Enhancement of the IEEE 802.15.4 MAC Protocol for Scalable Data Collection in Dense Sensor Networks

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ABSTRACT

We find that the IEEE 802.15.4 MAC protocol performs poorly for one-hop data collection in dense sensor networks, showing a steep deterioration in both throughput and energy consumption with increasing number of transmitters. We propose a channel feedback-based enhancement to the protocol that is significantly more scalable, showing a relatively flat, slow-changing total system throughput and energy consumption as the network size increases. A key feature of the enhancement is that the back-off windows are updated after successful transmissions instead of collisions. The window updates are based on an optimality criterion we derive from mathematical modeling of p-persistent CSMA.

1. INTRODUCTION

IEEE 802.15.4 is an important standard for low-rate low-power wireless personal area networks that is in increasing commercial use for a diverse range of embedded wireless sensing and control applications. The standard provides specifications for both the physical layer and the medium access control (MAC) protocol.

We characterize the performance of the IEEE 802.15.4 MAC for one-hop data collection in a star topology where there are multiple transmitters and a single receiver. Our primary focus is on settings where the number of transmitters is large. Because 802.15.4-enabled devices are meant to be low-cost and operate at relatively low rates, such dense deployments are of interest in many sensing applications involving these devices.

We model the IEEE 802.15.4 as a p-persistent CSMA with changing transmission probability p. We derive the optimal transmission probabilities to maximize the throughput and minimize energy consumption in p-persistent CSMA. We show that, particularly for large number of transmitters, the ratio of the expected idle time between successful receptions to the expected time between successful receptions is a constant for a given packet size when the transmission probabilities are optimal. Further, we find that when the transmission probability is lower (higher) than the optimal, the ratio is higher (lower) than this constant. This yields a distributed channel feedback-based control mechanism that changes the transmission probabilities of nodes dynamically towards the optimal. We develop an enhanced version of the IEEE 802.15.4 MAC protocol using this feedback scheme.

In our modeling and evaluation, we consider two extremes of the one-hop data collection spectrum in dense sensor networks: one-shot and continuous data collection. In one-shot data collection, each node sends only a single packet (this could be the response to a one-shot query) and once that packet is transmitted the node is no longer in contention for the channel. In continuous data collection, we assume that each node is backlogged, i.e. always has a packet to transmit.

In both cases, we find that the IEEE 802.15.4 protocol performs poorly in dense settings, showing a steep reduction in throughput and increase in energy with network size. In contrast, the enhanced protocol that we propose is significantly more scalable, showing a relatively flat, slow-changing total system throughput and energy as the number of transmitters is increased. This is illustrated in figure 1.

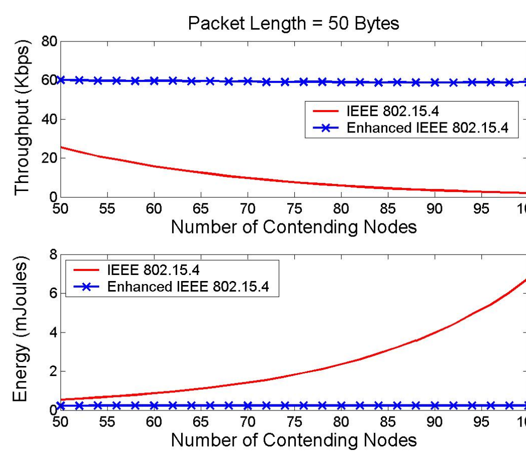


Figure 1: Performance of Proposed Enhancement compared to IEEE 802.15.4 for Continuous Data Collection

The rest of this paper is organized as follows. In Section 2 we present an overview of IEEE 802.15.4 and model it as a p-persistent CSMA with changing p. In Section 3 we present the modeling and optimization of p-persistent CSMA and characterize the performance of the IEEE 802.15.4 MAC in

Section 4. In Section 5 we present a channel feedback-based medium access control technique and adapt it to present the enhanced IEEE 802.15.4 MAC. In the same section we discuss directions of our future work. We conclude in Section 6.

2. IEEE 802.15.4

In this section we present an overview of the IEEE 802.15.4 MAC and model it as a p-persistent CSMA MAC with changing p.

2.1 Overview & Related Work

The IEEE 802.15.4 standard ([6]) allows different network topologies such as one-hop star and multi-hop. We consider the one-hop star topology with multiple data sources and a single sink. In the star topology, a global synchronization of nodes is assumed and the time is separated by beacons transmitted by a network coordinator. The beacon-interval consists of a *superframe* and an optional energy saving time in which the nodes switch off their radio and go to sleep. The superframe is divided into 16 time slots of $\delta = 320$ μsecs duration each. The superframe consists of a *contention access period* (CAP) and a period of *guaranteed time slots* (GTS). The GTS is dedicated for low latency applications. In this paper we consider only the CAP mode (without the energy saving mode, GTS, and beacons) where medium access is through slotted CSMA/CA.

In slotted CSMA/CA, a node can transmit its packet only after it senses the channel free for a contention window (CW) of 2 time slots. The main purpose of the CW is to avoid collisions between acknowledgement packets (ACKs) from the sink and data packets from the sources as the protocol does not specifically provision time slots for ACKs [16]. A node chooses a time slot uniformly at random from an initial window of $[0, 2^{BE} - 1]$, where BE is the back-off exponent with an initial value of 3. The node transmits its packet if the channel is sensed to be free in that and the next time slots; if the channel is sensed to be busy the node backs off to a bigger window with $BE = 4$. On a second busy channel sensing or a collision the node backs off to a window with $aMaxBE = 5$ and remains constant. If a node is unable to transmit its packet within 5 back-offs the transmission is assumed to be a failure and the packet is dropped. We relax this condition in this paper and allow a node to retransmit its packet until it is successful. Figure 2 shows the flow chart for a node using the IEEE 802.15.4 MAC. The IEEE 802.15.4 standard specifies a data rate of 250 kbps and a maximum MAC protocol data unit (MPDU) of 127 Bytes. Given this data rate, the transmission time for a typical packet of 50 Bytes is 5 time slots and for the MPDU it is 13 time slots.

