Cascaded Clear Channel Assessment: Enhanced Carrier Sensing for Dynamic Spectrum Access

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Abstract— **In this paper, a new clear channel assessment (CCA) method: cascaded-CCA, is proposed that is apropos for next generation dynamic spectrum access radios. The primary motivation for the proposed approach is to integrate the respective advantages of two 'standard' CCA mechanisms (energy detection and preamble detection) to arrive at a new dual-threshold CCA family that can provide greater flexibility towards tuning MAC performance. 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 as representative examples.**

I. INTRODUCTION

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 Dynamic Spectrum Access (DSA) technologies. Many of the MAC protocols employ a listen-before-talk or carrier sense multiple access component. In all such cases, *sensing the channel status* accurately and expeditiously is the fundamental design challenge for DSA [1], [2], [3]. Our work revisits this classical problem with a new twist, i.e. we present via cascaded CCA (Clear Channel Assessment), a new family of CCA solutions that can balance the twin objectives of enhanced MAC performance and energy efficiency.

There are several core flavors of channel sensing - notably energy and preamble detection - that are collectively known by the general term, CCA. CCA could be implemented in two different ways: the channel is sensed continuously or only when desired. Usually continuous channel sensing is known to be reliable; but it leads to considerable *idle* energy consumption, an important factor in the shortening of node lifetimes in energy-constrained sensor-net type devices. IEEE 802.11 [4] is one example that requires continuous channel sensing even when there are no active contentions.

Even in networks that do not require continuous channel sensing, one is forced to run CCA for extended periods of time for increased reliability. This sensing method is power 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 a constantly running CCA that will catch the preamble as and when it occurs on air. In IEEE 802.15.4 [5], nodes sense the channel only when they are ready for packet transmissions.

Thus, there is a need to devise enhanced channel sensing methods that enables a more fine-grained tradeoff between energy consumption and throughput. It has been shown in [6] and [7] that from a MAC performance perspective, ED (PD) is a good choice as the CCA method at low (high) traffic rates. Cascaded-CCA demonstrates that using a low-energy but less reliable mechanism (ED) to trigger a higher-energy but more reliable approach (PD) is a good architecture for CCA design; it enables a smooth transition between the best features of ED and PD so as to achieve optimal MAC performance at all traffic rates.

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. We illustrate how the cascaded-CCA method can be used to optimize MAC performance at all traffic rates by exploring it's impact on MAC performance of IEEE 802.11 and IEEE 802.15.4.

II. 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.

A. Energy Detection

This has been the traditional approach to *narrowband* CCA - 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.

B. 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).

C. ED-PD Comparison

ED is quite unreliable in detecting the presence of wideband signals, whose power levels are not much above the noise floor [8]. 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.

III. STRUCTURE OF CASCADED-CCA

A. Overview of Cascaded-CCA

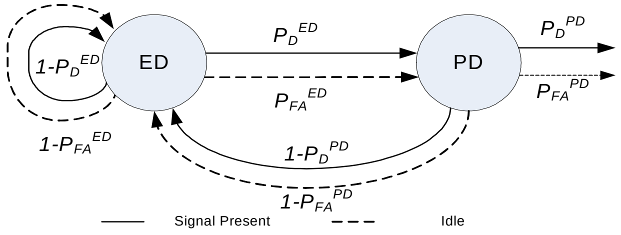

Fig. 1. State diagram representation of cascaded-CCA operation

Cascaded-CCA signifies, architecturally, a concatenation of ED and PD as follows. The ED block is always on and integrates the received RF signal over several symbol durations (say, n symbols) and produces an output at symbol rate. If the integrated output exceeds the ED threshold, Γ_{ED}, PD gets triggered. Once PD is turned on, the receiver performs a correlation of the received signal with the known spreading sequence over one symbol duration 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. 1 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.

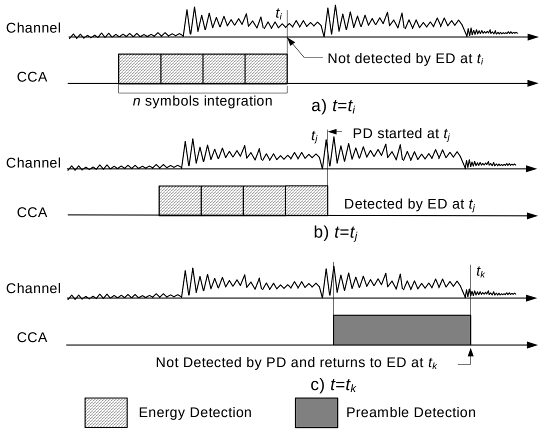

Fig. 2. Cascaded-CCA operation in idle channel

Fig. 2 shows an example of the operation of cascaded-CCA when the channel is idle. Here, ED threshold is not crossed at t_i as shown in Fig. 2 (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. 2 (b). At this point, ED triggers a PD module, which starts sampling the received signal at rate $1/T_c$ and correlates it over a 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. 2 (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}.

