and the number of taps of the MF itself needs to have several multiples of the code length. Alternatively, multiple matched filters could be employed each with a time shift corresponding to fractions of the chip duration.

• Decorrelation detection uses a bank of 16 filters, each matched to one of the 16 PN codes. If Y_i^j represents the output of the jth matched filter at the ith sampling instant (assuming an oversampling factor of S), the decision variable is given by

$$Z = \max_{l=1..32\times S}\left(\sum_{k=1}^{8}\max_{j}\left(Y^{j}_{(k-1)\times 32\times S+l}\right)\right), \qquad (1)$$

which is compared to a decision threshold for signal detection. The 16 matched filters are already present in the receiver for data demodulation, so no extra hardware cost is incurred.

CCA Performance

The probabilities of detection and false alarm can be derived quite easily for AWGN channels using simple analytical arguments, and are shown graphically in Fig. 4 for the three CCA implementations at a post-detection SNR of 5 dB. The curves, called the receiver operating characteristics (ROC), are obtained by varying the detection threshold and give us the ability to compare the performance of the CCA methods. For details about the calculation of these probabilities, please refer to [11].

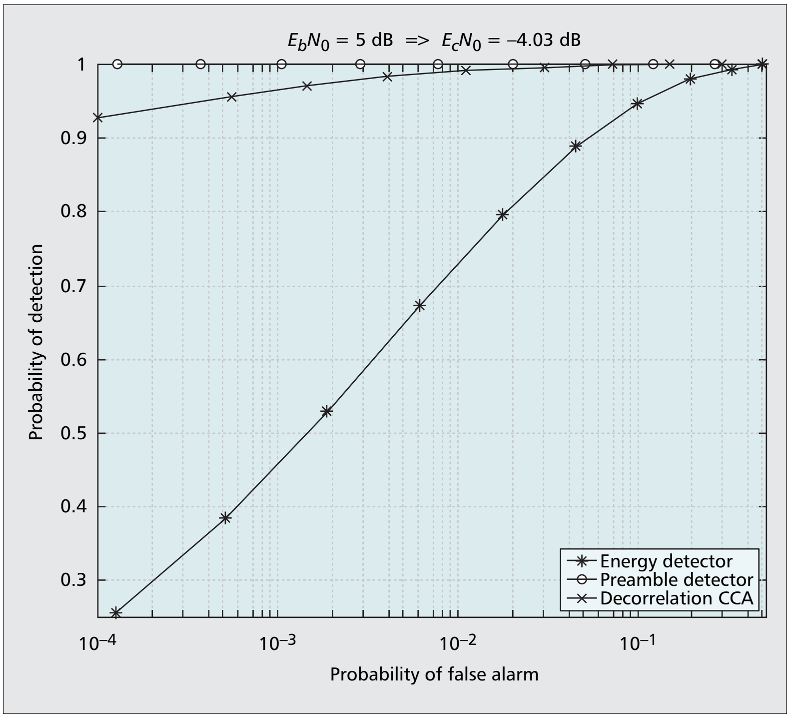


Figure 4. *Receiver operating characteristic of ED-, decorrelation-. and PD-based CCA in IEEE 802.15.4 at post-detection SNR = 5dB.*

It is seen from the figure that for a given P_{FA}, preamble detection has the best P_D and energy detection the worst. P_D takes full advantage of the coherent correlation gain of known preamble symbols. As expected, decorrelation detection provides intermediate performance — while it exploits the correlation gain, some loss in SNR results due to the unknown data modulation. While there are several ways to choose the threshold to achieve a desired $P_D - P_{FA}$ operating point, receivers usually base their threshold setting on constant false alarm rate (CFAR). During periods of channel inactivity, receivers average the channel power to determine the noise floor, which is used to set a threshold that will yield the predetermined P_{FA} ($10^{-2} - 10^{-3}$ are typical). The operating SNR then determines P_D.

Impact of CCA on IEEE 802.15.4 MAC Performance

To determine the impact of the CCA performance, we first used Matlab to determine P_D and P_{FA} for the three CCA methods by using the appropriate code sequences described in the IEEE 802.15.4 draft. These were then plugged into our ns-2 implementation of IEEE 802.15.4 MAC to determine the throughput and energy efficiency. Please refer to [12] for details of the ns-2 implementation.

