An Adaptive Contention Control Strategy for IEEE 802.15.4-Based Wireless Sensor Networks

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***Abstract*—The IEEE 802.15.4 standard is able to achieve low-power transmissions in low-rate and short-distance wireless personal area networks (WPANs). Due to the constitutional design of the sensor node and the transmission architecture (client–server model), any data communication between two sensor nodes will involve the coordinator. One shortcoming of redundant channel-access steps will result in excessive contention overheads and, thus, the decrease of channel utilization. This paper proposes an adaptive contention control strategy (ACCS) to solve the problem of transmission efficiency in IEEE 802.15.4. ACCS can be implemented in the IEEE 802.15.4 medium access control (MAC) protocol standard adding no new message type. An analytic model and a simulation model are developed to evaluate the performance of IEEE 802.15.4 and ACCS. The simulation results demonstrate that the proposed scheme significantly improves the goodput, the average queuing delay, the average MAC delay, and the energy consumption.**

***Index Terms*—Contention overheads, IEEE 802.15.4, medium access control (MAC) protocol, sensor, wireless personal area network (WPAN).**

I. Introduction

RECENTLY, wireless sensor networks have received tremendous attention from both academia and industry. With the advancement of technologies for microsensors, wireless networking, and embedded processing, wireless sensor networks are now being widely tested and deployed for different application domains [4], [12]. The existing applications include environmental monitoring, industrial sensing and diagnostics, health care, and data collecting for battlefield awareness. Most of the applications are developed by using low-rate, short-distance, and low-cost wireless technologies. Among the well-known specifications, IEEE 802.15.4, which was originally designed for low-rate wireless personal area networks (WPANs), has become one of the promising candidates adopted for interconnections between wireless sensor nodes [2].

The IEEE 802.15.4 standard targets ultralow complexity, cost, and power for low-rate wireless connectivity among inexpensive, portable, and moving devices [6]. Based on data-processing capabilities, two types of devices are provided in IEEE 802.15.4: 1) reduced function device and 2) full function device (FFD). These devices constitute a network, and a coordinator equipped with the FFD capability is responsible for organizing and managing the network. In IEEE 802.15.4, both star and peer-to-peer topologies are supported. In a star topology, the communication is established between end devices and a single central controller (i.e., coordinator). In a peer-to-peer topology, a device could communicate with any other devices within its transmission range. Multihop routing is allowed in the peer-to-peer topology, and routing paths could be dynamically updated. This topology provides more complex network formations, such as mesh networking.

The specifications of the physical (PHY) layer and the medium access control (MAC) layer for IEEE 802.15.4 are defined in [5]. Specifically, the MAC design of IEEE 802.15.4 follows the modified *carrier sense multiple access with collision avoidance* (CSMA/CA) contention-based mechanism. The details of IEEE 802.15.4 MAC operations will be elaborated upon in the following sections.

Previous work for IEEE 802.15.4 focused on analytical and simulation modeling for the existing MAC specifications. Gang *et al.* conducted a simulation-based performance evaluation for IEEE 802.15.4 [2]. In [8], Misic *et al.* derived the probability distribution of access delay and calculated the throughput of a beacon-enabled IEEE 802.15.4 network. Zheng and Lee [6] investigated whether IEEE 802.15.4 is fit for ubiquitous networking. Golmie *et al.* [3] evaluated the performance of IEEE 802.15.4 for medical applications in terms of goodput, delay, and packet loss. Misic *et al.* [7] pointed out bottlenecks in the MAC layer of 802.15.4, but only simple solutions were proposed. Sheu *et al.* proposed a schedule strategy by utilizing an inactive period to disperse traffic load and promoted system performance [13]. However, they added new control frames, which were not compatible with the IEEE 802.15.4 standard.

Although the performance analysis for IEEE 802.15.4 was extensively investigated, little work has been done on the problems of IEEE 802.15.4 transmission efficiency. Much of the literature previously discussed contention schemes in IEEE

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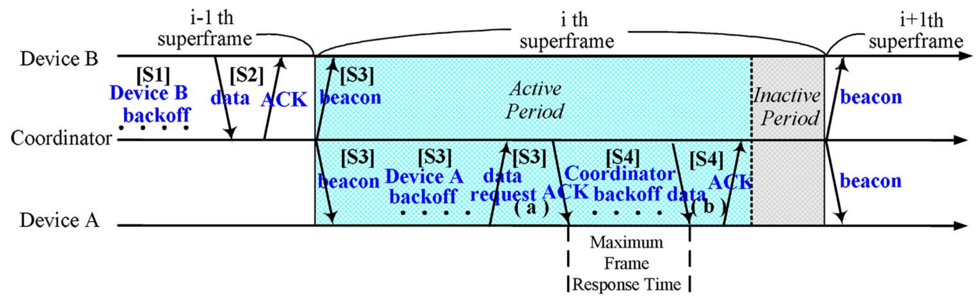

Fig. 1. Example of the IEEE 802.15.4 data transmission procedure, where [Si] represents Step i.