In [10] the the performance of the IEEE 802.15.4 MAC is evaluated in terms of throughput and energy efficiency using *ns – 2* simulations for a maximum of 49 nodes. In [14] the performance of the standard MAC is evaluated for medical applications where the IEEE 802.15.4 devices interface with the traditional MAC technologies such as Ethernet. [15] analyzes the performance in the context of medical body area networks (BAN) where the energy efficiency of body implanted sensors is the focus given that their required life time is in the order of 10-15 years in these applications. In [12] a queuing analysis is presented for the sleep mode with possible finite buffers. In [13] the performance of the standard MAC is evaluated in the presence of both uplink and downlink traffic in the one-hop star topology network.

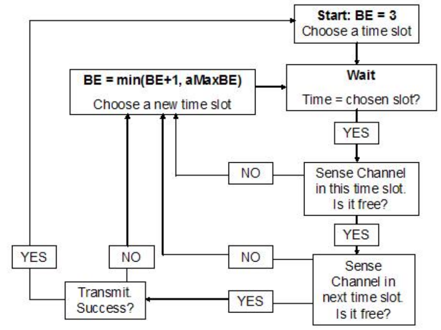


Figure 2: Flow chart for IEEE 802.15.4 operation at a node.

2.2 Application Space

We consider the two extremes of the spectrum of one-hop data collection applications in dense sensor networks. At one extreme of this spectrum is continuous data collection and the other extreme is one-shot data collection.

- **Continuous Data (CD)**: In this scenario the sources continuously send data to the sink. We assume that our observation time is such that all nodes always have a packet to send, *i.e.,* their queues are back-logged. This implies that the network reaches steady state and operates at the saturation throughput. Performance metrics of interest in this scenario are the system throughput[1] and energy consumption. Let Φ_{CD} and Σ_{CD} be the expected throughput in bps and expected energy consumption per node per successful packet transmission in Joules respectively.

- **One-Shot Data (OSD)**: In this scenario the sink is interested in one-shot data queries such as "Which nodes have observed the event?" or "Which nodes have recorded temperatures above 50F?", etc. The response to such one-shot queries is a single packet from each sensor node that contains the location of the node or a similar identification. Once the packet has been successfully transmitted from a node it is not in contention for the channel anymore, implying that the system does not attain steady state. The performance metrics of interest in this scenario are the delay in obtaining packets from all sensor nodes as a performance metric and energy consumption incurred by the sensor network in this operation. Let Δ_{OSD} and Σ_{OSD} be the expected delay in seconds and the amortized expected energy consumption per node in Joules respectively for successfully transmitting packets from all sources.

In this paper we mainly focus on dense sensor networks in which at-least 50 nodes contend for the channel in either scenario. We assume that the packet lengths are deterministic and constant.

[1]Please note that we are considering the total system throughput and not per node throughput. Per node throughput can be calculated by dividing the system throughput by the number of nodes.

2.3 Model

Now, we model the IEEE 802.15.4 MAC as a p-persistent CSMA MAC with changing p. Before we present the MAC model, we describe the assumptions made and the energy model used.

- **Assumptions**: Let the number of sensor nodes in the radio range of the sink be N. All sensor nodes are synchronized to a global time which is divided into slots of equal length and each node transmits at the beginning of a time slot. Let the packet length be L time slots. A sensor node is informed of its packets' successful transmission through acknowledgement packets (ACKs) from the sink. Failure to receive an ACK from the sink implies a collision. The ACK is sent by the sink as soon as the packet reception is completed. Table 1 summarizes the notations used.

- **Energy Model**: According to the IEEE 802.15.4 standard a node can exist in any one of the following four states - Shutdown, Idle, Transmit, Receive. For CD, we assume that the nodes are either in the Trasmit or the Recieve state and are not concerned with the Shutdown or Idle states. For OSD, again each node is either in the Transmit or the Recieve state until its packet is transmitted, after which the node moves to the Shutdown state permanently. Let the power consumed in the Transmit state be ξ_T and the power consumed in the Recieve state be ξ_R. According to [1], $\xi_R = 35$ mW and $\xi_T = 31$ mW for the highest transmission power. The power consumed in the Shutdown state is negligible .

- **MAC Model**: In [16] the authors model the IEEE 802.15.4 MAC in the contention access period (CAP) as a non-persistent CSMA with back-off. They approximate the three original uniform-random back-off windows to geometrically distributed back-off windows with parameters p_1, p_2 and p_3 such that $p_i = \frac{2}{BO_i+1}$, $(1 \le i \le 3)$ where BO_i is the original uniform-random back-off window size. With $BO_1 = 8$, $BO_2 = 16$ and $BO_3 = 32$, the respective values of p_1, p_2 and p_3 are $\frac{1}{4.5}$, $\frac{1}{8.5}$ and $\frac{1}{16.5}$.
  In this paper we further simplify this model to a p-persistent CSMA in which the probability of transmission changes from p_1 to p_2 to p_3 with each collision and remains constant after two collisions at p_3. The key difference in our model from the non-persistent CSMA model is that in our case the transmission probability changes with a packet collision instead of a busy carrier sense. Thus in our model, a node starts out with an initial transmission probability of p_1. The node senses the channel at the beginning of each time slot and if the channel is found to be free for two consecutive time slots, it transmits its packet with probability p_1. If the channel is busy, the node tries to transmit the packet with the same probability the next time it finds two consecutive free time slots. If more than one node transmits in the same time slot it results in a collision and if a node is involved in a collision for the first time it changes its transmission probability to p_2. On a second collision its transmission probability is changed to p_3 and it remains constant beyond the second collision.

N	Number of nodes in the network
p	Transmission probability
L	Length of packet in time slots
δ	Time slot length (320 μsecs)
ξ_R	Power consumption in Receive state
ξ_T	Power consumption in Transmit state
n	Number of nodes in an epoch
T_n	Delay in an epoch with n nodes
E_n	Energy consumption in an epoch with n nodes
$\Phi_{CD}(N)$	Throughput in bps in CD
$\Sigma_{CD}(N)$	Energy consumption per node per successful packet transmission in CD
$\Delta_{OSD}(N)$	Delay in secs to obtain packets from N nodes in OSD
$\Sigma_{OSD}(N)$	Energy consumption in Joules to obtain packets from N nodes in OSD
$p_{opt}^T(n, L)$	Transmission probability that minimizes epoch delay
$p_{opt}^E(n, L)$	Transmission probability that minimizes epoch energy consumption

Table 1: Notation

We evaluate the accuracy of our model using simulations[2]. The results are averaged over 1000 random trials with 100 different random seeds. For the CD scenario, we simulated the protocol for 10000 time slots for a packet length of 50 Bytes (or 5 time slots).

