KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS VOL. 6, NO. 12, Dec 2012

Design, Analysis and Evaluation of A New Energy Conserving MAC Protocol for Wireless Sensor Networks

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Received August 29, 2012; revised October 9, 2012; accepted October 31, 2012;
published December 27, 2012

Abstract

Low power listening (LPL) MAC protocols based on duty-cycling mechanism have been studied extensively to achieve ultra low energy consumption in wireless sensor networks (WSNs). Especially, recent ACK-based LPL schemes such as X-MAC employ *strobe preambles* and an *early ACK*, and show fair performances in communications and energy efficiencies. However, the state-of-the-art ACK-based LPL scheme still suffers from collision problems due to the protocol incompleteness. These collision effects are not trivial and make WSNs unstable, aggravate energy consumptions. In this paper, we propose two novel schemes; (i) τ-duration CCA to mitigate the collision problem in ACK-based LPL MAC protocols. (ii) Short Preamble Counter (SPC) to conserve more energy by reducing unnecessary overhearing. We demonstrate the performance improvement of our scheme via a mathematical analysis and real-time experiments. Both analysis and experimental results confirm that our proposed scheme saves energy by up to 36% compared to the naive ACK-based LPL MAC protocol thanks to τ-duration CCA and SPC.

Keywords: Low power listening, duty-cycling, CCA, wsn, energy efficiency, MAC

A preliminary version of this paper (won the best paper award) was presented in the International Conference on Information Networking (*ICOIN*), Chiang Mai, Thailand, 2009. While the preliminary version provided the motive and basic idea of our work, this extended version includes another novel idea and more detailed descriptions on related work, analysis and experiments. In addition, all sections are revised to improve the presentation and clarity. We clarify that this extended version has more than 30 percent substantial contributions. This research was supported by the Korean Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST) (No. 201208302002) and the IT R&D Program of MKE/KEIT [10035708, “The Development of CPS (Cyber-Physical Systems) Core Technologies for High Confidential Autonomic Control Software”].

http://dx.doi.org/10.3837/tiis.2012.12.001

1. Introduction

In wireless sensor networks (WSNs), energy efficiency is one of the most important performance criteria since WSNs consist of numerous battery-powered sensor devices. Especially, idle listening (*i.e.*, listening for potential packets) and overhearing (*i.e.*, receiving a packet destined for other nodes) problems are two main sources of energy consumption at the MAC layer [1]. To tackle these problems, novel and diverse schemes [2][3][4][5][6][7][8][9] have been proposed. These solutions adopt a *duty-cycling* mechanism which alternates periodically between sleep state and active state. Duty-cycling approaches are divided into the following two categories according to whether the sensor nodes in the same network are synchronized or not; (i) scheduled listening (SL) [2][3][4][5] and (ii) low power listening (LPL) [6][7][8][9].

The SL approaches periodically broadcast a control packet specifying the asleep/awake period for all sensor nodes, and thereby maintain all nodes to be synchronized. Thus, it can reduce idle listening by turning off its radio during the asleep period. Since the synchronization among all nodes in a network is not a trivial work, the SL approaches fit well in small-sized WSNs in general.

In contrast, the LPL schemes do not require any time synchronization among sensor nodes and can be widely utilized in both large and small sized networks. The LPL approaches minimize idle listening by devising a preamble-based asynchronous rendezvous between a sender and a receiver. We can further divide the LPL schemes into two groups; (i) basic LPL [7] and (ii) ACK-based LPL [8]. The basic LPL scheme such as B-MAC [7] transmits a long preamble to wake up its one hop neighbors, obliterating tight time synchronizations among sensor nodes. However, the excessive preamble of basic LPL brings out an overhearing problem. To remedy this overhearing problem, the ACK-based LPL schemes (ACK-LPL) [8] are proposed. The ACK-LPL employs *strobe (short) preambles* and an *early ACK*. Each short preamble conveys a destination address. After sensing and decoding an ongoing short preamble, only an intended receiver among neighbors immediately replies via an early ACK. Briefly, the strobe preamble eliminates overhearing and the early ACK reduces per-hop latency significantly.

Even though the ACK-LPL conserves energy substantially, it still suffers from collisions in an ACK listen period. Suppose a sender successfully grabs a channel and initiates a transmission. In the middle of this transmission, a contending node can initiate a transmission if it incorrectly assesses the channel as an idle (indeed busy due to the ongoing transmission). This situation can be possible if the contending node performs a CCA (Clear Channel Assessment) in the middle of the ACK listen period. As a matter of fact, we measured the CCA duration of current commercial sensor motes such as TelosB [10] and found out that the measured CCA duration (=128*usec*) is not enough to avoid collisions effectively in the ACK listen period. A concurrent transmission attempt induced by an incorrect CCA destroys an ongoing transmission as well as a new transmission and results in compromising the benefits of the ACK-LPL schemes severely. For this reason, it is a challenging task to resolve the collision problem in an ACK listen period.