802.3 and IEEE 802.11, but a more accurate contention control scheme should be used in IEEE 802.15.4 due to the modified CSMA/CA. The major difference between the modified CSMA/CA protocol and the original CSMA/CA protocol is that the sensor node desiring to transmit data actually performs carrier sensing only when the backoff process is completed. Owing to the characteristics of blind backoff processes in IEEE 802.15.4, the low-channel utilization and the long average access delay resulted.

With a large-scale wireless sensor network, sensor nodes might densely be deployed. In such a case, the data exchange between sensor nodes would relatively be frequent, particularly when flooding is adopted for routing. Under this situation, any redundant message handshaking and unnecessary contentions would result in significant system performance degradation and extreme power consumption of devices. The contention control scheme cannot effectively solve the channel busy problem due to the many control messages of the sensor nodes. That is, the transmission efficiency can be improved by using a schedule scheme to separate the traffic load of the channel into different subperiods. Therefore, in this paper, we propose an adaptive contention control strategy (ACCS) to improve the transmission efficiency and reduce the overall energy consumption for IEEE 802.15.4-based wireless sensor networks.

The rest of this paper is organized as follows: Section II presents the IEEE 802.15.4 MAC layer transmission procedures and our motivation. Section III describes our ACCS, and an analytical model for our ACCS is presented in Section IV. In Section V, a series of simulation experiments are conducted to demonstrate the capability of the proposed strategy. Section VI presents the conclusion.

II. IEEE 802.15.4 Transmission Procedure and Motivation

An IEEE 802.15.4 network can operate in either beacon-enabled mode or non beacon-enabled mode. In the non beacon-enabled mode, a device can send data at any time based on CSMA/CA. On the contrary, in the beacon-enabled mode, a coordinator periodically broadcasts a Beacon Frame to end devices for network synchronization and association. Following the Beacon Frame, devices could transmit their data based on the superframe structure specified in the received Beacon Frame. To ease system management, most of the sensor networks adopt the beacon-enable mode for sensor interconnections [10]. Thus, in this paper, we present our ACCS with consideration of an IEEE 802.15.4 beacon-enabled network.

A. IEEE 802.15.4 Beacon-Enabled Transmission Procedure

A superframe consists of an active period and an inactive period. All devices, including a coordinator and several end devices, operate in the active period and enter a sleeping phase in the inactive period. Two parameters, i.e., Beacon Order (BO) and Superframe Order (SO) set by the coordinator, determine the lengths of active and inactive periods. They are equal to $48 \times 2^{\mathrm{SO}}$ UBPs and $48 \times (2^{\mathrm{BO}} - 2^{\mathrm{SO}})$ UBPs, respectively, where UBP is a basic time unit (i.e., 20 symbol periods[1]) used for backoff. In the beginning of an active period, a Beacon Frame is sent from the coordinator to the end devices. The Beacon Frame includes the information for timing synchronization and system configuration, a list of the end devices that have to receive data frames from the coordinator, and so on. The remaining active periods are divided into two parts. The first part is the contention access period (CAP), and the second part is the contention-free period (CFP). In CAP, the end devices equally access the medium by using CSMA/CA. On the other hand, the slots in CFP are reserved for some specific end devices assigned by the coordinator. The coordinator is also in charge of the adjustment for the lengths of CAP and CFP based on traffic loads and request types.

With the foregoing described superframe structure, Fig. 1 illustrates an example of the CAP transmission procedure for IEEE 802.15.4-based networks. Assume that *Device B* would like to transmit a data frame to *Device A* and that the following steps are executed.

1) First, *Device B* randomly selects a backoff time according to the predefined contention window (CW) (i.e., the default minimum CW, $\mathrm{CW}_{\min}$[2]) and counts it down to zero.
2) After the countdown process, *Device B* checks the channel condition by executing two clear channel assessments (CCAs). If the channel is determined to be free, then a data frame will be transmitted to the coordinator. Upon receipt of the data frame, the coordinator delays for a predefined T_{ack} duration and then issues an ACK frame to respond to *Device B*. On the contrary, if the channel has been occupied by other devices, then the size of the CW for *Device B* will be doubled, and Steps 1 and 2 will be executed again. The contention process will repeatedly be executed until the data frame is successfully transmitted or the maximal retry count is reached (in this case, the

[1]A symbol period is defined as the time that four data bits are transmitted. In IEEE 802.15.4, its length approximates to 16 ns.

[2]In IEEE 802.15.4, $\mathrm{CW}_{\min} = 2^3$.

frame will be dropped). Note that once the maximum CW value ($\mathrm{CW}_{\max}$[3]) defined in IEEE 802.15.4 is reached, the value is retained for the following contentions of this data frame.