Figure 3 plots the simulation results comparing the IEEE 802.15.4 and our p-persistent CSMA model and shows that our model is reasonably accurate. Next, we determine the optimal performance of a generic p-persistent CSMA MAC with a similar time slot structure and characterize the performance of IEEE 802.15.4 MAC in comparison to that.

3. P-PERSISTENT CSMA MAC

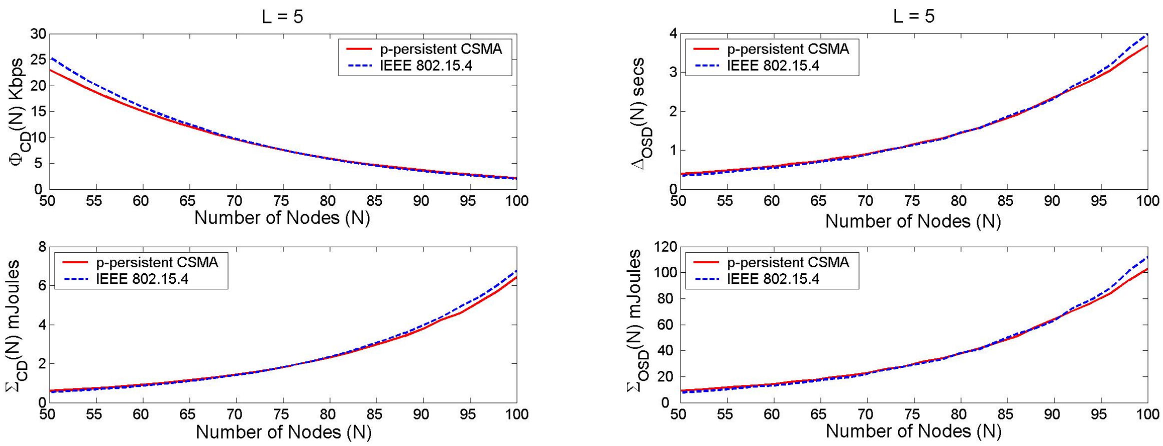
In this section we model and analyze a generic p-persistent CSMA MAC and determine the transmission probabilities that optimize its performance.

3.1 Overview

In a slotted p-persistent CSMA ([2]), each node senses the channel at the beginning of each time slot and if the channel is found to be free of any transmissions, it transmits its packet with a probability p. If the channel is not free, the node attempts to transmits its packet in the next free time slot. If more than one node transmits in the same time slot it results in a collision.

Traditionally, system dynamics due to the p-persistent CSMA protocol have been modeled using renewal theory (example [8], [9], [5], [4]). The key assumption that makes the use of renewal or regenerative models feasible is that the system attains stationarity and that the models capture the system behavior at the state. While this assumption is still true for the CD scenario, it is not true for the one-shot data scenario. Nevertheless, we observe the system at every successful packet transmission like in [9] and [5], for both scenarios and derive expressions for throughput, delay and

[2]We have written our own simulators in C for the IEEE 802.15.4 and p-persistent CSMA MAC protocols. They are available for download at http://ceng.usc.edu/~anrg/downloads.html.



(a) Continuous Data (b) One-shot Data

Figure 3: IEEE 802.15.4 standard is modeled as a p-persistent CSMA with probability of transmission reducing in three steps – $p_1 = \frac{1}{4.5}$, $p_2 = \frac{1}{8.5}$, $p_3 = \frac{1}{16.5}$ **– with each new collision.**

energy consumption.

3.2 Model

We observe the system at every successful packet transmission. The time interval between two consecutive successful transmissions is defined as an *epoch*. An epoch is made up of idle time, in which the channel is free of any transmissions, collision time, in which more than one node is transmitting and a single successful transmission time which marks the end of the epoch, as illustrated in Figure 4.

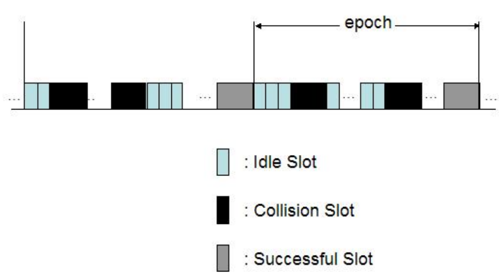


Figure 4: An epoch illustrating the time interval between consecutive successful transmissions.

It is important to note that, for CD, the number of nodes remain constant in all epochs. However, for OSD the number of nodes decreases by one with each passing epoch. Let T_n be the epoch delay – the time interval between two consecutive successful packet transmissions – in seconds and E_n be the energy consumption – the total energy consumed by all contending nodes – in Joules, for the epoch with n contending nodes. Then

$$\Phi_{CD}(N) = \frac{1}{E[T_N]} \cdot (80L) \ \text{ bps} \tag{1}$$

$$\Sigma_{CD}(N) = \frac{E[E_N]}{N} \ \text{ Joules} \tag{2}$$

$$\Delta_{OSD}(N) = \sum_{n=1}^{N} E[T_n] \ \text{ seconds} \tag{3}$$

$$\Sigma_{OSD}(N) = \frac{1}{N} \sum_{n=1}^{N} E[E_n] \ \text{ Joules} \tag{4}$$

where $80L$ in Equation 1 is the packet length in bits. Clearly, the above metrics are optimized when $E[T_n]$ and $E[E_n]$ are minimized. First we determine expressions for $E[T_n]$ and $E[E_n]$.

