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Performance Analysis of IEEE 802.15.4 MAC Protocol under Light Traffic Condition in IoT Environment

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Abstract– **In this paper, we propose analytic models for throughput and latency performance of the IEEE 802.15.4 MAC protocol operating under very low duty cycles in the Internet of Things applications. Our analytic models are intended for IEEE 802.15.4 MAC protocol in beacon-enabled star topology with random and light traffic conditions. Accuracy of the analytic models is verified through extensive simulations using the network simulator ns-2. A strong agreement between simulation results and our theoretical analysis is observed. In addition, we compare throughput and latency performance of two different CSMA/CA protocols in IEEE 802.15.4 and IEEE 802.11. This is motivated by a significant discrepancy of the CSMA/CA mechanisms in IEEE 802.15.4 and IEEE 802.11 standards. We observe a remarkable difference in throughput between two protocols. The simulation results also demonstrate an interesting fact that increasing the packet size will degrade the throughput of IEEE 802.15.4 due to the nature of the CSMA/CA mechanism, while a throughput improvement is usually expected.**

Keywords– **Wireless sensor network, IEEE 802.15.4, Wireless PAN, MAC protocol, CSMA/CA algorithm, Performance analysis, Beacon-enabled mode, Inactive and active periods.**

1 Introduction

In recent years, one of the active research areas gaining a remarkable interest is the Wireless Sensor Networks (WSNs) for the Internet of Things (IoT) [1]. The most distinguished feature of WSNs is that it consists of networked sensor devices that are powered by small batteries and distributed densely large areas to monitor physical quantities. Hence, energy efficiency is the utmost priority to be considered when designing any algorithm or protocol for WSNs. While offering a wide range of applications, WSNs were also facing some difficulties in standardization. Many studies have been dedicated to developing the general standard protocols for WSNs for the IoT [2–6]. In particular, the release of the IEEE 802.15.4e standard for low-data-rate and low-power consumption in Wireless Personal Area Network (WPAN) [7] is considered as one of the promising candidates for WSN for the IoT.

The IEEE 802.15.4 MAC protocol uses a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, which is similar to that of IEEE 802.11, to improve the probability of successful data transmission. Specifically, the CSMA/CA mechanism in IEEE 802.15.4 also uses the binary exponential backoff but differs in the way of handling busy medium. In addition, the IEEE 802.15.4 standard supports both star and peer-to-peer topologies with two operational modes depending on the application requirements. One operational mode is the non beacon-enabled mode using the simply unslotted CSMA/CA protocol. The other is the beacon-enabled mode employing the slotted CSMA/CA protocol. In this mode, the duty cycle is the main factor determining the energy efficiency. An improvement on throughput and latency can be achieved if the value of the duty cycle is large enough. In terms of throughput and energy consumption, several efforts have been made to study the performance of IEEE 802.15.4 by using probability models as well as network simulation tools. In [8], the theory of discrete-time Markov chain and M/G/1 queuing is applied to analyze throughput of the beacon-enabled cluster network with bidirectional traffic for both uplink and downlink. But, it is difficult to follow the method in [8] due to the exact behavior modeled without much simplification. The authors in [9] proposed a Markov chain model for throughput performance of the IEEE 802.15.4 networks with a star topology. It seems to be less useful in that it is based on the heavy traffic condition. In practice, the sensor networks often operate under light traffic condition. In [10], the throughput and energy consumption of the contention access period (CAP) are evaluated in the context of a one-hop star topology operating in the beacon-enabled mode with acknowledgement off (ACK off) and duty cycle 100%. However, the impacts of the low duty cycles were not investigated in [10]. The authors in [11] proposed a tele-medicine protocol (TMP) under the IEEE 802.15.4 slotted CSMA/CA with beacon-enabled mode in which the duty cycle is adjusted by three factors: offered network traffic load, delay-reliability factor, and superframe duration. The TMP provides the required set of QoS (delay, reliability, and efficient energy consumption) for patient monitoring applications simultaneously. An analytical model for IEEE 802.15.4 non beacon-enabled mode under non-saturated traffic pattern and large-scale network in Internet of Vehicle (IoV) applications is presented in [12]. The proposed scheme dynamically adjusts the broadcasting rate to achieve a higher probability of success in Vehicle to Vehicle (V2V) communications.