3) In the beginning of the next superframe (i.e., the ith superframe), the coordinator broadcasts a Beacon Frame to inform *Device A* that a data frame at the coordinator is destined for *Device A*. After receiving the Beacon Frame, *Device A* repeats Steps 1 and 2 to send Data Request to the coordinator. When *Device A* receives the ACK frame (corresponding to Data Request) from the coordinator (Step 3 in Fig. 1), it will be awake for the duration of the maximum frame response time[4] to wait for the receipt of the data frame from the coordinator.
4) Assume that, in Step 3, the coordinator successfully receives the Data Request frame. Then, following CSMA/CA, the coordinator transmits the data frame back to *Device A*. Upon receipt of the data frame, *Device A* responds with an ACK frame.

B. Motivation

Based on the data-transmission procedure described in the previous section, we observe that a successful data transmission between any two IEEE 802.15.4 end devices passes through at least three times of channel accesses. Specifically, one channel access is for uplink transmission (see Steps 1 and 2 in Fig. 1), and the other two channel accesses are for downlink transmission (see Steps 3 and 4 in Fig. 1). These redundant channel-access steps will result in excessive contention overheads and, thus, the decrease of channel utilization. In addition, such an "indirect" downlink transmission (i.e., "Pull" model for data transmission from the coordinator to the end devices) increases the load of the coordinator. In a wireless sensor network, the coordinator is generally a bottleneck device, and the increase in the load of the coordinator definitely leads to the degradation of system performance. Furthermore, in "indirect" downlink transmission, the receiving device (i.e., *Device A*) has to be awake to wait for the data sent from the coordinator upon receipt of the ACK frame (corresponding to Data Request in Step 3 of Fig. 1). If the coordinator could not obtain the channel-access right in a short period, then the receiving device would waste its energy by staying in the active mode to get the data from the coordinator.

In addition to the preceding issue for transmission efficiency in IEEE 802.15.4, a considerable amount of contention overhead results from the iterative backoff operations of a standard IEEE 802.15.4 CSMA/CA mechanism, particularly when the system traffic load is heavy. Fig. 2(a) illustrates the backoff flow for a standard IEEE 802.15.4 CSMA/CA mechanism. When the data frames $A1$ and $C1$, respectively, arrive at *Devices A* and *C* in the ith superframe, the two end devices randomly select a backoff time based on $\mathrm{CW}_{\min}$. If collision occurs (e.g., due to the same backoff time selected by *Device A* and *C*), then the size of the CW is doubled, and the contention process is repeated

[3]In IEEE 802.15.4, $\mathrm{CW}_{\max} = 2^5$.

[4]In IEEE 802.15.4, a MaxFrameResponseTime $= 1220$ symbol periods.

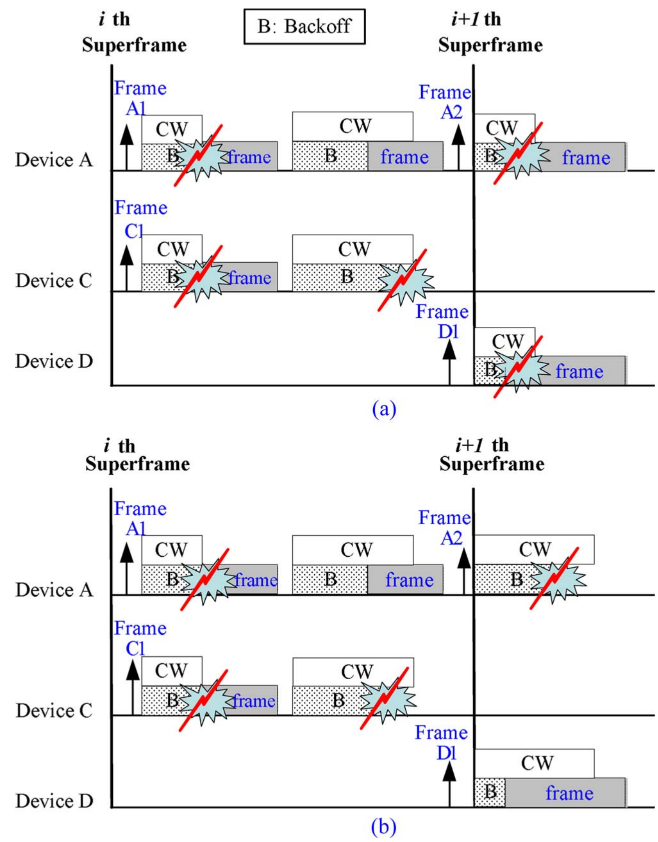

Fig. 2. Backoff flows for (a) IEEE 802.15.4 and (b) our MBS.

until one of the devices successfully occupies the channel. As shown in Fig. 2(a), *Device A* obtains the channel access in the ith superframe and successfully transmits its data frame. Then, when the next superframe (i.e., the $(i+1)$th superframe) starts, the window size will be reset to $\mathrm{CW}_{\min}$. Suppose that *Devices A* and *D* intend to send the frames in the $(i+1)$th superframe. The two devices probably select the same backoff time due to the small CW, and another collision may occur. When the network load is heavy, the serious contention could not be resolved within a narrow backoff window, which leads to the increase of the number of collisions and, hence, performance degradation. If a broad CW is initially used in the $(i+1)$th superframe, then collisions could be reduced, and the devices have higher opportunities to successfully transmit their data frames. However, when the network load is light, a large CW causes the reduction of network utilization. In addition, the frame transmission delay may be raised because of a relatively large backoff period to determine a specific device that could access the channel.