Proposition 1. *For a constant packet length L, the expected epoch delay for n contending nodes is given by*

$$E[T_n] = \frac{L - (L-1)(1-p)^n}{np(1-p)^{n-1}} \cdot \delta \tag{5}$$

Proof. As illustrated in Figure 4 the delay in an epoch is due to idle time, collision time and successful transmission time. Therefore, the expected delay in epoch n, is given by

$$E[T_n] = E[T_{Idle,n}] + E[T_{Collision,n}] + E[T_{Success}] \tag{6}$$

where $E[T_{Idle,n}]$ is the expected number of idle time slots, $E[T_{Collision,n}]$ is the expected number of collision time slots and $E[T_{Success}]$ is the expected number of time slots of successful transmission. Since the packet length L is a constant $E[T_{Success}]$ is equal to $L\delta$ and independent of n.

If $E[N_{coll,n}]$ is the expected number of collisions in an epoch with n nodes, then

$$\begin{aligned} E[T_{Idle,n}] &= (E[N_{coll,n}] + 1) \cdot E[T_{IdlePeriod,n}] & (7)\\ E[T_{Collision,n}] &= E[N_{coll,n}] \cdot E[T_{CollisionPeriod,n}] & (8) \end{aligned}$$

where $E[T_{IdlePeriod,n}]$ is the expected number of idle time slots between two consecutive packet transmissions (collision or successful) and $E[T_{CollisionPeriod,n}]$ is the expected number of collision time slots at each collision. Owing to the constant probability of transmission p within an epoch, the $IdlePeriod$s between any two consecutive packet transmissions are $i.i.d$ random variables with the same mean value. Also, since the decision to transmit in a time slot after a free channel sense is independent of the number of previous free channel senses, the number of collisions is independent of the length of $IdlePeriod$s. This holds true for $CollisionPeriod$s also, thus justifying the above two equations.

$E[N_{coll,n}]$ and $E[T_{IdlePeriod,n}]$ are given by [5]:

$$E[N_{coll,n}] = \frac{1-(1-p)^n}{np(1-p)^{n-1}} - 1 \quad (9)$$

$$E[T_{IdlePeriod,n}] = \frac{(1-p)^n}{1-(1-p)^n} \cdot \delta \quad (10)$$

We use the above two equations to derive the expected delay in the epoch n. Since the packet length is constant $E[T_{CollisionPeriod,n}] = L\delta$. Therefore,

$$E[T_{Idle,n}] = \frac{1-p}{np} \cdot \delta \quad (11)$$

$$E[T_{Collision,n}] = \frac{L\delta(1-(1-p)^n - np(1-p)^{n-1})}{np(1-p)^{n-1}} \quad (12)$$

Substituting the above equations in Equation 6, we get Equation 5. □

Proposition 2. *For a constant packet length of L, the expected epoch energy consumption for n contending nodes is given by*

$$E[E_n] = \xi_R\delta \cdot \frac{L-(L-1)(1-p)^{n-1}}{p(1-p)^{n-2}} + \xi_T\delta \cdot \frac{L}{(1-p)^{n-1}} \quad (13)$$

Proof. Similar to Equation 6, the energy consumption in the epoch n is equal to the sum of the energy consumption in idle time, the energy consumption in collision time and the energy consumption in a successful transmission.

$$E[E_n] = E[E_{Idle,n}] + E[E_{Collision,n}] + E[E_{Success}] \quad (14)$$

Using equations from Proposition 1, $E[E_{Idle,n}]$ can be calculated as

$$E[E_{Idle,n}] = (E[N_{coll,n}]+1) \cdot n\xi_R \cdot E[T_{IdlePeriod,n}] \quad (15)$$

$$= n\xi_R\delta \cdot \frac{1-p}{np} = \xi_R\delta \cdot \frac{1-p}{p} \quad (16)$$

Surprisingly, for a constant p, the idle time energy consumption is independent of the number of contending nodes in an epoch, and depends only on p. Similarly, the collision time energy consumption is given by

$$E[E_{Collision,n}] = E[N_{coll,n}] \cdot E[E_{CollisionPeriod,n}] \quad (17)$$

The expected energy consumption in a $CollisionPeriod$, $E[E_{CollisionPeriod,n}]$, is equal to the sum of the expected energy consumption by nodes involved in packet transmissions and the expected energy consumption by nodes in idle state during the $CollisionPeriod$. Therefore,

$$E[E_{CollisionPeroid,n}] = L\xi_T\delta \sum_{i=2}^{n} iP\{Trans. = i|Collision\} + L\xi_R\delta \sum_{i=2}^{n}(n-i)P\{Trans. = i|Collision\} \quad (18)$$

where $P\{Trans. = i|Collision\}$ is the probability that i (≥ 2) nodes transmit their packets given that a collision has occurred, and it is given by

$$P\{Trans. = i|Collision\} = P\{Trans. = i|Trans. \geq 2\} = \frac{\binom{n}{i}p^i(1-p)^{n-i}}{1-(1-p)^n - np(1-p)^{n-1}} \quad (19)$$

Substituting the above equation in Equation 18, we get

$$E[E_{CollisionPeriod,n}] = \frac{L(\xi_T-\xi_R)\delta \cdot np(1-(1-p)^{n-1})}{1-(1-p)^n - np(1-p)^{n-1}} + nL\xi_R\delta \quad (20)$$

Substituting the above equation in Equation 17, we get

$$E[E_{Collision,n}] = \frac{L(\xi_T-\xi_R)\delta \cdot (1-(1-p)^{n-1})}{(1-p)^{n-1}} + \frac{L\xi_R\delta \cdot (1-(1-p)^n - np(1-p)^{n-1})}{p(1-p)^{n-1}} \quad (21)$$

And finally, the expected energy consumption during a successful transmission is give by

$$E[E_{Success}] = \xi_T \cdot L\delta + \xi_R \cdot L\delta \cdot (n-1) \quad (22)$$

Substituting the above equations in Equation 14 we get Equation 13. □

3.3 Optimality

Let $p^T_{opt}(n,L)$ and $p^E_{opt}(n,L)$ respectively be the transmission probabilities at which $E[T_n]$ and $E[E_n]$ are minimized.