In this paper, our goal is to present the performance analysis of the IEEE 802.15.4 MAC protocol under very low duty cycles. Particularly, we focus on the WPAN network with a star topology operating in the beacon-enabled mode under the light traffic condition. The probability model is employed to derive the throughput and latency. The numerical results are verified using an extensive ns-2 simulation tool. As the second contribution of this work, we compare the throughput and latency of two CSMA/CA mechanisms implemented both in IEEE 802.15.4 and IEEE 802.11. This is motivated by the different characteristics of IEEE 802.15.4 versus IEEE 802.11. In order to make the CSMA/CA protocol of IEEE 802.11 comparable with that of IEEE 802.15.4 fitted into sensor networks, we modify some aspects of the CSMA/CA mechanism in IEEE 802.11 such as adding an clear channel assessment (CCA) operation at each backoff slot and freezing the backoff time when channel senses busy. The performance comparison is made with ACK on since the IEEE 802.11 protocol uses a positive ACK to signal a successful data transmission [13]. The simulation results indicate that the IEEE 802.15.4-based CSMA/CA has superior performance compared to IEEE 802.11-based CSMA-CA in terms of packet latency.

2 Overview of IEEE 802.15.4 Operation

Depending on the application requirements, IEEE 802.15.4 operates on either star or peer-to-peer topology. In the star topology, all communications between sensor devices must roam through a single central controller, called the PAN coordinator. On the other hand, in the peer-to-peer topology, the PAN coordinator also exists, but the devices can directly communicate to each other if they are in the transmission range. In addition, the beacon-enabled mode and non beacon-enabled mode are both supported in this standard. However, the most unique features of the IEEE 802.15.4 standard are only obtained in the beacon-enabled mode. This mode utilizes the slotted CSMA/CA mechanism based on a superframe structure which is defined by a coordinator as shown in Figure 1. The superframe consists of a beacon frame at the beginning responsible for synchronizing with sensor devices. The beacon frame is followed by an active period, which encompasses a contention access period (CAP), a contention free period (CFP), and an inactive period. The time between two consecutive beacon frames is defined as the beacon interval (BI). All sensor devices in WPAN only communicate to each other during the active portion and enter low-power mode or sleep mode in the inactive portion of superframe. Thus, the duty cycle defined as the ratio of the active period and BI plays a key role in determining the energy efficiency. The large duty cycle can obviously offer a throughput enhancement but result in significant energy loss. Thus, there exist tradeoffs among energy, latency, and throughput.

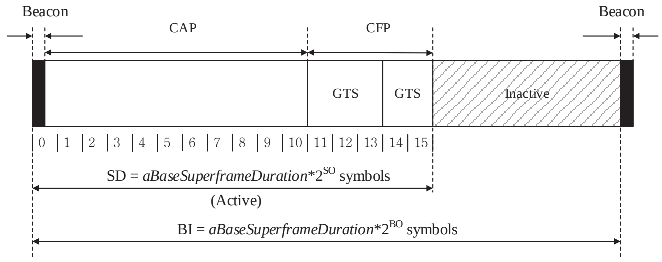

Figure 1. A superframe structure in IEEE 802.15.4.

3 Performance Analysis

We now proceed to analyzing the performance of the IEEE 802.15.4 MAC protocol. It is worth pointing out again that our derivations in this section are based on the star topology operating in the beacon-enabled mode under the light traffic condition.

3.1 Throughput

Generally, throughput is proportional to the probability of successful packet transmission. In case of ACK off, the packet collision can result in throughput loss since retransmission is disabled. We consider a WPAN in which n sensor nodes communicate with a PAN coordinator operating in beacon enabled mode. We assume that the traffic load is sufficiently light such that the packet arrives at inactive period (A_{off}) and active period (A_{on}) following Bernoulli distributions with parameter λ and $\alpha\lambda$, where α is the duty cycle given by $2^{(SO-BO)} \ll 1$. We denote, respectively, by (N_{off}) and (N_{on}) the number of packet arrivals during the inactive and active periods. The probabilities of k packet arrivals to the k sensor nodes in the WPAN over inactive and active periods, $\Pr[N_{\text{off}} = k]$, $\Pr[N_{\text{on}} = k]$ follows the binomial distribution, which are given by

$$\begin{aligned} \Pr[N_{\text{off}} = k] &= \binom{n}{k} \alpha^k (1-\alpha)^{n-k}, \\ \Pr[N_{\text{on}} = k] &= \binom{n}{k} (\alpha\lambda)^k (1-\alpha\lambda)^{n-k}. \end{aligned} \tag{1}$$