In this paper, we first analyze the collision probability in an ACK listen period to confirm that the collision problem significantly affects a system performance and then propose a simple yet effective method called τ-duration CCA to remedy this problem. By simply extending and guaranteeing the CCA duration of the ACK-LPL schemes to be longer than the gap between two consecutive short preambles (*i.e.*, ACK listen period), we can increase the transmission success probability greatly compared to current ACK-LPL solutions.

To further enhance the performance of the ACK-LPL, we devise another clever scheme called Short Preamble Counter (SPC). Once a contending node senses a channel busy, it initiates a congestion back-off in order to avoid a collision with an ongoing transmission. This congestion back-off also may cause excessive energy consumption because all contending nodes keep a radio state in a receiving state until the ongoing transmission is finished. To address this problem, we insert an 8-bit sequence number into each short preamble to inform contending nodes of the duration of an ongoing transmission. The contending nodes go back to sleep state during the ongoing transmission instead of taking a congestion back-off by interpreting the SPC information.

The analytic and experimental results in a small scale test-bed consisting of 11 commercial sensor motes verify that our proposed scheme saves energy by up to 36% compared to the state-of-the art ACK-LPL scheme thanks to the power of τ-duration CCA and SPC.

Our main contributions on this paper are summarized as follows.

- We characterize the collision problem in an ACK listen period of the ACK-LPL schemes and demonstrate the impact of this problem by analyzing the collision probability in the ACK listen period.
- We propose τ-duration CCA and SPC methods to remedy the collision problem in the ACK listen period and to reduce an unnecessary overhearing in a congestion back-off, respectively.
- We demonstrate that effectiveness of our proposed scheme through real-time experiments consisting of 11 sensor motes. The experimental results confirm that the ACK-LPL adopting the combination of τ-duration CCA and SPC saves energy significantly compared to the naive ACK-LPL scheme.

The rest of this paper is organized as follows. Section 2 summarizes and reviews the related work on exemplary duty-cycling solutions in WSNs. In Section 3, we introduce the design and operation of our scheme in detail. Section 4 presents a mathematical modeling and performance results from the numerical analysis and simulation results. The experimental results are provided in section 5. Finally, we conclude the paper in Section 6.

2. Related Work

There have been a plethora of research efforts to improve energy efficiency [11][12] of wireless sensor networks, especially at the MAC layer. Idle listening is the most significant source of energy consumption for most sensor MAC protocols. This motivates the duty-cycling technique that alternates the sleep and awake states periodically. Previously proposed MAC protocols based on duty-cycling can be categorized into the following two approaches: (i) synchronous and (ii) asynchronous.

2.1 Synchronized Duty-Cycling Approaches

S-MAC [2] is one of the well known synchronized duty-cycling MAC protocols for WSNs. All nodes are time synchronized, so that they wake up and sleep at the same time. For synchronous wakeup scheduling, all nodes exchange a SYNC packet containing sleep interval to their neighbor nodes periodically. Each node transmits a data packet to an intended receiver based on the RTS-CTS mechanism during the predetermined active period and goes to the sleep state during the sleep interval to avoid idle listening. All nodes, however, must wait for a fixed active period even though there is no packet to send or to receive, and thereby bring out substantial overheads. To remedy this drawback, T-MAC [3] dynamically adapts a listen and sleep duty cycle through fine-grained timeouts, eliminating additional idle listening. Under heterogeneous traffic load, the adaptive duty-cycling outperforms static duty-cycling in terms of an end-to-end latency and energy efficiency. In addition, RMAC [4] has been proposed to reduce the latency of SL approaches in a multi-hop forwarding and DW-MAC [5], a low-overhead synchronized scheduling algorithm, has proposed on-demand wake-up during the sleep period. This demand wake-up adaptively determines effective channel capacity during a duty-cycle according to the traffic loads to reduce the end-to-end delivery latency. However, synchronized schemes induce severe overheads for multi-hop time synchronizations, especially in large scale WSNs. In addition, unreliable links common in wireless networks make global time synchronizations more difficult [13].