Proposition 3. *For $n > 1$, the transmission probability that minimizes the expected epoch delay $E[T_n]$ is given by*

$$p^T_{opt}(n,L) = \frac{1}{n}, \quad L = 1 \quad (23)$$

$$p^T_{opt}(n,L) \approx \frac{\sqrt{n^2+2n(n-1)(L-1)} - n}{n(n-1)(L-1)}, \quad L > 1 \quad (24)$$

Proof. The value of p that minimizes $E[T_n]$ is obtained by equating its first derivative with respect to p to zero.

$$\frac{dE[T_n]}{dp} = 0 \quad (25)$$

For $L = 1$,

$$E[T_n] = \frac{\delta}{np(1-p)^{n-1}} \quad (26)$$

Taking the derivative and equating it to zero results in $p = \frac{1}{n}$. Similarly, for $L > 1$, equating the derivative of $E[T_n]$ from Equation 5 to zero yields the following equation.

$$(1-p)^n = \frac{L}{L-1} \cdot (1-np) \tag{27}$$

For $np < 1$, $(1-p)^n$ can be approximated to $1 - np - \frac{n(n-1)}{2}p^2$. Using this approximation and further simplification, Equation 27 reduces to Equation 24 as an unique root to a quadratic equation. It can be verified that $\frac{d^2 E[T_n]}{dp^2} > 0$ for $p = p^T_{opt}(n, L)$, thus minimizing $E[T_n]$. $\square$

Proposition 4. *For $n > 1$ and $\gamma = \frac{\xi_T}{\xi_R}$ the transmission probability that minimizes the expected epoch energy consumption $E[E_n]$ is given by*

$$p^E_{opt}(n, L) \approx \frac{\sqrt{n^2 + 2n(n-1)(L-1) + 4L(n-1)(\gamma-1)} - n}{n(n-1)(L-1) + 2L(n-1)(\gamma-1)} \tag{28}$$

PROOF. Similar to the previous Proposition equating $\frac{dE[E_n]}{dp}$ to zero yields

$$(1-p)^n = \frac{L}{L-1} \cdot (1 - np - p^2(n-1)(\gamma-1)) \tag{29}$$

The same approximation as in the previous proposition and further simplification of the above equation results in Equation 28. It can be verified, as in the previous Proposition, that the second derivative of $E[E_n]$ with respect to p is positive for $p = p^E_{opt}(n, L)$, thus minimizing $E[E_n]$. $\square$

Numerical calculations show that the approximations are very close to the actual values. For $n = 1$, the optimum transmission probability is equal 1, *i.e.,* when there is a single sensor node left, delay and energy are minimized when it transmits its packet with probability 1. Figure 5 plots $p^T_{opt}(n, L)$ and $p^E_{opt}(n, L)$ as a function of the number of contending nodes from $n = 100$ to $n = 2$ for different values of γ. As the figure shows, for optimal performance the probability of transmission should increase with decreasing number of nodes in an epoch in order to avoid excessive idle time slots. We can also see that the transmission probabilities are higher for lower values of γ. This is because if the node spends more energy in the Receive state than in the Transmit state, energy is saved if it transmits more than it receives.

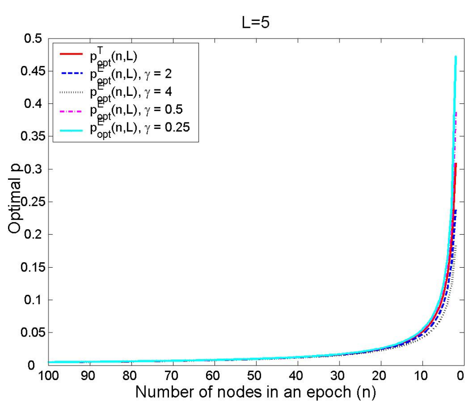


Figure 5: The optimal probability of transmission.

Corollary 1. *If $\xi_T = \xi_R$, then $p^T_{opt}(n, L) = p^E_{opt}(n, L)$, i.e., the delay and energy consumption are jointly optimized with a single probability of transmission for $\xi_T = \xi_R$.*

PROOF. For $\gamma = 1$ Equations 24 and 28 are equal, which proves the corollary. $\square$

3.4 Optimality Criteria

Now, we discuss some interesting optimality criteria for the epoch delay and energy consumption.

- **Proposition** 5. *Let $\Gamma(L) = \frac{L-\sqrt{2L-1}}{(L-1)(\sqrt{2L-1}-1)}$. If $L > 1$ and n is large such that $\frac{n-1}{n} \approx 1$, then for optimal transmission probability the ratio of idle time in an epoch to the epoch delay is a constant equal to $\Gamma(L)$. Also, if the transmission probability is greater than optimal then the ratio is lower than $\Gamma(L)$ and vice versa.*

$$p = p^T_{opt}(n, L) \Rightarrow \frac{E[T_{Idle,n}]}{E[T_n]} \approx \Gamma(L) \tag{30}$$

$$p \lessgtr p^T_{opt}(n, L) \Rightarrow \frac{E[T_{Idle,n}]}{E[T_n]} \gtrless \Gamma(L) \tag{31}$$

PROOF. Using Equations 9, 5 and 27 for optimal p,

$$\frac{E[T_{Idle,n}]}{E[T_n]} = \frac{1}{L-1}\left(\frac{1}{np^T_{opt}(n, L)} - 1\right) \tag{32}$$

For $\frac{n-1}{n} \approx 1$, using Equation 24

$$np^T_{opt}(n, L) \approx \frac{\sqrt{2L-1} - 1}{L-1} \tag{33}$$

Substituting the above equation into the previous equation the first part of the proposition is proved.

Similarly, for $p \lessgtr p^T_{opt}(n, L)$

$$np \lessgtr \frac{\sqrt{2L-1} - 1}{L-1} \tag{34}$$

$$\Rightarrow \frac{E[T_{Idle,n}]}{E[T_n]} \gtrless \Gamma(L) \tag{35}$$

Hence the proposition is proved. $\square$

Figure 6 illustrates Proposition 5 for $L = 5$. The approximation of the ratio to $\Gamma(L)$ is primarily due the approximation in Equation 24. As the figure shows, for low values of n the ratio deviates away from $\Gamma(L)$.