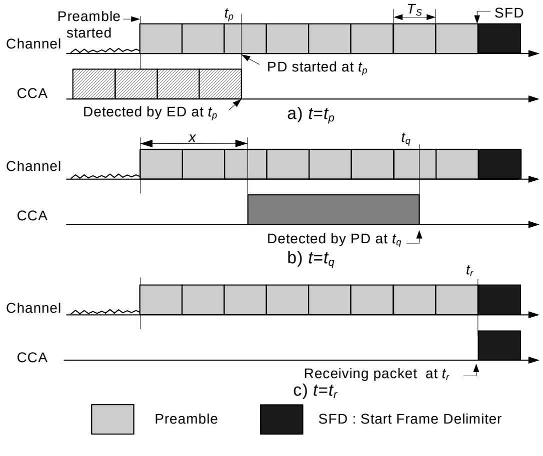

Fig. 3. Cascaded-CCA operation in busy channel

Fig. 3 shows an example operation of cascaded-CCA when the channel is busy. When an actual packet arrives, the ED threshold crossing happens x symbols into the packet at t_p, which is a random variable as shown in Fig. 3 (a). Now, the PD has $N-x$ remaining symbols to correlate over and make a final decision about signal presence. The preamble is said to have been 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). 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 (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.

IV. APPLICATION TO IEEE 802.11B

PD and cascaded-CCA were implemented into the CCA module of IEEE 802.11. Note that pure ED is not applicable in IEEE 802.11 as every node needs to continually monitor the channel to accept packets that is destined to it. According to IEEE 802.11b standard, CCA must determine the channel state within 15 μs[1]. Each symbol is spread using 11 chips Barker code. A backoff slot is 20 μs, i.e., 20 symbol durations. For simplicity, the switching time between the ED and the PD is ignored in our analysis.

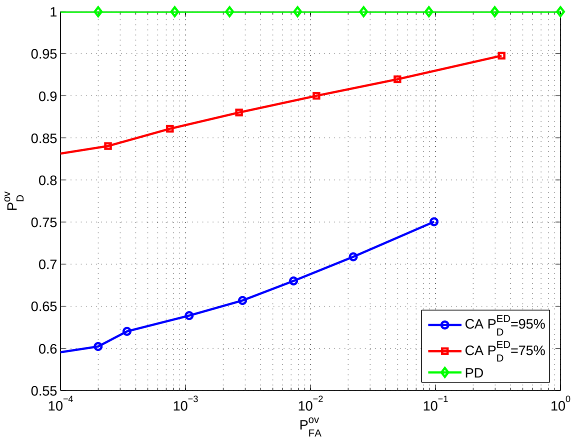

Fig. 4. Receiver operating characteristics of PD and cascaded-CCA in IEEE 802.11 at SNR=7 dB

P_D^{ov} and P_{FA}^{ov} of all CCA methods can be shown using a Receiver Operating Curve (ROC) as in Fig. 4, obtained by varying the thresholds, Γ_{ED} and Γ_{PD}. An additive white guassian noise (AWGN) channel with a signal-to-noise ratio (SNR) of 7 dB has been used. Abbreviation 'CA' means the cascaded-CCA.

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, two different detection probabilities of the front-end ED, P_D^{ED}=95 % and P_{FA}^{ED}=75 % are used. The integration duration of the front-end ED is set to 4 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 size 500 bytes (about 224 slot durations), with Poisson arrivals. The parameters of the radio were obtained from [9], which has idle, transmit and receive states with respective power consumptions of P_{idle}=0.83 W, P_{tx}=1.4 W, and P_{rx}=1 W. An extra CCA state has been introduced to capture the differences in power consumptions among different CCA methods. For PD, the CCA power consumption of the PD is set to P_{rx} and for cascaded-CCA, the CCA power consumptions of the ED and the PD components are set to $P_{rx}/4$ and P_{rx}, respectively. For our simulations, we have used an overall CCA detection probability of 70%.