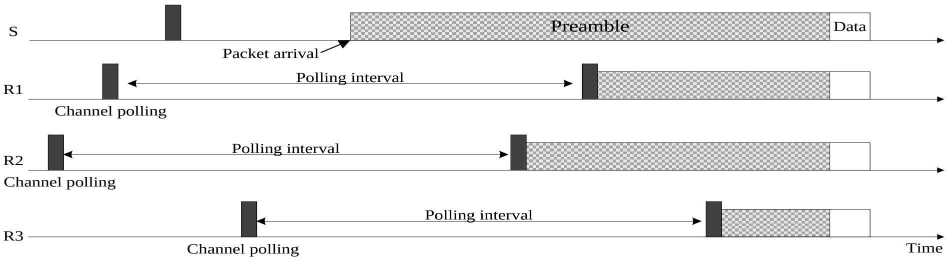


Fig. 1. LPL (Aloha with preamble sampling and B-MAC)

2.2 Asynchronous Approaches

Asynchronous duty-cycling MAC protocols such as Aloha with preamble sampling [6] and B-MAC [7] do not require any time synchronization and reduce idle listening by *Low Power Listening* (LPL). In LPL, each node usually sleeps to reduce the energy consumption and periodically wakes up at each polling interval to communicate with neighbor nodes. **Fig. 1** shows the overall packet transmission operations of LPL (*i.e.*, Aloha with preamble sampling and B-MAC). There are one sender S and three neighboring nodes (R1, R2 and R3). Suppose R1 is the intended receiver. When S fetches a packet from the upper layer, it attaches a preamble longer than the polling interval in front of each data packet so that the receiver will be in the awake state when the data packet is transmitted. Remember that S does not know the exact wake up time of the target node R1. Upon detecting the long preamble, all one-hop neighbors of S keep its radio in receiving state (*i.e.*, idle listening) irrespective of whether it is the intended receiver or not. For this reason, the LPL schemes waste energy due to the long idle listening duration at the target node R1 and overhearing at the non-target nodes R2 and R3.

The ACK based LPL schemes (ACK-LPL) such as X-MAC [8] have been proposed to overcome the drawbacks of the basic LPL. Instead of using one long preamble, X-MAC strobes short preambles that each contains the destination address. Therefore, the ACK-LPL wakes up only when the destination receiver either receives or overhears the non-target nodes. In addition to the strobe preamble strategy, the ACK-LPL employs an early ACK mechanism that solves idle listening at the receiver node. As shown in **Fig. 2**, a sender S repeats a transaction in which it transmits a short preamble and waits for an ACK. Suppose R2 wakes up earlier than R1. Detecting a short preamble and examining the destination address in the short preamble, R2 goes back to the sleep state immediately since it is not the intended receiver. The strobe preamble transmission is continued until the intended receiver R1 detects a short preamble and responds with an early ACK. The sender S transmits a data packet immediately after receiving the early ACK packet from the intended receiver R1 and then terminates its transmission. Although it is well known that the performance of ACK-LPL is better than the other duty-cycling MAC protocols, its improvement on energy conservation is limited due to the collision problem during the ACK listen period. In fact, it is possible that a contending node initiates a new transmission in the middle of ACK-Listen period of an ongoing transmission because the current CCA duration set on sensor motes such as TelosB is shorter than the ACK-Listen period. Our τ-duration CCA mechanism effectively eliminates this problem and achieves higher energy efficiency. Since the collision problem in ACK-Listen period arises from an insufficient CCA duration, we regulate the CCA duration (*i.e.*, τ-duration) to be longer than the ACK listen period. As a result, τ-duration increase the transmission success probability significantly and save more energy compared to current ACK-LPL solutions.

Until now, we have reviewed some sender-based preamble sampling schemes belong to the asynchronous approaches. The sender-based preamble sampling schemes, however, may lead long channel occupancy and overhearing of non-targeted nodes, consuming much energy. To resolve these problems, several receiver-initiated approaches [14][15][16][17][18] have been introduced.

RI-MAC [16] eliminates both the excessive channel occupying problem and the overhearing problem by a receiver-initiated beaconing technique instead of a long preamble of a sender. The potential sender in RI-MAC remains active and waits silently for a short beacon message specifying when to start data transmission from the receiver. Despite these advantages, RI-MAC may still suffer from collisions when multiple receivers transmit beacon frames simultaneously. In contrast, our solution resolves transmission contentions effectively via τ-duration CCA.

In PW-MAC [17], a *pseudorandom* function is introduced to control the wake time of each node. This mechanism allows senders accurately to predict the wake-up time of each node, so that both a sender and a receiver save the duty-cycle energy near-optimally. PW-MAC spreads the wake-up time of each node to reduce collisions among multiple senders. For this reason, it can minimize idle listening and overhearing, thereby achieving high energy efficiency. However, this prediction-based approach is prone to miss the rendezvous point between senders and receivers repeatedly due to the several reasons such as hardware clock drifts or operating system latency. In contrast, our scheme is not relevant to the tight clock function since it is based on a real-time CCA function.