For our simulations we used M = 12 nodes

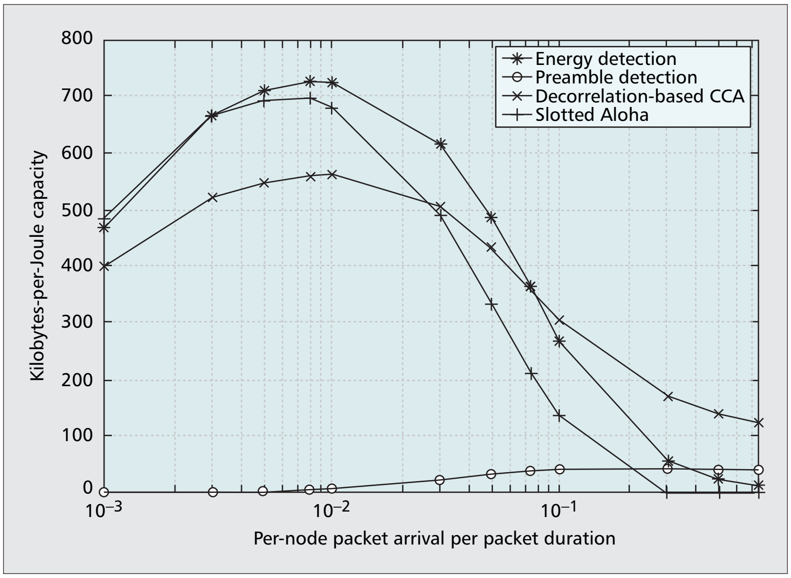


Figure 5. *Bytes-per-Joule capacity of IEEE 802.15.4 MAC using the ED, decorrelation and PD based CCA methods and slotted- Aloha at post-detection SNR = 5dB.*

transmitting to a coordinator in a star topology, each generating packets of size $N = 10$ backoff slots as a Poisson process. A superframe of length 0.9988 s was used, the whole of which is active and contains only the CAP. Since our intent is to observe the impact of CCA, we only consider uplink transmissions; that is, the nodes only transmit packets for the coordinator but do not receive anything other than beacons that arrive at fixed time slots.

The parameters of the radio used for simulations were obtained from Chipcon 802.15.4 radio CC2400 [13], 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 consumption among the CCA methods. Since exact models are not available for power consumption of the various CCA methods nor are such numbers revealed in data sheets, we have used some heuristic arguments to come up with reasonable estimates, as described next.

The fact that preamble detection requires only one matched filter compared to 16 in the normal receive state and that most of the other digital blocks are off during preamble detection causes P_{cca} using PD to be lower than P_{rx}. On the other hand, the oversampling and faster correlation requirements of preamble detection, due to the lack of knowledge about correct symbol boundary and sampling instant, cause the power consumption to be higher. It is reasonable to assume that these factors offset each other so that $P_{cca} = P_{rx}$ for PD. Note that the idle and sleep states are nonexistent when using preamble detection since the CCA module has to be always on. For decorrelation-based CCA, in addition to the oversampling and faster correlation requirements, 16 matched filters need to be running simultaneously. However, since the matched filters contribute only a part of the net power consumption in CCA mode, and the other contributors like the analog front and analog-to-digital converter (ADC) are common to all the receive and CCA states, the power consumption of decorrelation-based CCA is assumed to be $P_{cca} = 2 \times P_{rx}$. For energy detection, while neither the matched filters nor the digital baseband blocks need to be running, the analog front-end and ADC have to be; hence, we make $P_{cca} = P_{rx}/2$

The results of our simulation are plotted in Fig. 5 which shows the bytes-per-Joule capacity (defined as the number of bytes that a node can successfully transmit per Joule of energy) of IEEE 802.15.4 MAC using each of the three CCA methods as a function of the per-node packet arrival rate using CFAR with P_{FA} of 10^{-3}. The plot also shows the performance of slotted Aloha protocol, which does not use any CCA mechanism. Several key observations can be made from these results.

- Preamble-detection-based CCA provides the best P_D for a given P_{FA}, which helps it reach the highest throughput among the three CCA methods. However, the requirement that it be kept always on proves very costly in terms of power consumption; hence, its energy efficiency is intolerably low at low packet rates. At higher packet rates, its energy efficiency shows improvement and in fact at very high rates (close to saturation), it would overtake the other schemes in energy efficiency performance.
- Thanks to its very low power consumption, ED-based CCA provides the best energy efficiency at low packet rates. Although P_D can be as low as 0.5 for the P_{FA} chosen, the throughput performance does not suffer at low rates since collisions that are an artifact of P_D are relatively infrequent. As packet rate increases however, the effect of collisions become apparent and consequently throughput drops causing the energy efficiency to drop as well.
- In spite of its extremely high power consumption, decorrelation-based CCA shows a satisfactory performance. In fact, its throughput is very close to that of preamble detection. At higher packet arrival rates it overtakes ED in energy efficiency much earlier than PD.
- If the CCA method is not chosen appropriately, the MAC performance may end up being worse than not using any CCA at all, as in slotted Aloha.

In conclusion, it may be said that at very low packet rates, ED with an appropriately chosen P_{FA} is the best choice since P_D is not important. When the packet arrival rates are very high and throughput is an important consideration, one may choose PD as the CCA method. At intermediate rates, decorrelation-based CCA would be most appropriate if one desires no drop in throughput relative to PD and ED, and when energy efficiency is a priority.