III. Adaptive Contention Control Strategy

To solve the transmission-efficiency problem of IEEE 802.15.4, we introduce an ACCS based on a two-stage approach. In the first stage of our ACCS, we present a memorized backoff scheme (MBS) to detect the traffic load of IEEE 802.15.4 networks and to dynamically adjust the size of the backoff window based on the network load. Once the network load is considered as a heavy state by MBS, the second stage of

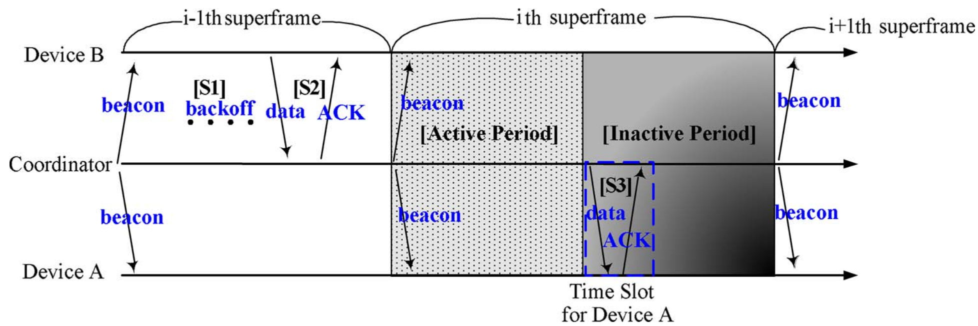

Fig. 3. Example of the LAPS data transmission flow, where [Si] represents Step i.

our ACCS is a load-aware packet scheduling scheme (LAPS) to distribute the tremendous amount of downlink packet transmission to the inactive period.

Fig. 2(b) illustrates the backoff flow for MBS. In this scheme, the CW value for the successful data delivery in the previous superframe is recorded to predict the initial value of the CW for the current superframe. The coordinator announces the initial CW value for the current superframe to end devices via the Beacon Frame. In Fig. 2(b), *Device A* obtains channel access in the ith superframe by using a suitable backoff window and successfully transmits its data frame. Then, as the next superframe (i.e., the $(i+1)$th superframe) starts, the size of the backoff window will not be reset to $\mathrm{CW}_{\min}$. The coordinator informs the end devices with the CW value that *Device A* successfully transmits its data frame in the ith superframe. Suppose that *Devices A* and *D* intend to send the frames in the $(i+1)$th superframe. The two devices probably select different backoff times due to a relatively large CW, and the probability of data collision may decrease. To avoid the backoff window expanding too quickly in MBS, a window-shrinking operation is designed. That is, if three consecutive successful transmissions occur with the 2^k-slot CW (which implies that the CW may be too large), the initial window value for the next superframe is decreased to 2^{k-1}.

To accurately estimate the initial value of the CW for each superframe, a "weighted-average" concept similar to the exponential weight moving average [9] approach is incorporated into our proposed MBS. The equation for MBS window-size estimation is shown as $EP_{i+1} = \lceil E_A + (1-X)E_i \rceil$, where $X = 1 - [|E_i - E_A|/C]$. E_i denotes the exponent of the CW size for the successful transmission in the ith superframe, and E_A represents the average value of E_{i-1}, E_{i-2}, and E_{i-3}. Then, the predicted initial value EP_{i+1} of the CW for the $(i+1)$th superframe is a weighted combination of E_A and E_i. The weight X depends on the difference of E_i and E_A, and the C value is set to the difference between the exponents of $\mathrm{CW}_{\max}$ and $\mathrm{CW}_{\min}$ (i.e., $C = 2$ in this paper).

Although our MBS effectively reduces the backoff overheads based on the detected network load, the problem of excessive data collisions/contentions could not completely be solved when data transmission requests exponentially grow during a CAP period. To address this issue, the second stage of our ACCS develops a LAPS to further improve the transmission efficiency for IEEE 802.15.4 networks. Our LAPS scheme schedules contention-based downlink data transmission to the original inactive period based on the load indication provided by MBS. When $\mathrm{CW} > 2^3$, the contention-based downlink data requests in the current superframe would be fulfilled by using the original inactive period of the coming superframe. The coordinator would extend its active period to accommodate the downlink data deliveries. The lengthened part would be partitioned into several time slots, and each time slot would be dedicated to one device that requests downlink data.