EM-MAC [18] enhances PW-MAC by exploiting an *exponential chase* algorithm for an efficient resynchronization between a sender and a receiver whose clocks may have drifted apart. In addition, EM-MAC spreads the traffic load to different channels to minimize the collisions among multiple senders. While EM-MAC operates on a multi-channel environment, our proposed solution targets a single channel environment which is a typical setting in WSNs.

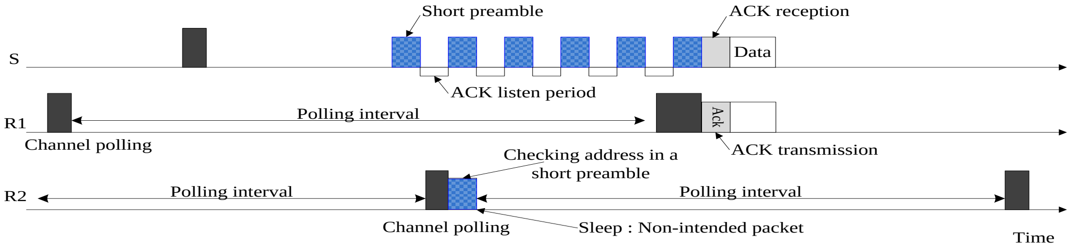


Fig. 2. Basic ACK-LPL

3. Collision Mitigation and Effective Back-off of the ACK-LPL

In this section, we first point out a collision problem of the ACK-LPL and then propose two novel performance enhancement strategies; (i) τ-duration CCA and (ii) SPC.

A. *Collision Problem of the* ACK-LPL

The ACK-LPL scheme may cause collisions among contending nodes during an ACK listen period. We elaborate on this problem with a simple example as illustrated in **Fig. 3.** Suppose there are two contending senders competing for a channel. If one of the senders assesses the channel idle, it starts transmitting short preambles. Note that the basic operation of the ACK-LPL is alternating two activities, transmitting a short preamble and receiving for a potential ACK packet (*i.e.*, ACK listen period), repeatedly until the end of transmission. Suppose a contending sender performs a CCA in an ACK listen period, incorrectly assesses the channel *idle* (*i.e.*, the channel is indeed *busy*), and initiates its transmission. This misbehavior raises two problems. First, both the ongoing sender and the contender suffer from collisions and therefore additional retransmissions which waste scarce wireless bandwidths are required. Second, they have to spend unnecessary energy for eventual failed transmissions during the entire packet transmission duration. Since the ACK listen period plays an important role in guaranteeing the reliable transmission of an ACK, it must be protected from interfering transmissions and be fixed as much as maximum ACK wait duration recommended by the IEEE 802.15.4 standard (*i.e.*, ZigBee) [19]. However, each node only checks a channel status at the starting point of the first short preamble and does not care about the gaps between short preambles. In our experimental measurements, current sensor motes perform a CCA only for 128*usec*. We argue that the CCA check duration at every wake-up moment must be longer than the ACK waiting duration of a sender to safely detect the short preambles.

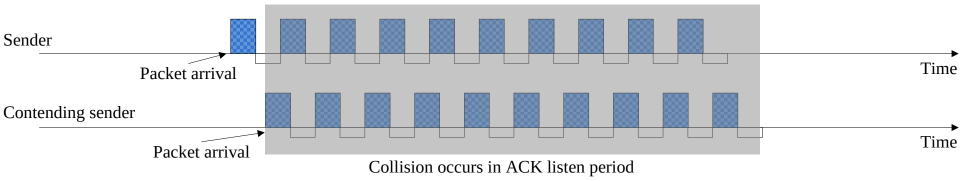


Fig. 3. Collision problem of the basic ACK-LPL

B. *τ-duration CCA Method*

To mitigate the collision probability of the naive ACK-LPL, we propose a τ-duration CCA method as a complimentary means. Let τ-duration be the maximum ACK wait duration in the ACK-LPL. In our method, every node continuously senses whether radio channel is busy or not during the τ-duration before sending the first short preamble as shown in **Fig. 4**. In this paper, we set the CCA duration as 1.92*msec* to guarantee the successful channel assessment. If a node senses a channel busy while performing a CCA, the node recognizes that another node already occupies the channel. With the proper CCA duration, other contending nodes defer their transmissions by taking a congestion back-off and then perform the τ-duration CCA again. Since all contending nodes perform the τ-duration CCA, the node in the middle of ongoing transmission does not need to consider any collision by other contending senders. This simple τ-duration CCA method makes up for the performance drawback of the ACK-LPL schemes and further improves the energy efficiency by reducing the transmission energy that could be wasted by packet collisions.