We also denote $\Pr[S|A_{\text{off}}]$ and $\Pr[S|A_{\text{on}}]$ as the probability of a successful packet transmission, given that a packet arrives during the inactive and active periods, respectively. Since we focus on the light traffic scenario of WPAN, traffic rate is supposed to be much less than transmission rate. As a result, $\Pr[N_{\text{on}} = k] \approx 0$ and hence, $\Pr[S|A_{\text{on}}] \approx 1$ because this induces very little contention in the network. The probability of a successful packet transmission, given that a packet arrives during the inactive period, $\Pr[S|A_{\text{off}}]$, is determined by the level of contention at the beginning of the next on period and given by

$$\Pr[S|A_{\text{off}}] = \sum_{k=1}^{n} \Pr[S|A_{\text{off}}, N_{\text{off}} = k] \Pr[N_{\text{off}} = k]. \tag{2}$$

The conditional probability $\Pr[S|A_{\text{off}}, N_{\text{off}} = k]$ in (2) can be computed through its complementary probability $\Pr[\overline{S}|A_{\text{off}}, N_{\text{off}} = k]$, where $\overline{S}$ means the event of an unsuccessful packet transmission or a lost packet. It is clear that, in the CSMA/CA mechanism of IEEE 802.15.4, a packet is lost if more than one node take the same backoff delay and collide at the same time or the number of transmission attempts is exceeded (this also means a channel access failure). Thus, we have

$$\Pr[\overline{S}|A_{\text{off}}, N_{\text{off}} = k] = \Pr[X|N_{\text{off}} = k] + \Pr[Y|N_{\text{off}}, \tag{3}$$

where X is the event that a channel access failure occurs, and Y is the event that more than one node take the same backoff delay and collide at the same time.

To evaluate the conditional probability of the event X, we need to assess the following probabilities [14]:

- The probability of a data transmission which is detected by CCA:

$$q = \frac{2L}{T_{CAP}} \tag{4}$$

where L is $PSDU$ (bytes), and $TCAP = aBaseSuperFrameDuration \times 2^{SO}$ is the CAP duration. The value of the parameter $aBaseSuperFrameDuration$ is 960 symbols (1 symbol corresponds to 4 bits) [7].

- The probability of an idle-sensed channel by two consecutive CCAs:

$$PCCA = (1-q)^{2k} \tag{5}$$

- The probability of a successful channel access with $macMaxCSMABackoffs$ backoff attempts, which is given by

$$P_{CCAS} = \sum_{n=1}^{m} P_{CCA}(1 - P_{CCA})^{n-1} \tag{6}$$

where m is denoted as the constant $macMaxCSMABackoffs$, representing the maximum value of the number of backoff attempts (NB).
The conditional probability of the event X is determined by

$$\Pr[X|N_{\text{off}} = k] = 1 - P_{CCAS}. \tag{7}$$

The conditional probability of event Y is found with the proposed discrete Markov chain model for each node shown in Figure 2. We take into account all possible values of backoff exponent (BE), CCA times, and NB.

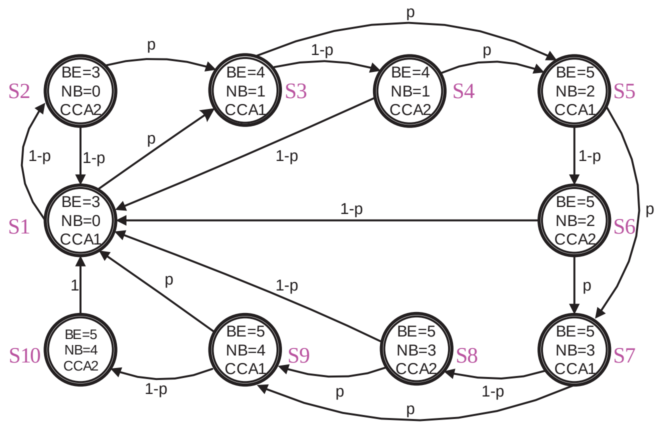

Figure 2. A discrete Markov chain model for BE states of each node.