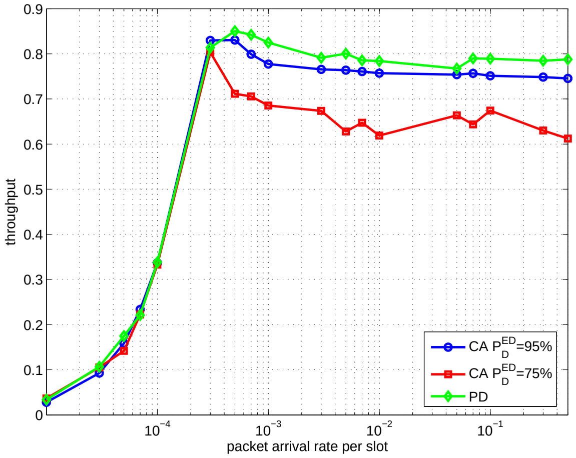

Fig. 5. Utilization of IEEE 802.11 channel using different CCA methods

Fig. 5, 6, and 7 show throughput, power consumption, and metric which is defined as number of bytes that a node can successfully transmit per unit energy (Joule), $Kbyte/J$, of IEEE 802.11 using different CCA methods against the packet arrival rate per slot, λ. As shown, 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. 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

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[1] In 802.11, the preamble is a binary sequence always transmitted at 1 Mbps irrespective of the subsequent data rate, yielding a symbol duration of 1 μs.

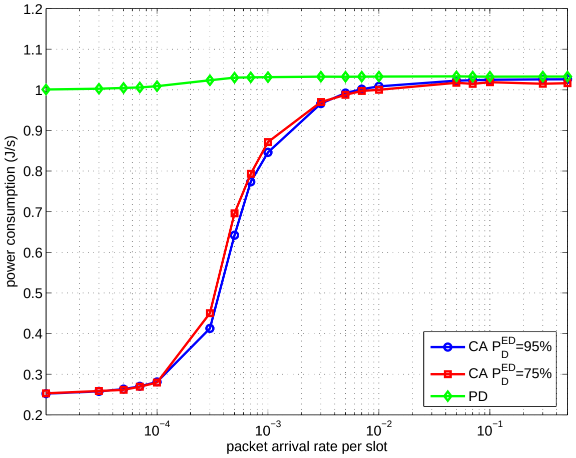

Fig. 6. Energy consumptions of IEEE 802.11 using different CCA methods

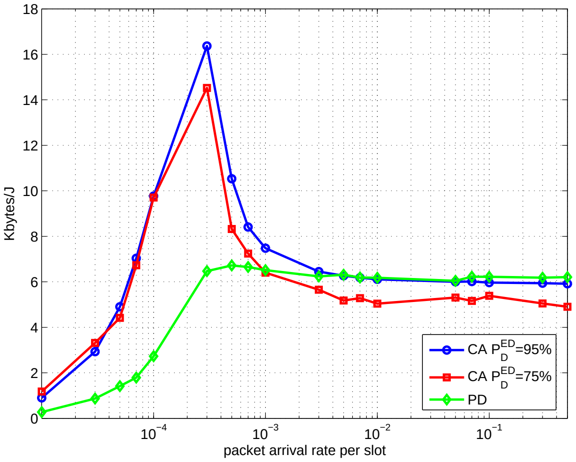

Fig. 7. Kbytes/J of IEEE 802.11 using different CCA methods

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. 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, $\lambda < 10^{-3}$, cascaded CCA is the preferred approach for channel detection instead of PD.

V. APPLICATION IN IEEE 802.15.4

ED, PD and cascaded-CCA were implemented in the CCA module of 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 (128 μs corresponding to one symbol duration of 16 μs). 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., 320 μs.

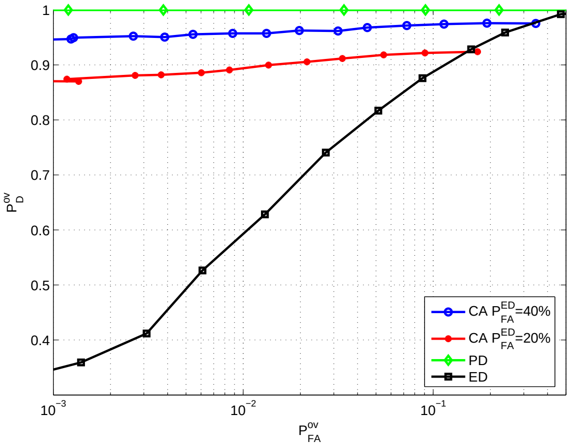

Fig. 8. Receiver operating characteristics of ED, PD and cascaded-CCA in IEEE 802.15.4 at SNR=5 dB

ROCs of the different CCA methods for IEEE 802.15.4 are shown in Fig. 8 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 % and P_{FA}^{ED}=20 % with the 4 symbols integration duration of the front-end ED are shown. Cascaded-CCA provides intermediate performance. 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.