Fig. 3 shows an example of the LAPS data transmission flow. Similar to that shown in Fig. 1, this example presents a scenario that *Device B* would like to transmit data to *Device A* through the coordinator. Upon receipt of the data destined to *Device A* from *Device B* (see Step 2 in Fig. 3), the coordinator buffers the data and allocates a time slot in the inactive period of the next superframe. Then, the coordinator informs the slot-allocation information to *Device A* by using the Beacon Frame. *Device A* only needs to wake up during its time slot for receiving the data (see Step 3 in Fig. 3), which significantly reduces the power consumption of end devices.

Instead of the "Pull" model provided by the IEEE 802.15.4 transmission flow standard, our LAPS provides a "Push" model for downlink data accesses. The "Push" model leads to the decrease of the number of message exchanges for downlink data transmission and upgrades the transmission efficiency from the viewpoint of system performance. Comparing the flow of Fig. 3 with that of Fig. 1, it is obvious that the Data Request/ACK frames in Step 3 of Fig. 1 are omitted from our LAPS scheme. In addition, with our LAPS, the congestion of uplink data traffic could lessen since the contention-based downlink data have been scheduled in the dedicated time slots of the inactive period. Although the IEEE 802.15.4 standard provides a guaranteed time slot (GTS) mechanism to allocate a specific duration (i.e., CFP) within a superframe, it is inappropriate to use GTS for downlink data transmission in LAPS because IEEE 802.15.4 GTS was originally designed for high-priority data deliveries with strict timing constraints. Utilizing GTS for LAPS downlink data could reduce the transmission opportunities of the high-priority frames and worsen the quality of service requested by real-time applications.

Our ACCS is fully compatible with the existing IEEE 802.15.4 implementations. In MBS, the bits 7–9 for the *Frame Control* field in the Data frame are used to carry the exponent of the CW value [5]. Once the coordinator receives an Data frame from end devices, the CW value in the Data frame for this successful frame transmission would be maintained in the coordinator. As the next superframe starts, the coordinator announces the initial CW value to all end devices based on all

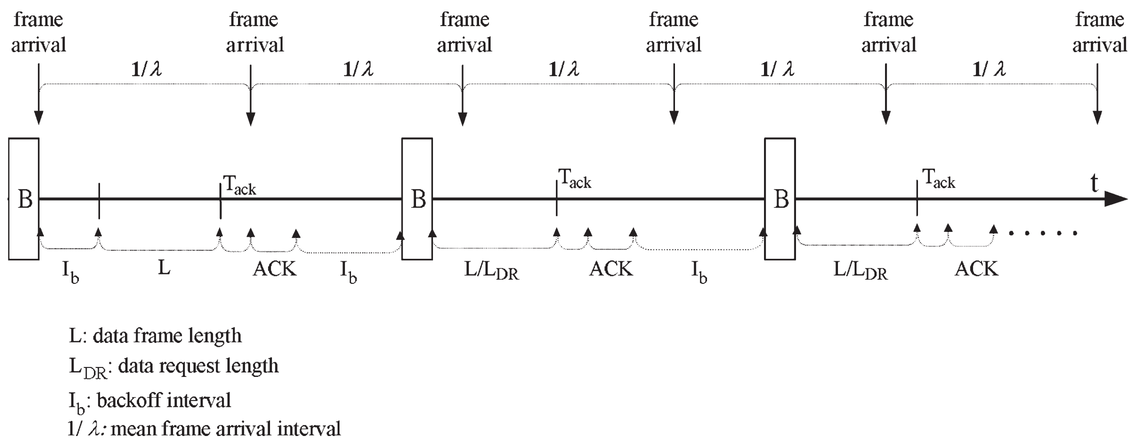

Fig. 4. Timing diagram of the standard MAC transmission procedure.

CW values collected in the current superframe. In addition, an optional field, i.e., *Beacon Payload*, in the Beacon Frame is adopted for the coordinator to broadcast the LAPS scheduling information to all end devices [5].

IV. Performance Analysis

We now introduce the model and notations used in our analysis. The system goodput, which is denoted by G as an output measure of our analysis, is defined as the ratio of the data transmission periods to the time the system operates. Notice that goodput excludes system overheads, such as control frames and backoff intervals. Some notations used in this analysis are listed as follows:

N	Number of mobile devices.
L	Data frame length.
λ	Packet arrival rate of a mobile device.
R	Transmission rate.
T_{CCA}	CCA execution time.
$P_S(\Delta t)$	Probability that a frame is successfully transmitted, where Δt is a UBP.
T_{ACK}	ACK frame length.
T_{ack}	Gap between the frames and the ACK.
T_S	Duration of a superframe.