In Figure 2, p is the probability of an clear channel by one CCA sensing which is written by

$$p = (1-q)^k. \tag{8}$$

We can easily find the steady-state probability $\Pr[S_j] \triangleq \Pi_{S_j}$ of the j^{th} state of the Markov chain in Figure 2 by solving a set of the balance equations as follow

$$\begin{aligned} \Pi_{S_1} &= p \sum_{i=1}^{4} \Pi_{S_{2i}} + (1-p)\Pi_{S_9} + \Pi_{S_{10}} \\ \Pi_{S_{2i}} &= p\Pi_{S_{2i-1}}, i = 1,2,...,5 \\ \Pi_{S_{2i+1}} &= (1-p)(\Pi_{S_{2i}} + \Pi_{S_{2i-1}}), i = 1,2,...,4 \\ \sum_{\text{i}=1}^{10} \Pi_{\text{S}_\text{i}} &= 1 \end{aligned} \tag{9}$$

By substituting the steady-state probability obtained from (9), the conditional probability of the event Y can be expressed as

$$\begin{aligned} \Pr[Y|N_{\text{off}} = k] &= \sum_{j=1}^{10} \Pr[Y|N_{\text{off}} = k, S_j] \Pr[S_j] \\ &= \sum_{j=1}^{10} \Pr[Y|N_{\text{off}} = k, S_j] \times \Pi_{S_j}, \end{aligned} \tag{10}$$

where $\Pr[Y|N_{\text{off}} = k, S_j]$ is given as follows

$$\Pr[Y|N_{\text{off}} = k, S_j] = \sum_{i=2}^{k} \frac{1}{(2^{BE_j})^{i-1}}. \tag{11}$$

Let $p_s \triangleq \Pr[\text{Successful - transmission}(S)]$ denote the probability of the event (S) that a packet is successfully transmitted. From the total probability theorem, p_s is given by

$$p_s = \Pr[S|A_{\text{on}}] \Pr[A_{\text{on}}] + \Pr[S|A_{\text{off}}] \Pr[A_{\text{off}}]. \tag{12}$$

Finally, the throughput with ACK off is evaluated as follows

$$S = n \times G \times p_s, \tag{13}$$

where G is the traffic load or data rate and n is the number of devices in WPAN excluding the PAN coordinator.

Table I
PARAMETER VALUES USED IN THE SIMULATIONS AND NUMERICAL RESULTS

Parameters	Values
Number of nodes	5 (4 sensor nodes + 1 PAN coordinator)
Network field	50 (m) x 50 (m)
CS threshold range	35 (m)
Rx threshold range	35 (m)
Traffic type	CBR
Packet size	90 (bytes)
Data rate	6 (bps)
CBR packet arrival period	120 sec
ACK	off

3.2 Latency

Let L_{on} and L_{off} denote the latency of a packet when it arrives at the active and inactive periods, respectively. Latency with ACK off can be approximated by

$$Latency = \alpha \times L_{on} + (1 - \alpha) \times L_{off}, \tag{14}$$

where α is duty cycle. In our analysis, we make use of following assumptions (a) the arrival of constant-bit-rate (CBR) packet follows the uniform distribution over time and L_{on} is negligible and (b) packet transmission time is much less than waiting time for the next active period. Accordingly, L_{off} can be approximated to be half of the whole inactive period

$$Latency \approx \frac{(1 - \alpha)^2 \times BI}{2}. \tag{15}$$

4 NUMERICAL RESULTS AND SIMULATIONS

4.1 Verification of Analytical Model

In this section, our numerical results based on probability models are verified, using the ns-2 simulator. First, we compare our analysis with simulation results for different duty cycles. To vary the duty cycle, we set the beacon order (BO) parameter to be fixed at 12, and change the superframe order (SO). Table I lists the input parameters for a light traffic condition of WPAN. The average packet latency and the network throughput are measured at the PAN coordinator.

The simulation results of throughput and latency are shown in Figure 3, and Figure 4, respectively. A strong agreement between the analytical results and simulated ones can be observed. Furthermore, we investigate the impacts of the number of sensor nodes on throughput. The number of active nodes is varied, and the duty cycle is set to be 25%.

Figure 5 provides throughput performance with different number of active nodes. If the number of sensor nodes is small, our analytical results are identical to the simulation results, and there is a slight difference as the number of nodes is large. We recall that our analysis is based on assumption of the light traffic model.