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 N=13 backoff slots at a Poisson rate to the coordinator. The packet reception in the coordinator is also assumed to be error-free. The parameters of the radio used for simulations were obtained from [10], 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_{rx}/4 and P_{rx}, respectively. Here again, P_{FA}^{ov} is also set to 5 %.

Figs. 9, 10, and 11 show the performance comparisons of IEEE 802.15.4 using different CCA methods with varying λ. 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. The large value of P_{FA}^{ED} means that the first ED stage triggers the subsequent PD more frequently. Because of the PD, the channel will be detected more precisely and the throughput is improved comparing to the ED only. 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

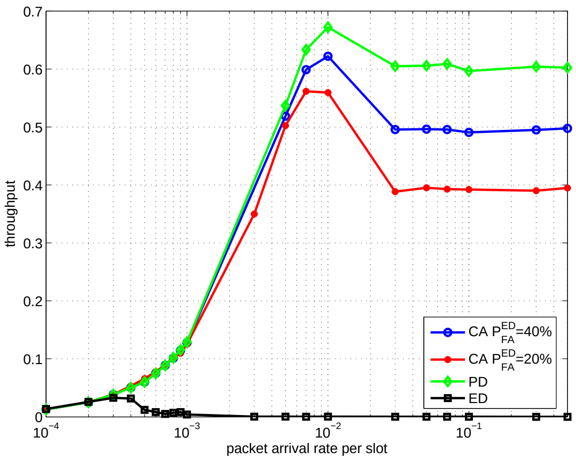

Fig. 9. Utilization of IEEE 802.15.4 channel using different CCA methods

of the energy efficiency of the front-end ED. Although PD shows the best throughput, its energy efficiency is significantly lower than that of cascaded-CCA with 40 % P_{FA}^{ED}. Although the throughput of ED is the worst, its energy efficiency very good for the low packet rates ($\lambda < 3 \times 10^{-3}$) as shown in Fig. 11. Cascaded-CCA outperforms PD in energy consumption and ED in sensing reliability. Therefore, cascaded-CCA shows better energy efficiency for $\lambda > 3 \times 10^{-3}$. So to maximize the energy efficiency, if the packet arrival rate is small (for example, $\lambda < 3 \times 10^{-3}$, ED is the best choice while cascaded-CCA is the best for $\lambda > 3 \times 10^{-3}$. PD could be chosen to maximize the throughput when the power consumption is not a big issue.

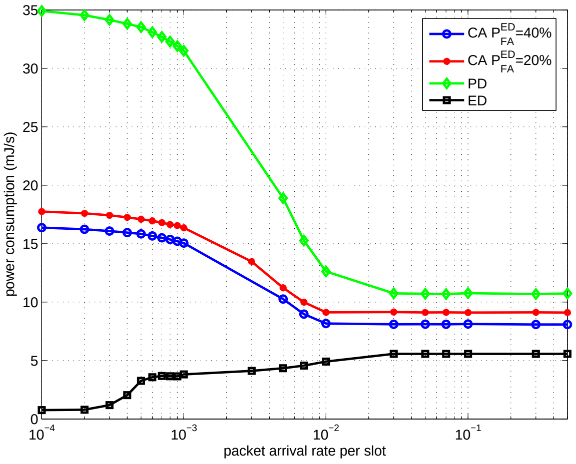

Fig. 10. Energy consumptions of IEEE 802.15.4 using different CCA methods

VI. CONCLUSIONS

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). 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.

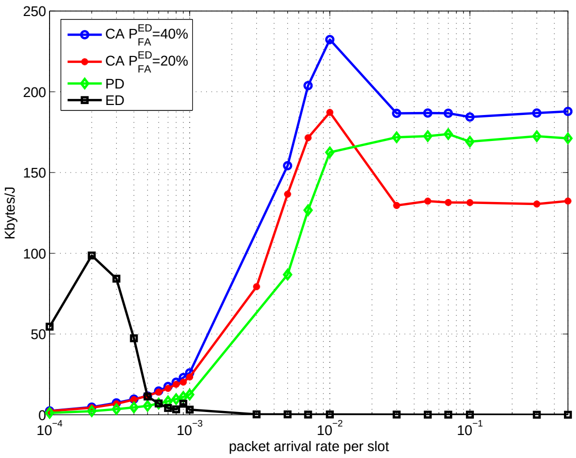

Fig. 11. Kbytes/J of IEEE 802.15.4 using different CCA methods

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