- Figure 7 plots the expected delay and energy consumption for an epoch with $n = 50$ nodes as a function of the transmission probability p for different values of the packet length L. The figure can be explained through the following question:

> *In p-persistent CSMA, if the length of the packet is increased from L to $L + l$ $(l > 0)$, should the value of transmission probability p be increased or decreased to maintain the delay and energy consumption constant?*

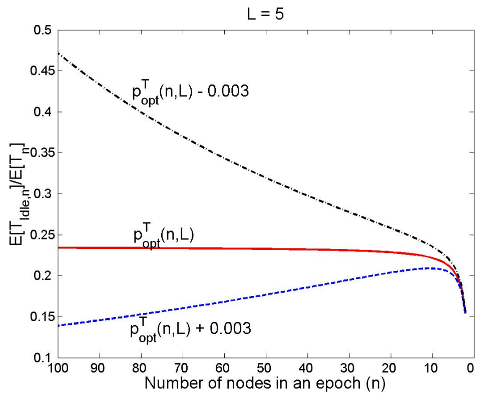


Figure 6: Ratio of expected idle time to expected epoch delay.

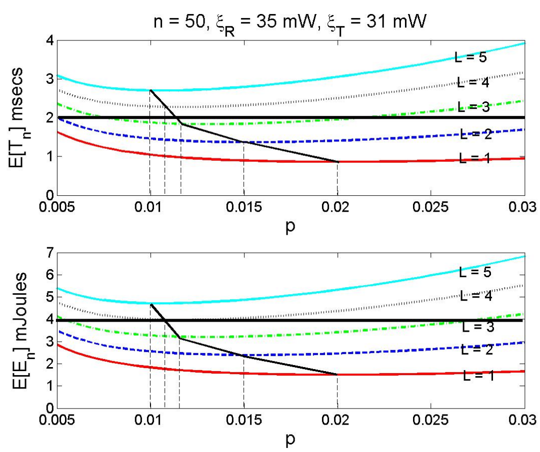


Figure 7: Expected delay and energy consumption in an epoch with n nodes as a function of transmission probability, p, for different values of packet length L.

Figure 7 shows us that the answer to the above question is that *it depends on the value of p*. If $p < p^T_{opt}(n,L)$, then for the same delay, p should be increased and if $p > p^T_{opt}(n,L)$ then p should be decreased. The same answer holds true for energy if $p^T_{opt}(n,L)$ is replaced by $p^E_{opt}(n,L)$. The figure also shows that the optimal transmission probability values $p^T_{opt}(n,L)$ and $p^E_{opt}(n,L)$ decrease with increasing L.

- Figure 8 plots ratios of consecutive epoch delays and energy consumptions as functions of n. In this figure, if the ratio is greater than 1 it implies that the delay or energy value increases with decreasing n and *vice versa*. Greater the difference from 1 higher the rate of increase or decrease. The following observations can be made from the figure:
  - For $p = p^T_{opt}(n,L)$, $E[T_n]$ is almost constant over all n. For $p > p^T_{opt}(n,L)$, $E[T_n]$ shoots up for higher values of n due to higher number of collisions. For $p < p^T_{opt}(n,L)$, $E[T_n]$ shoots up for lower values of n due to higher number of idle time slots.
  - For $p = p^E_{opt}(n,L)$, $E[E_n]$ increases monotonically with increasing n. For $p > p^E_{opt}(n,L)$, $E[E_n]$ shoots up for higher values of n due to higher number of collisions. For $p < p^E_{opt}(n,L)$, $E[E_n]$ is higher than the optimal energy consumption values for lower values of n due to higher number of idle time slots.

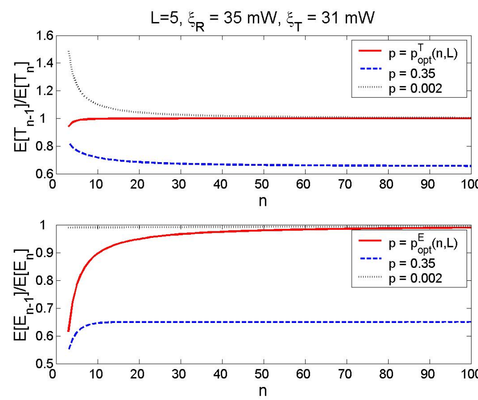


Figure 8: Ratio of expected delays and energy consumptions for consecutive epochs.

For CD the implication of this criterion is that the delay between two successful packet transmissions is independent of the number of nodes in the network as long as the nodes are transmitting at optimal transmission probabilities. For OSD, the implication is the following proposition.

Proposition 6. *For OSD, if n is large such that $\frac{n-1}{n} \approx 1$, then the transmission probability is optimal if and only if the epoch of delay of two consecutive epochs are equal.*

$$p = p^T_{opt}(n,L) \;\Leftrightarrow\; E[T_{n-1}] = E[T_n] \tag{36}$$

PROOF. Refer to [18] for the proof. □

4. CHARACTERIZATION OF IEEE 802.15.4

Having determined the performance of optimal p-persistent CSMA, we characterize the performance of IEEE 802.15.4 MAC in this section.

Figure 9 plots the average transmission probabilities for the IEEE 802.15.4 MAC (obtained using the p-persistent CSMA model) in comparison to the transmission probabilities for optimal p-persistent CSMA for both CD and OSD. The transmission probabilities shown for IEEE 802.15.4 are obtained using the default values specified in the standard including the two required sensing slots, which is not required for the generic p-persistent CSMA MAC. For OSD, the transmission probability for IEEE 802.15.4 quickly stabilizes at $\frac{1}{16.5} = 0.0606$ and for CD, close to that value. This behavior is in contrast to the trend shown by optimal probabilities. This implies that the back-off mechanism of IEEE 802.15.4 protocol can be modified for optimal performance as follows:

- The change of back-off window sizes should happen at successful transmissions instead of at collisions or busy channel senses. Further, for OSD, successful packet transmissions are a better indicator for future congestion than collisions or busy channel senses.

- For CD, the average transmission probability for IEEE 802.15.4 MAC remains almost constant irrespective of the number of contending nodes, while for optimal p-persistent CSMA it reduces with N. For optimal performance the window sizes should be reflective of the number of contending nodes.
- For OSD, the "back-off" window size should actually *decrease* with every successful transmission as the optimal transmission probability increases.