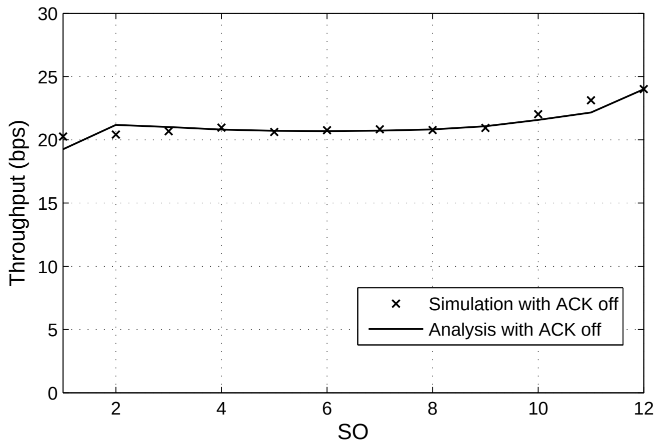

Figure 3. Network throughput versus SO parameter.

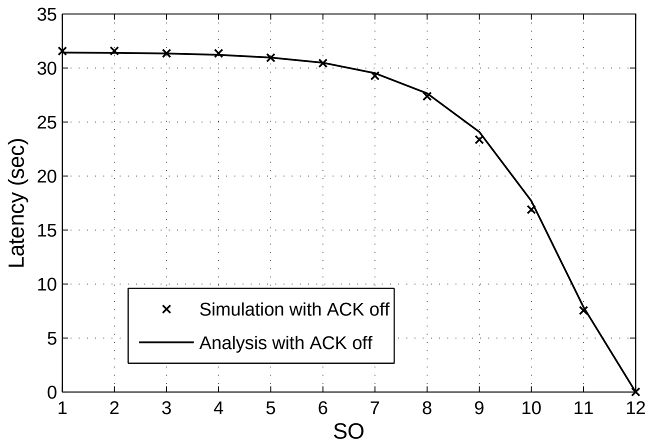

Figure 4. End-to-End latency versus SO parameter.

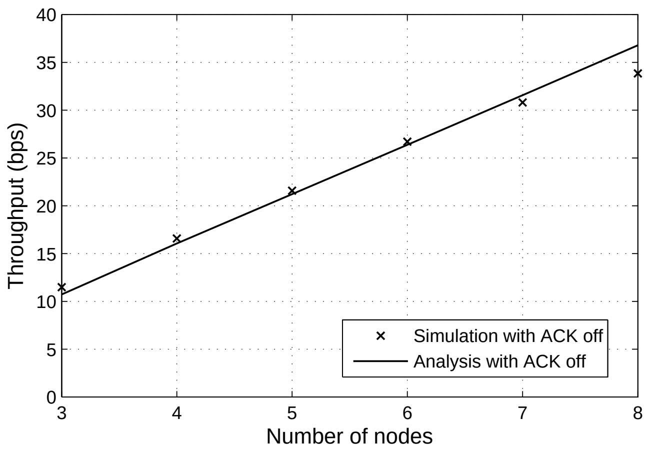

Figure 5. Network throughput versus the number of nodes.

4.2 Two Different CSMA/CA Protocols of IEEE 802.15.4 and IEEE 802.11

In this section, we compare the CSMA/CA protocol of IEEE 802.15.4 with that of IEEE 802.11 in terms of throughput and latency performance. Although sharing some similarities, they differ in one another in the way of handling busy medium. That is, IEEE 802.11 freezes the backoff counter when busy medium is sensed, and then continues backing off after the channel becomes idle. In contrast, IEEE 802.15.4 continues backing off,

Table II
Parameter Values Used in Performance Comparison of Two Different CSMA/CA Protocols in IEEE 802.15.4 and IEEE 802.11

Parameters	Value
Number of nodes	11 (10 sensor nodes + 1 PAN coordinator)
Network field	50 (m) x 50 (m)
CS threshold range	35 (m)
Rx threshold range	35 (m)
Traffic type	CBR
Packet size	90 (bytes)
Data rate	12 (bps)
CBR packet arrival period	60 sec
BO	12
SO	$5 \sim 12$
ACK	on