In the analysis, SO and BO are set to 2 and 3, respectively, and the superframe duration T_S is equal to 192 $\times$ UBPs. For simplicity, the data frame length is assumed a fixed value of L bytes and the arrival process of frames at a mobile device forms a Poisson stream with arrival rate λ. Then, the network traffic load is calculated as $N\lambda L$. In the following sections, we analyze G for the MAC implementation of IEEE 802.15.4 and the proposed ACCS scheme.

A. Standard IEEE 802.15.4 MAC Implementation

In the IEEE 802.15.4 standard, each device has to take a backoff interval countdown before its transmission. The average backoff interval denoted as I_b, as shown in Fig. 4,[5] is defined as an interval from the time that a mobile device attempts to access the channel for a frame to the time that the device actually transmits the frame over the channel. Let w_i denote the size of the CW for a frame transmission in the ith backoff retry, and the basic CW unit is UBP. By following the IEEE 802.15.4 specification, at most, retry is allowed three times per frame. Thus, the CW size of the ith retry will be $w_i = \min(2^i w_0, 2^5)$ for $i = 1, 2,$ and 3, where $w_0 = 8$. Let $I_{i,s}$ and $I_{i,f}$ represent the average time duration of successful and failed channel accesses in the ith retry, respectively. In IEEE 802.15.4, a successful channel access implies two times of successful CCA operations. If one of the CCAs is not successfully executed, then it is considered that the channel access for this frame transmission fails. Thus, we have $I_{i,s} = w_i/2 + 2T_{\mathrm{CCA}}$, and $I_{i,f} = w_i/2 + 3T_{\mathrm{CCA}}/2$.

Then, I_b can be expressed as

$$I_b = \sum_{i=0}^{3} P_S(\Delta t)\left\{[1 - P_S(\Delta t)]\right\}^i \left[I_{i,s} + \sum_{j=0}^{i-1} I_{j,f}\right]$$

where $I_{-1,f} = 0$, $P_S(\Delta t) = e^{-\Lambda \Delta t}$, and $\Lambda = N\lambda T_S$ is the total frame arrival rate in the system. Let N_i^u and N_i^d respectively denote the numbers of uplink and downlink transmissions generated in the ith superframe. N_i^r represents the number of Data Request frames generated in the ith superframe. Moreover, the numbers of successful uplink data, Data Request, and downlink data transmissions in the ith superframe are denoted as $N_{i,s}^u$, $N_{i,s}^r$, and $N_{i,s}^d$, respectively.

Since only uplink transmissions (from mobile devices to the coordinator) occur in the first superframe $(i = 1)$, $N_{1,s}^u$ can be derived as $T_S/(I_b + L + T_{\mathrm{ack}} + T_{\mathrm{ACK}})$. The number of packet arrivals in the first superframe is probably less than N_1^u. Thus, the number $N_{1,s}^u$ in the first superframe can be derived as $\min(\Lambda, N_1^u)$. Let K_2^r be the number of mobile stations to which the successful uplink transmissions in the first superframe are destined. In the second superframe, several Data Request frames triggered by the uplink transmissions in the first superframe are issued from the K_2^r mobile devices, where $K_2^r = \sum_{n=1}^{N_{1,s}^u} nP_n$, and P_n denotes the probability that the $N_{1,s}^u$ frames are distributed to n mobile stations. P_n can be derived as

$$P_n = \left[\frac{N!}{n!(N-n)!N^{N_{1,s}^u}}\right] \sum_{j=0}^{n} (-1)^j (n-j)^{N_{1,s}^u} \left[\frac{n!}{(n-j)!j!}\right].$$

[5]The hidden-terminal problem is not considered in this paper.