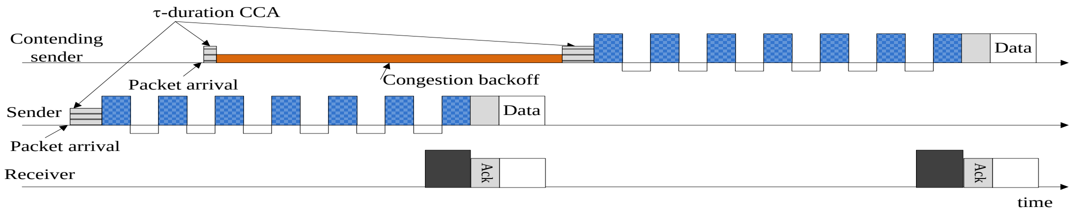


Fig. 4. Collision avoidance of the ACK-LPL with τ-duration CCA

C. SPC for eliminating Congestion Back-off

As we explained in the previous subsection, once a contending node senses a channel busy, it initiates a congestion back-off process to avoid a collision with an ongoing transmission as shown in **Fig. 4**. The congestion back-off, however, also causes excessive energy consumption since the node performing a congestion back-off keeps a radio state in a receiving state (*i.e.*, overhearing) until the ongoing transmission is finished. This kind of energy consumption stems from the fact that the contending node in the middle of congestion back-off does not know the end of the ongoing transmission. To resolve this inefficacy in the congestion back-off, we devise a simple yet powerful technique called SPC. Note that the basic idea of SPC has been previously proposed in our earlier work [20][21]. We elaborate on the detailed operation of SPC further in this paper.

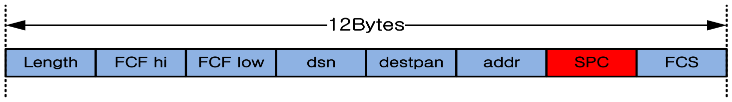
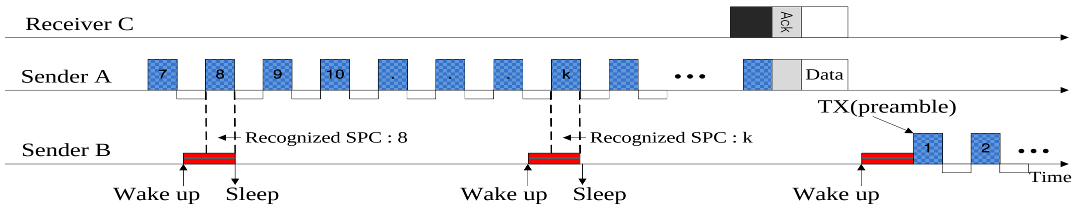


Fig. 5. Short Preamble Structure: an 8-bits SPC is embedded in each short preamble

We divide a maximum channel polling interval into n short preambles and insert an 8-bits sequence number into each short preamble as shown in **Fig. 5.** Each sequence number specifies the elapsed time from the start time of the transmission. From this information, the neighbors can calculate the residual time to the maximum transmission duration of current sender. Let us explain the operation of SPC with an example as illustrated in **Fig. 6.** Suppose sender A wins a channel contention and initiates the transmission of short preambles. Upon hearing a preamble, sender B returns to the sleep state immediately instead of carrying **out** a congestion back-off and wakes up after the predicted channel busy time Δ. The predicted channel busy time is calculated as the following equation.

$$\text{The predicted channel busy time } (\Delta) = \frac{\text{channel polling time } (n) - \text{ elapsed time } (k)}{2}.$$



Calculated sleep duration = (Channel Polling Interval − Elapsed Time)/2

Fig. 6. Avoiding an overhearing problem by calculating the predicted channel busy time

The rationale behind this equation is to reduce energy consumption during a congestion back-off process via opportunistic channel polling instead of overhearing the entire preamble transmissions.

4. Analysis

A. *Mathematical Modeling*

We compare the performance of the basic ACK-LPL with that of the ACK-LPL *with* τ-duration CCA via an analytic modeling. To analyze the successful transmission probability and the energy consumption of the ACK-LPL MAC, we assume that each packet has the same length, requires one time unit for transmission and arrives for transmission according to independent Poisson process. Let λ and G be the overall arrival rate to the system and the attempt rate in a slot, respectively. A new packet arrives at a node in the normalized slot σ and each of n_b backlogged nodes transmits a packet independently in the given slot with probability λ_b.