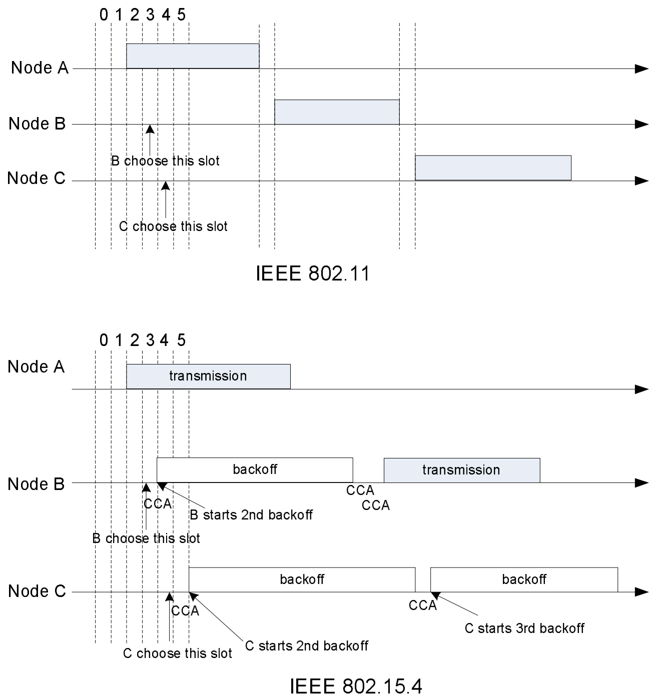

Figure 6. Two operating mechanisms of IEEE 802.11 and IEEE 802.15.4.

regardless of channel status and executes two consecutive CCA operations at the end of backoff for collision avoidance as we can see in Figure 6. This deteriorates the overall throughput especially in the heavy traffic model.

In order to make the CSMA/CA mechanism of IEEE 802.11 MAC protocol comparable with that of the IEEE 802.15.4 MAC protocol fitted into WSNs, we modify the CSMA/CA mechanism of the IEEE 802.11 MAC protocol as follows: The CCA operation at each slot is added and the backoff timer is frozen while the channel is sense busy. To show the different performance of the above mentioned CSMA/CA protocols, we set up a star topology including 10 nodes sending CBR packets to a PAN coordinator. The input parameters are listed in Table II.

Figures 7 and 8 show the throughput and latency with ACK on of both protocols. There is negligible discrepancy in latency, whereas significant difference is observed in throughput. Such difference certainly re-

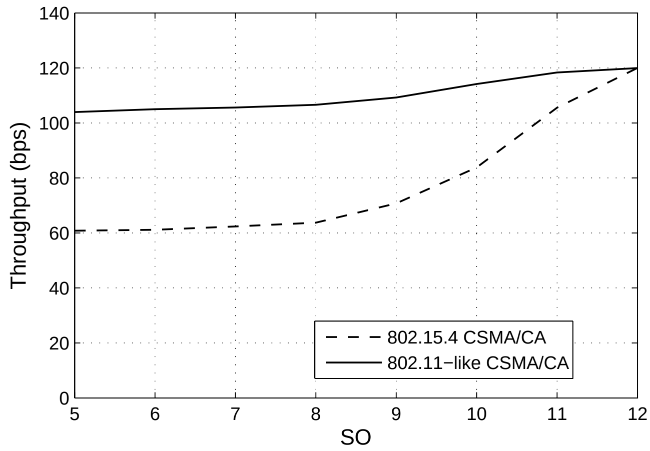

Figure 7. Network throughput versus SO with ACK on of IEEE 802.15.4 MAC and IEEE 802.11 MAC protocols.

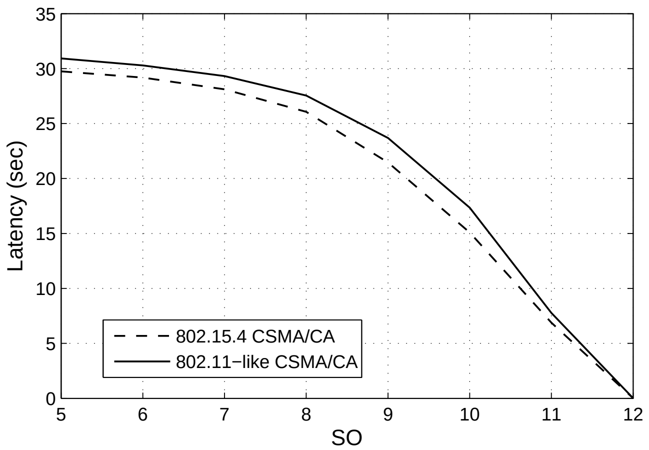

Figure 8. End-to-End latency versus SO with ACK on IEEE 802.15.4 MAC and IEEE 802.11 MAC protocols.