CCA IN IEEE 802.15.4A

IEEE 802.15.4a is an alternative PHY extension to 802.15.4, being developed with the intent of providing high precision ranging and location capability, high aggregate throughput, low power, and low cost, and is based on time-hopping impulse radio (TH-IR) ultra-wideband (UWB) signaling [14]. UWB signals are characterized by very wide bandwidths and very low power spectral densities, causing the received power levels to be lower than noise power spectral density (i.e., the UWB pulses would be "buried" in noise). If an energy detector were employed for CCA, it would suffer from poor SNRs; thus, this is not an option. Since the standard targets low-power applications with sporadic traffic, preamble detection based CCA is not a good idea either because of its requirement to keep the CCA module running constantly.

Due to the very wide bandwidths used, code acquisition will most likely be done using analog serial correlators, which suffer from long acquisition times even in the presence of a preamble. Acquisition time would be much longer in the absence a preamble (i.e., in the data portion of a packet), so decorrelation-based CCA is not an option either. Due to the above factors, it has been concluded by the 802.15.4a WG members that CSMA is probably not a suitable medium access scheme, and the standard has resorted to the use of slotted Aloha, which requires no CCA [15]. Slotted Aloha yields good throughput performance at low rates, with no energy being wasted on CCA. At higher rates, however, there is a sharp drop in slotted Aloha throughput due to collisions. This has led to a proposal for an optional scheme that provides CCA functionality anywhere within a packet, by interspersing the data portion of the packet with known preamble like structures that a sensing node can look for. While this results in more packet overhead, it is conjectured that the CCA performance is sufficient to enhance aggregate system performance considerably under heavy loads. Interspersing of a preamble-like structure within data for CCA purposes will result in approaches akin to decorrelation-based CCA.

Cross-Layer Consideration of CCA and MAC

In wired and traditional narrowband wireless networks, MAC design and CCA implementation (which is considered a PHY responsibility) have been done independently in keeping with the philosophy of the layered architecture. In the foregoing sections, we have illustrated how the choice of CCA in wideband wireless networks affects MAC performance. In the presence of such interdependence, treating MAC and CCA independently leads to suboptimal designs. Significant performance gains can be realized by joint design of CCA and MAC (i.e., adopt a *cross-layer design* approach) [16].

We illustrate the significance of a cross-layer approach with the example of CCA threshold setting. We have seen that the CCA $P_D - P_{FA}$ performance is affected by SNR and CCA threshold. Adaptive threshold setting based on SNR is commonly implemented in today's radios (e.g., for constant false alarm rate) independent of MAC. We have also seen that the impact of the same $P_D - P_{FA}$ values on MAC performance varies significantly with traffic rate depending on the CCA method. At very low packet arrival rates, it may be more important to keep the P_{FA} low than to attempt to achieve high values of P_D. This is because false alarms that keep the radio running for longer than necessary would be more harmful than an occasional collision caused by a missed detection. As rates increase however, the balance may change and it may be more important to have a high probability of detection. *Adaptive threshold setting* algorithms which take into account both the SNR (PHY layer parameter) and the packet arrival rate (MAC and upper layer parameter) to arrive at a suitable balance between P_D and P_{FA} could result in significant performance gains, suggesting the benefits from a truly cross-layer design.

Similarly, analysis of MAC performance metrics need to be performed by taking the impact of CCA performance into account. Collisions happen not only when two devices start their transmissions at the same time, but also when they fail to detect other transmissions. Considering that different CCA methods have different performance levels and power consumptions, there is a strong case to incorporate these into MAC performance analysis for realistic predictions. For example, expressions for CSMA performance as functions of channel characteristics like SNR (as in [7]) would be useful in choosing MAC parameters like backoff interval based on channel conditions and packet arrival rates to optimize network performance.

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Conclusions

We have described in detail the structure and methods for clear channel assessment in the context of wideband wireless networks. The impact of sensing imperfections and power consumption of the various CCA methods on MAC performance was investigated, unveiling clear cross-layer interactions between the PHY activity (CCA) and MAC functions. We illustrate the need for joint design for improved system performance (particularly crucial for wideband wireless networks) and better understanding of trade-offs (as a function of various network parameters, such as traffic rate for example).

More accurate cross-layer modelling requires that the CCA methods be more accurately characterized in terms of their power consumption, ramp-up times, and so on. Neither are such models readily available from the circuit design community nor are representative numbers disclosed in data sheets. Second, simulators that are widely used for performance evaluations, like ns-2 and OPNET, do not contain detailed models for PHY layer modules like CCA and need to be upgraded to enable the study of MAC-PHY interactions. The joint consideration of CCA and MAC is thus a largely unexplored, problem-rich area that could yield handsome returns.

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BIOGRAPHIES

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