According to the assumption of non-persistent CSMA, the successful transmission probability P_{succ} of ACK-LPL *with* τ-duration CCA is given by

$$P_{succ} = Ge^{-G} \tag{1}$$

where

$$G = \lambda\sigma E[B] + \lambda_{\mathrm{b}} n_b,$$
$$\sigma = \frac{S_b}{\frac{l_p}{2} + l_D}$$

In (1), $E[B]$ denotes the average number of back-off slots and σ presents the ratio of one slot, S_b, to the average packet transmission time, $l_p/2+l_D$, where l_p and l_D are the entire polling time and the time to transmit a data packet, respectively.

In the case of the ACK-LPL *without* τ-duration CCA, P_{succ} is defined as

$$P_{succ} = Ge^{-G}e^{-\alpha G} \tag{2}$$

where

$$\alpha = \frac{l_p r_{ack}}{l_p + 2l_D}.$$

Here, α and r_{ack} represent the normalized ACK listen period in average packet transmission time and the ratio of the ACK listen period to the entire preamble transmission duration, respectively. The successful transmission occurs only if other nodes do not attempt a transmission during σ and α.

With the transmission success probability, we can derive the energy consumption model in a single hop environment consisting of n nodes. The energy model is composed of three different energy states: the successful transmission, the collided transmission, and the idle state. Thus, the expected energy consumption is

$$\begin{aligned} E = P_{succ}\left(P_{tx}\left(\frac{l_p(1-r_{ack})}{2}+l_{ack}+l_D\right)+P_{rx}\left(\frac{l_p r_{ack}}{2}+l_{ack}+l_D\right)+\frac{(n-2)}{2}P_{rx}l_{pl}\right) \\ +P_{fail}\left(2l_p\left(P_{tx}(1-r_{ack})+P_{rx}r_{ack}\right)+(n-2)P_{rx}l_{pl}\right) \\ +P_{idle}\left(nP_{rx}\frac{l_{pl}}{l_p}\sigma\right) \qquad (3) \end{aligned}$$

where

$$P_{idle}=e^{-G}, \qquad P_{fail}=1-(P_{succ}+P_{idle}).$$

In (3), P_{tx} and P_{rx} are powers used in transmitting and receiving respectively, and l_{pl} is the time to poll the channel in every polling interval. We assume that the wake up times of receivers are uniformly distributed. Therefore, the time for a successful transmission is made up of a half of polling interval and a data transmission time (*i.e.*, $l_p/2+l_D$) on average. From (3), we can see that the energy consumption significantly depends on both P_{succ} and P_{fail}. We can increase the transmission success probability with our τ-duration CCA. Consequently, the energy efficiency of ACK-LPL can be significantly improved. To show the collision resolution effect, we express the normalized energy consumption per successful transmission as

$$E_{succ}=\frac{E}{P_{succ}} \qquad (4).$$

TABLE 1. SYMBOLS USED IN ANALYSIS AND EXPERIMENTS

symbol	Meaning	CC2420
P_{tx}	Power in transmitting	52.2mW
P_{rx}	Power in receiving	56.4mW
r_{ack}	The ratio of ACK listen period to the entire polling	0.6
S_b	interval	320us
τ	One back-off slot size	1.92ms
l_p	The time to perform CCA	100ms (variable)
l_D	The entire polling time	1.6ms (measured)
l_{pl}	The time to transmit a DATA packet	9.3ms (measured)
l_{ack}	The time to poll the channel	0.8ms (measured)
	The time to send an ACK packet	

B. *Numerical Results*

We evaluate our analytic model using the specifications of the well-known CC2420 radio [22]. In addition, we have performed simulation-based evaluations to verify the correctness of our mathematical analysis. **Fig. 7, 8** and **Fig. 9** show both analytical and simulation results and we can find very similar trends in both evaluation results. **Table 1** lists symbols and parameters used in the analysis and experiments. **Table 1** lists symbols and parameters used in the analysis and experiments. **Fig. 7** shows the transmission success probabilities of the basic ACK-LPL and the ACK-LPL with τ-duration CCA when there exist ten sensors and the packet arrival rate varies from 0 to 5. Our proposed scheme reduces possible collisions in an

ACK-listen period effectively through τ-duration CCA, thus achieving higher transmission success probability than that of the basic ACK-LPL.