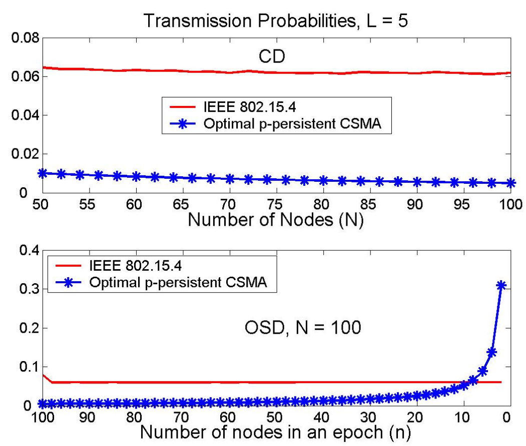


Figure 9: Comparison of transmission probabilities for IEEE 802.15.4 and optimal p-persistent CSMA for CD and OSD.

In the next section, we present a channel feedback enhanced IEEE 802.15.4 MAC that incorporates the above features.

5. ENHANCED IEEE 802.15.4

The key idea in enhancing the performance of the IEEE 802.15.4 is to use the optimality criteria for p-persistent CSMA derived in Section 3. In particular, we consider the criterion described in Proposition 5 which requires measurement of the idle time as well as the delay between two consecutive successful transmissions. These measurements can be construed as feedback from the channel. Before we describe how this feedback can be used, we review the related work in channel feedback-based medium access control techniques.

5.1 Related Work

The idea of using feedback from the channel to control the transmission probabilities of contending nodes has been used for a long time. Rivest in [17] has proposed a ternary feedback model in which each node has to monitor three channel conditions - absence of transmissions, successful transmissions and, collisions. Rivest has shown that estimating the true value for the number of nodes n and setting the transmission probability to $\frac{1}{n}$ maximizes the throughput in slotted-Aloha type protocols (in which the packet length is equal to a single time slot). If the packet length is of multiple time slots, this results does not hold true as we have shown in Proposition 3 in Section 3. In [4] a control mechanism has been presented that uses the energy consumed by a tagged node in the network in the above three channel conditions between two successful packet transmissions. This mechanism is not applicable in the case of OSD because each node has a single successful packet transmission. Similar strategies based on the estimation of the three channel conditions have been proposed ([11], [3], [7]) all of which are more suitable for steady state conditions (like in CD) in which the number of contending nodes remain constant.

A good control mechanism should depend on the network and traffic conditions as well as the application requirements. Our objective is to present a feed-back control mechanism that is suitable for both CD and OSD scenarios. One major challenge presented in OSD is to estimate the true system state using channel conditions in the face of constantly changing state of the system (decreasing number of contending nodes). Nevertheless, the analysis presented in Section 3 presents us with unique opportunities to efficiently control the transmission probabilities in real time.

5.2 Our Approach

Our approach for channel feedback-based control of transmission probabilities is mainly based on Proposition 5. According to the proposition, if the transmission probability is optimal then the ratio of idle time to the delay between two consecutive successful packet transmissions is $\Gamma(L)$. If the transmission probability if higher than the optimal value then the ratio is lower than $\Gamma(L)$ and *vice versa*.

First we describe how this optimality criterion can be used for an enhanced p-persistent CSMA and then adapt it to design an enhanced IEEE 802.15.4 MAC protocol.

5.2.1 Enhanced p-Persistent CSMA MAC

Each contending node can start by choosing a transmission probability uniformly at random in a small interval of say $(0, 0.05)$. Each node in the network measures the current epoch's idle time and delay and uses these measurements to determine the transmission probability for the next epoch. If the ratio of idle time to the delay is lower than $\Gamma(L)$ then it means that the transmission probability would have been greater than the optimal value. Therefore the transmission probability of the next epoch should be lower than the current epoch's to bring the delay closer to optimal. Similarly, if the ratio if higher than $\Gamma(L)$ the next epoch's transmission probability should be increased for optimal delay. Thus, the transmission probability update rule is given by

$$p_{next} = p_{current} \cdot \frac{\alpha}{\Gamma(L)} \tag{37}$$

where $\alpha = \frac{T_{Idle,current}}{T_{current}}$. In this update rule the increase or decrease in the transmission probability is directly proportional to the value of the ratio α.

5.2.2 Enhanced IEEE 802.15.4

The IEEE 802.15.4 MAC protocol uses different window sizes to control the transmission of packets. In order to use the above optimality criterion the transmission probability update rule should be converted into a window size update rule. For this we make use of the approximation we used in Section 2 to model the IEEE 802.15.4 MAC as a p-persistent

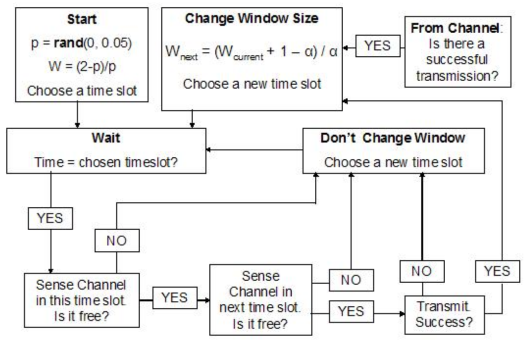


Figure 10: Flow chart for Enhanced IEEE 802.15.4 operation at a node.

CSMA MAC with changing p. In this, if a uniform-random back-off window has a size of W time slots then it can be closely modeled as a geometric-random choice of time slot with parameter p as long as $p = \frac{2}{W+1}$. Thus a transmission probability can be converted into window size by using the inverse relationship, *i.e.,* $W = \frac{2-p}{p}$. Based on this and the transmission probability update rule given above, the window update rule for the Enhanced IEEE 802.15.4 MAC is:

$$W_{next} = \frac{W_{current} + 1 - \alpha}{\alpha} \tag{38}$$

A key aspect of this update rule is that, all nodes in the network should updated their windows at every successful packet transmission. Figure 10 shows the flow chart for the Enhanced IEEE 802.15.4 MAC operation at a node.

It should be noted that all aspects of the original IEEE 802.15.4 MAC have been preserved except for when the window is changed and how it is changed.