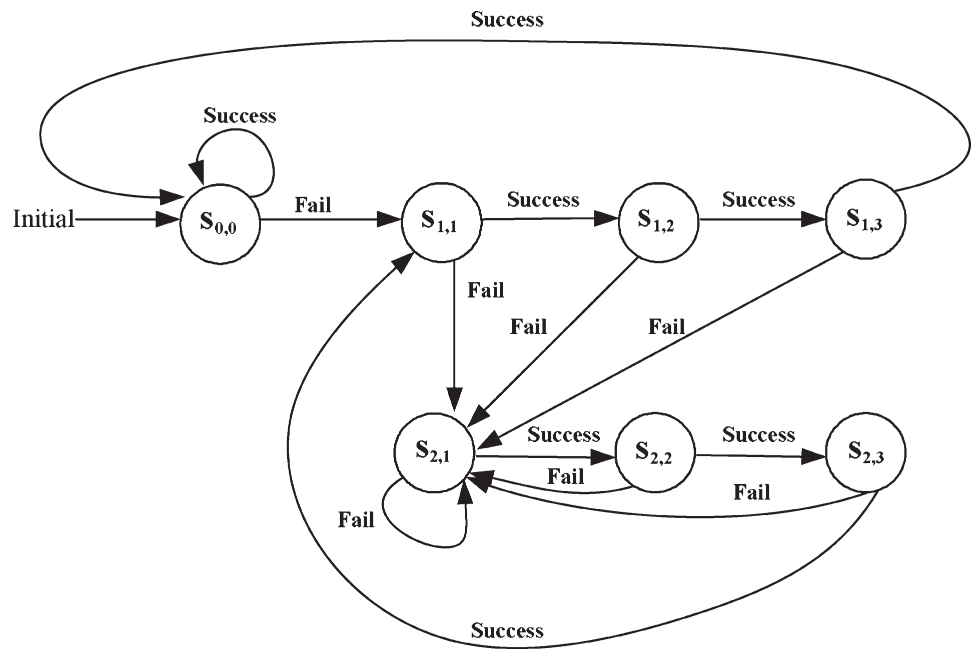

Fig. 5. State diagram for CW adaptation in MBS.

Then, N_2^u and N_2^r are, respectively, equal to $(N - K_2^r)T_S\lambda + (N_1^u - N_{1,s}^u)$ and $N_{1,s}^u$. Here, the mobile stations send the Data Request frames to the coordinator and expect to receive the download frames from the coordinator and do not issue the uplink frames in the same superframe. In addition, N_2^d is equal to $(N_{1,s}^u/N_1^u)N_2^r$.

With N_2^u, N_2^r, and N_2^d, the derivation of $N_{2,s}^u$, $N_{2,s}^r$, and $N_{2,s}^d$ is described as follows. With equal channel access for uplink, Data Request, and downlink transmissions, $N_{2,s}^u$, $N_{2,s}^r$, and $N_{2,s}^d$ can be obtained based on the ratio of N_2^u, N_2^r, and N_2^d. Let Y and Z denote $I_b + L + T_{\text{ack}} + T_{\text{ACK}}$ and $I_b + L_r + T_{\text{ack}} + T_{\text{ACK}}$, respectively, where L_r is the Data Request length. $N_{2,s}^u$, $N_{2,s}^d$, and $N_{2,s}^r$ are, respectively, equal to

$$\min\left\{\frac{\left[LN_2^u/\left(LN_2^u + LN_2^d + L_rN_2^r\right)\right] \times T_S}{Y}, N_2^u\right\}$$

$$\min\left\{\frac{\left[LN_2^d/\left(LN_2^u + LN_2^d + L_rN_2^r\right)\right] \times T_S}{Y}, N_2^d\right\}$$

$$\min\left\{\frac{\left[L_rN_2^r/\left(LN_2^u + LN_2^d + L_rN_2^r\right)\right] \times T_S}{Z}, N_2^r\right\}.$$

The derivation of N_i^u, N_i^r, N_i^d, $N_{i,s}^u$, $N_{i,s}^r$, and $N_{i,s}^d$ for $i \geq 3$ is similar to that of the second superframe, and the details are omitted. Based on the iterative analysis, when the number i of superframe periods is sufficiently large, N_i^u, N_i^d, and N_i^r approximate to constants. Therefore, the system goodput G of the standard MAC protocol can be derived as

$$G = \frac{\left(N_{i,s}^u + N_{i,s}^d\right)L}{T_S - T_B} \times R \tag{1}$$

where T_B represents the transmission time of a beacon frame.

From the results of our analysis against simulation experiments for the standard IEEE 802.15.4 MAC, we observe that our analytical results pretty well match the curves of the simulation.

B. ACCS

The system performance of our ACCS is derived by the following two steps: First, we analyze the average backoff interval length I_b^{MBS} of a device in an MBS-supported contention-based period. Second, by adopting the analytical result of I_b^{MBS}, the goodput of a contention-based period in ACCS can be calculated. Then, the overall performance of ACCS can be obtained by further considering the LAPS downlink transmissions scheduled in the original inactive period.

Fig. 5 illustrates the state diagram of the system for the adaptation of CW w_i in MBS. Let $P_\ell(0,0)$ be the probability that the size of the CW of the device is set to 2^3 in the beginning of the ℓth superframe, and let $P_\ell(i,j)$ be the probability that the device stays in state $s_{i,j}$ in the beginning of the ℓth superframe, where i represents the index of w_i, and j represents the consecutive times for which the i value is maintained. *In this paper, the number of consecutively successful data transmissions is setting in three by using our simulation result.* Initially, the device stays in state $s_{0,0}$. All devices in this state contend for channel usage by using $w_0 = 2^3$ and $P_1(0,0) = 1$.

The probability $P_{s,k}(w_i)$ that the k frames contend in w_i CW and that at least one frame successfully transmits is

$$P_{s,k}(w_i) = \begin{cases} 1 - \left(\frac{1}{w_i}\right)^{k-1}, & k \geq 2 \\ 1, & k = 1. \end{cases} \tag{2}$$

The system state may stay in $s_{0,0}$ or transits to $s_{1,1}$, depending on $P_{s,k}(w_i)$. If at least one frame transmission is successful in the first superframe, then w_i is maintained in $w_0 = 2^3$.