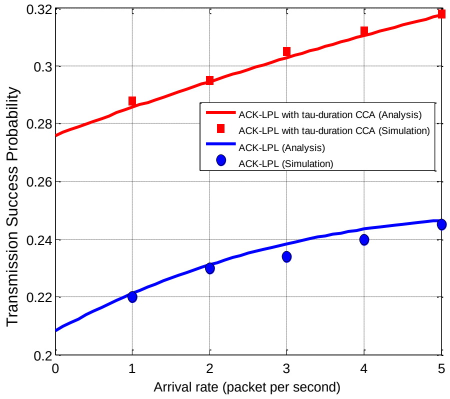


Fig. 7. Transmission Success Probability (n=10, $\lambda = 0 \sim 5$)

Fig. 8 shows the collision probabilities of both schemes. Other settings are same with those in **Fig. 7.**

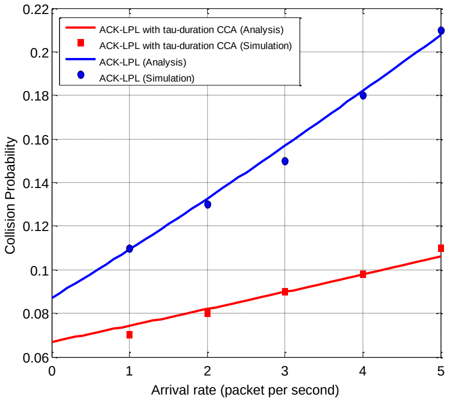


Fig. 8. Packet Collision Probability (n=10, $\lambda = 0 \sim 5$)

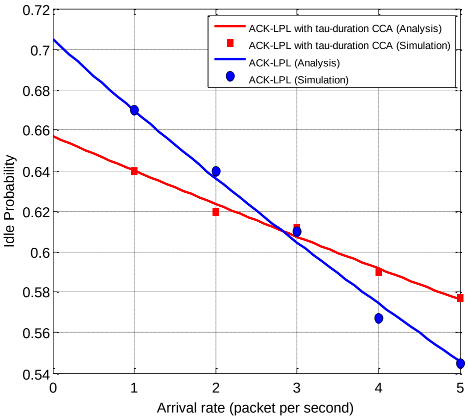


Fig. 9. Idle Probability (n=10, $\lambda = 0 \sim 5$)

As the packet arrival rate increases, both schemes experience more collisions. However, the collision probability of τ-duration CCA increases gradually while that of the basic ACK-LPL increases rapidly. Note that the higher collision frequency exacerbates an exponential back-off more and more and results in escalating the idle time of the system as we can see in **Fig. 9**.

5. Experimental Evaluations

A. Experimental Setup

To validate the energy consumption model, we have implemented both the ACK-LPL and the ACK-LPL with τ-duration CCA on TelosB sensor devices running TinyOS 1.1 [23] and measured the energy consumption by recording the sojourn time at different radio states (*i.e.*, active or sleep state). TelosB [10] sensor node consists of a MSP430 Micro Control Unit (MCU) [24] and a CC2420 radio chipset [22]. The CC2420 chipset is an 802.15.4 compliant device which operates in the 2.4GHz ISM band and has a data rate of 250kbps. The Chipcon CC2420 packetizing radio inserts its own preamble in the front of a payload. We organize a simple single-hop topology; a receiver in the center and ten senders around the receiver. All nodes perform a duty-cycling and senders transmit a unicast packet to one receiver according to their arrival rates. The information for each node is gathered by one receiver which is connected to the monitoring system.

B. Experimental Evaluation Results

- The effect of τ-duration CCA on Energy Consumption

Fig. 10 shows both analytical and experimental results for the normalized energy consumption per successful transmission as a function of the average arrival rate. As we can observe in **Fig. 10**, the overall energy consumption trends in both analytic and experimental results are similar by and large. In the basic ACK-LPL, the collision happens more and more as the packet arrival rate increases, thereby much energy is wasted by nodes maintaining longer active state during the entire transmission period. In a real environment, as the arrival rate increases, more packets are dropped and the normalized energy consumption increases linearly. As a result, the ACK-LPL with τ-duration CCA consumes less energy than basic ACK-LPL due to the effect of collision avoidance. In particular, the ACK-LPL with τ-duration CCA outperforms basic ACK-LPL around 23% in terms of energy efficiency when the arrival rate is 5pps.