5.2.3 Evaluation

Figure 11 shows the performance gains for the Enhanced IEEE 802.15.4 MAC in comparison to the original. The figure also shows the performance of the optimal p-persistent CSMA and enhanced p-persistent CSMA. It should be noted that the performance of the enhanced IEEE 802.15.4 MAC matches that of the enhanced p-persistent CSMA MAC for CW = 0, *i.e.,* if the nodes do not sense the channel for two consecutive free slots but transmit their packet once their chosen time slot occurs. Thus, for the enhancement we use, the performance of the enhanced p-persistent CSMA is an upper-bound on the performance of the enhanced IEEE 802.15.4 MAC.

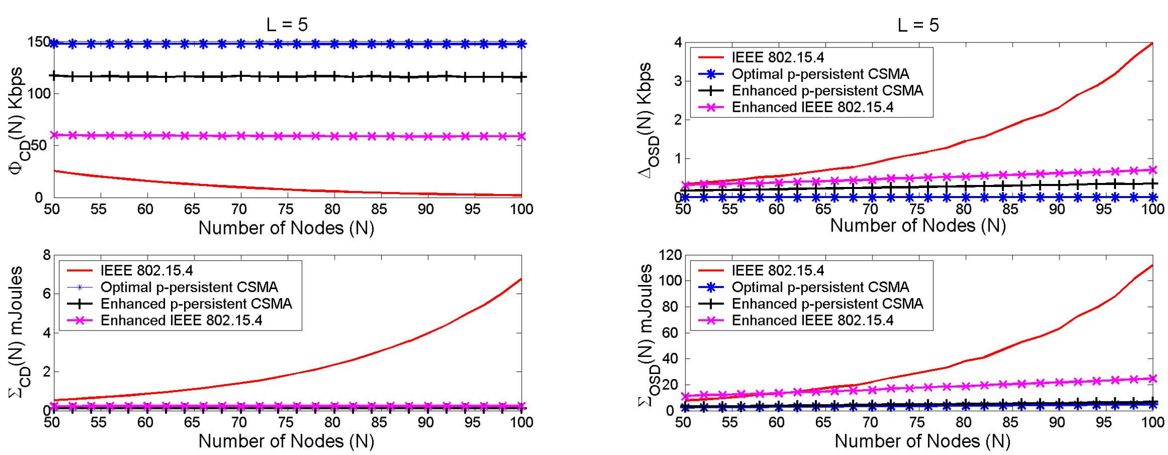
An important observation from the figure is that the system throughput reduces drastically with increasing number of contending nodes for the original IEEE 802.15.4 MAC. But for the enhanced version, the system throughput is almost constant with the number of nodes. Implying that it is much more scalable than the original. This holds for energy also. These significant gains in performance are observed for both CD and OSD scenarios.

5.2.4 Discussion

In actual implementation the measurement of idle time and the delay between two consecutive successful packet transmissions can be achieved easily at each node by observing ACKs from the sink. If all nodes in the network are in the radio range of each other then all nodes see the same idle time between two consecutive successful packet transmissions. If on the other hand, all nodes are in the radio range of the sink but not in the radio range of each other then each node sees an idle time that is based on the number of nodes in its neighborhood. Thus, the above update rule tries to optimize the transmission probability for the number of nodes in the neighborhood of each node and not for the entire network. However, the sink can measure the idle time for the entire network and piggy back this value in the ACKs to the sensor nodes. The sensor nodes measure the epoch delay as the interval between the ACKs. Thus, in this case, the channel feedback is via the sink.

The performance difference in terms of degradation or improvement, if any, between the local feedback and global feedback based mechanisms needs to be investigated. This will be one of the directions for our future work.

An important aspect of the Enhanced IEEE 802.15.4 MAC



(a) Continuous Data　　(b) One-Shot Data

Figure 11: Performance of Channel Feedback Enhanced IEEE 802.15.4.

protocol is that all nodes should change their window sizes and choose a new time slot (or start a new counter) at every successful packet transmission. Otherwise, only a few nodes optimize their window sizes and this could lead to unfairness in the CD scenario.

Another important aspect to consider is the effect of channel errors. The current standard MAC assumes channel errors based packet losses to be collisions and backs-off accordingly, thus misconstruing channel errors as congestion. But the enhanced MAC protocol does not change any protocol parameters due to channel errors based packet losses, as successful packet transmissions are taken as the only indicators of channel congestion. Nevertheless, a thorough investigation of the effect of channel errors will be an important part of our future work.

In this paper we have focused on dense sensor networks. The following table shows the throughput performance comparison of the original and enhanced IEEE 802.15.4 MAC protocols for lower number of nodes. Clearly, according to the results, the current MAC performs better than the enhanced MAC for low number of nodes. But with increasing number of nodes, the enhanced MAC increasingly performs better.

N	10	20	30	40
Original	110	85	58.75	38.75
Enhanced	13.75	63.75	63.75	61

Table 2: Performance comparison of Original and Enhanced IEEE 802.15.4 MAC for CD in term of throughput ($\Phi_{CD}(N)$) in Kbps for *Low* density networks.

In the enhanced MAC protocol we have used a single optimality criterion from Section 3. We would like to investigate the use of the other criteria also. Recent research has focused on the effect of capture effect on wireless MAC protocols. In the future we wish to study the influence of capture effect on the enhanced IEEE 802.15.4 MAC for the two data collection scenarios.

6. CONCLUSION

We have shown that the current IEEE 802.15.4 MAC performs poorly for data collection in dense sensor networks. We presented a channel feedback enhanced MAC protocol that performs significantly better than the current version. For this we modeled the IEEE 802.15.4 MAC as a p-persistent CSMA with changing p, optimized a generic p-persistent CSMA MAC and used the resulatant optimality criteria to propose a channel feedback-based enhancement for the original IEEE 802.15.4 MAC. Results showed that our Enhanced IEEE 802.15.4 MAC scales significantly better for both continuous data and one-shot data collection scenarios in dense networks (number of nodes is greater than 50). For low density networks the performance of the current MAC is better for upto 25 nodes after which the performance of the enhanced MAC is better.

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