sults from the different way of handling busy medium as stated above. IEEE 802.11 takes collision as a sign of intense contention, thus doubling contention window when collision occurs. However, IEEE 802.15.4 takes busy medium as a sign of contention and subsequently doubles the interval of backoff delay by increasing the backoff exponent BE regardless of how many contending nodes in the network. This fact indicates that IEEE 802.15.4 has a quite conservative behavior on contention because of BE adjustment mechanism. This makes the contention resolution scheme of IEEE 802.15.4 relatively less inefficient. Obviously, in terms of energy efficiency, the scheme of IEEE 802.15.4 in which CCA operations are performed at the end of backoff is favorable. In IEEE 802.11, the power consumption is remarkably high since no sleep period exists. Its radio is frequently turned on to monitor the channel and transmit data if possible. In contrast, for IEEE 802.15.4, the radio is only turned on when performing CCA at the end of backoff delay and transmitting data on the wake-up period. Thus, energy consumption is considerably reduced in IEEE 802.15.4.

Figure 9 provides throughput of IEEE 802.11 and IEEE 802.15.4 based CSMA/CA for several values of packet size. In this simulation setting, the packet size ranges from 20 to 100 bytes. In general, increasing in

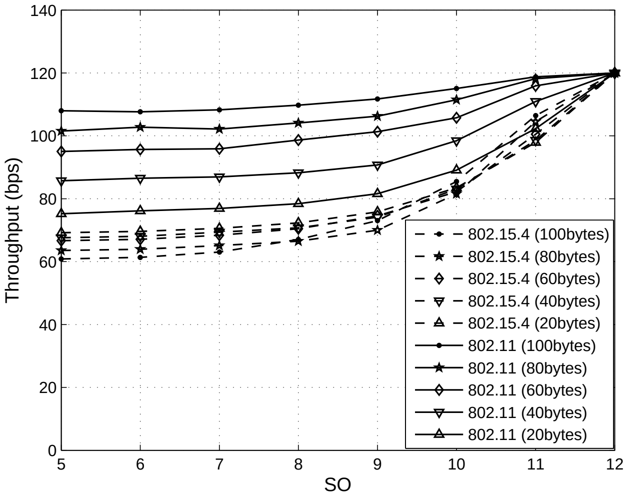

Figure 9. Throughput versus SO with ACK on under various packet sizes of IEEE 802.15.4 MAC and IEEE 802.11 MAC protocols.

packet size yields higher throughput in most MAC protocols. Similar behavior is observed for IEEE 802.11 based CSMA/CA. However, increasing packet size leads to throughput degradation in IEEE 802.15.4 based CSMA/CA. The reason is that longer packet size makes the collision resolution scheme in IEEE 802.15.4 inefficient. For instance, 100 bytes packet size corresponds to 10 backoff slots. Any other nodes that sense the channel busy because of the current transmission will have higher chance to sense the channel busy again even after the second round backoff. Again, in IEEE 802.11, the collision is a sign of contention, whereas IEEE 802.15.4 perceives a transmission as a sign of it. Thus, such a conservative estimation on contention drastically delays the channel access time and yields lower throughput

5 Conclusion

Our contributions to this paper include two parts. Firstly, the mathematical analysis of throughput and latency of IEEE 802.15.4 is presented by using probability models. In the context of the light data traffic load and low duty cycles, the numerical results are obtained and verified by the network simulator ns-2. Secondly, throughput and latency of two different CSMA/CA protocols in IEEE 802.15.4 and IEEE 802.11 are compared. A significant discrepancy of these protocols in terms of throughput is observed. More interestingly, we find out that an increase in packet size leads to a decrease in throughput in IEEE 802.15.4 due to the characteristics of its CSMA/CA mechanism. For future works, an enhancement of the CSMA/CA protocol of IEEE 802.15.4 to obtain better performance seems to be an attractive topic.

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