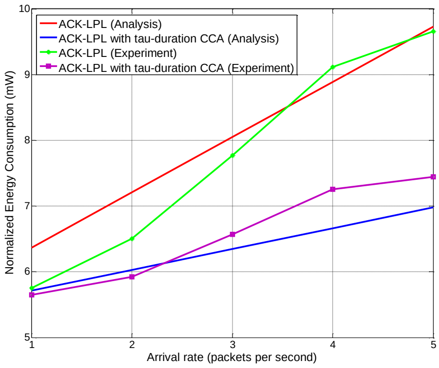


Fig. 10. Energy consumption as a function of arrival rate

- The effect of τ-duration CCA on collision resolution

In WSNs, event detection is one of the main requirements for most of the applications [25][26]. In the case of event detection application, each node deployed in the sensing field reports the physical information to the sink node after detecting a special event. At that time, several nodes that sense the event in the region transmit the information to the sink node immediately. To compare the collision resolution performance improvement of our scheme in this basic scenario, we generate unicast packets of all nodes simultaneously every 5 seconds. **Fig. 11** shows the transmission success rate of both protocols according to the number of contending nodes. We perform the experiments with two different channel polling intervals (100*msec* and 300*msec*). As the number of simultaneous packet transmissions increases, basic ACK-LPL severely suffers from packet losses. Note that each preamble-ACK listen iteration can cause packet collisions, more packets are dropped at the 300*msec* polling interval than at the 100*msec* polling interval in the basic ACK-LPL. In contrast, ACK-LPL with τ-duration CCA prevents packet collisions substantially, achieves high transmission success probability. Consequently, the ACK-LPL with τ-duration CCA conserves much energy than that of the basic ACK-LPL.

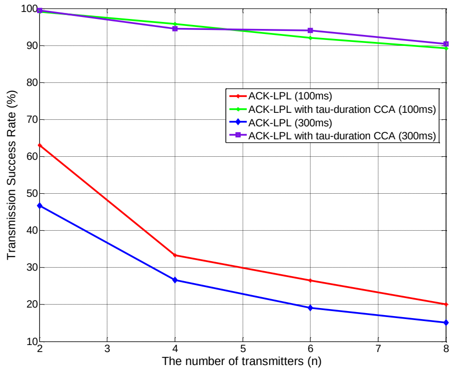


Fig. 11. Transmission success rate as a function of the number of transmitters

- The effect of SPC on Energy Consumption

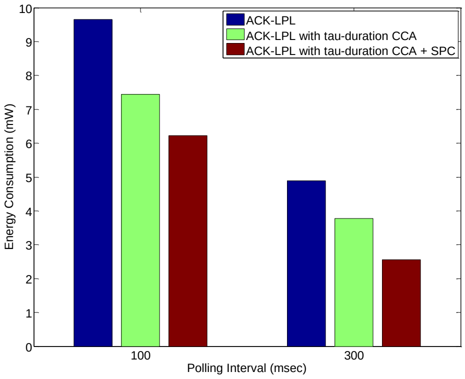


Fig. 12. Energy consumption comparison: ACK-LPL, ACK-LPL with τ-duration CCA, and ACK-LPL with both τ-duration CCA and SPC

Fig. 12 shows the energy consumption of (i) the basic ACK-LPL, (ii) the ACK-LPL with τ-duration CCA and (iii) the ACK-LPL with τ-duration CCA and SPC at 100*msec* and

300*msec* polling intervals, respectively. We conduct the experiment with the fixed arrival rate, 5pps. Through this experiment, we have the following results. First, all schemes show better performances (*i.e.*, low energy consumption) at the 300*msec* polling interval than at the 100*msec* polling interval since the long polling interval is beneficial to save more energy in a low traffic environment. Second, we can observe that τ-duration CCA resolves the contentions effectively, and thereby reduces the energy consumption up to 23% compared to basic ACK-LPL. In addition, SPC reduces unnecessary overhearing in the congestion back-offs and achieves additional energy saving effects. Consequently, the combination of τ-duration CCA and SPC reduces energy consumption by up to 36% compared to the naive ACK-LPL.

6. Conclusions

In this paper, we argued that current CCA duration set in typical commercial devices such as TelosB is not enough to avoid packet collisions during the ACK-Listen periods in the ACK-LPL schemes. To address this problem, we have proposed a τ-duration CCA method to prevent the collisions. In addition, SPC, an adaptive sleep scheduling method, has been introduced to reduce unnecessary overhearing energy during the congestion back-offs. To demonstrate the performance of our proposed scheme, we have conducted a mathematical analysis and empirical experiments in a small test-bed. Both results verified that our τ-duration CCA and SPC mitigate the collision problem effectively and reduce excessive overhearing energy significantly. In particular, the combination effect of both τ-duration CCA and SPC reduces energy consumption by up to 36% compared to naive ACK-LPL when the packet arrival rate is 5pps and the polling interval is 300*msec*.

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