Otherwise, w_i will change to $w_1 = 2^4$. The probabilities $P_2(0,0)$ and $P_2(1,1)$ can be derived as $P_2(0,0) = P_{s,k}(w_0)$ and $P_2(1,1) = 1 - P_{s,k}(w_0)$, respectively. According to the state diagram in Fig. 5, we get

$$I_b^{\mathrm{MBS}} = 4P_\ell(i,0) + 8\sum_{m=1}^{3} P_\ell(i+1,m) + 16\sum_{n=1}^{3} P_\ell(i+2,n).$$

Based on the analysis of MBS, the performance of ACCS can further be derived. ACCS assigns a contention-based downlink to the inactive period based on the load indication provided by MBS. ACCS, according to the size of w_i, decides whether the scheduling mechanism is turned on/off. If w_i is equal to 2^3, then the coordinator does not execute transmission for downlink frames in the inactive period and utilizes the transmission procedure of IEEE 802.15.4. Otherwise, as the coordinator gets the w_i not equal to 2^3, it executes transmission for downlink frames in the following inactive period and utilizes the next beacon frame to inform all mobile devices.

Afterward, we will calculate the goodput of LAPS. Following the CSMA/CA method, the collision probability $P_{c,k}(w_i)$ of k contending frames with w_i can be derived by recursion, as shown in the following:

$$P_{c,k}(w_i) = \begin{cases} \frac{1}{w_i}^{k-1} + 1 - P_{c,(k-1)}(w_i)\frac{1}{w_i} & \\ \quad +P_{c,(k-1)}(w_i) - \frac{1}{w_i}^{k-2}C_k, & k \geq 3 \\ \frac{1}{w_i}, & k = 2 \\ 0, & k = 1. \end{cases} \tag{3}$$

The term $(1/w_i)^{k-1}$ represents the probability that the same UBP is selected for k frames. The term $[1 - P_{c,(k-1)}(w_i)](1/w_i)$ represents the probability that any two of the k frames select the same UBP. Finally, the term $[P_{c,(k-1)}(w_i) - (1/w_i)^{k-2}]C_k$ is the probability of the other permutation, where

$$C_k = \sum_{j=2}^{j=k-2} \left\{ \frac{k-j}{k-j-1} \times \frac{(k-j)^{j-2} \times \prod_{g=1}^{g=k-j-1}(w_i - g)}{\sum_{l=2}^{l=k-2}\left[(k-l)^{l-2} \times \prod_{g=1}^{g=k-j-1}(w_i - g)\right]} \right\}$$

when $k \geq 4$.

$P_{1,no}$ denotes the probability that $N_{1,s}^u$ frames are not collided in the first superframe. Utilizing (3), we calculate collision probability, which is α number of contending frames with w_0. We get $P_{1,no} = \prod_{\alpha=N_{1,s}^u+1}^{k}[1 - P_{c,\alpha}(w_0)]$. Contrarily, the probability that there is at least one collision in the first superframe will be $1 - P_{1,no}$. If there is no collision in the first superframe, then the coordinator utilizes the transmission procedure of IEEE 802.15.4 to transmit the frames of downlink transmission. On the contrary, when the transmission frames had collided in the first superframe, the coordinator will schedule the downlink frames in the inactive period of the second superframe and adjust the BO value.

In the second superframe, the collision probability is similar to that of the first superframe. There are two kinds of situation occurrence in the second superframe, depending on the result of collisions in the first superframe. If there is no collision in the first superframe, then the probability that $N_{2,s}^u + N_{2,s}^d + N_{2,s}^r$ frames do not have collisions in the second superframe denoted by $P_{2,no}$ is given by $P_{2,no} = \prod_{\alpha=N_{2,s}^u+N_{2,s}^d+N_{2,s}^r+1}^{k}[1 - P_{c,\alpha}(w_0)]$. Then, the probability that $N_{2,s}^u + N_{2,s}^d + N_{2,s}^r$ frames collide at least one time in the second superframe is equal to $1 - P_{2,no}$.

On the contrary, if collisions occur in the first superframe, then the value of w_i will be changed, depending on its collision situation. Therefore, the probability that the frames collide in the first superframe but not in the second superframe denoted by $P'_{2,no}$ is equal to $\prod_{\alpha=N_{2,s}^u+N_{2,s}^d+N_{2,s}^r+1}^{k}[1 - P_{c,\alpha}(w_i)]$. Similarly, the probability that there is at least one collision in the first and second superframes is equal to $1 - P'_{2,no}$, and so on.

A superframe in LAPS consists of a contention period and an inactive period. If data can be transmitted in contention periods, then the G of contention periods can be derived from (1). On the other hand, if the transmission of data frames can be executed in the contention and inactive periods, then the goodput G_S of contention periods and inactive periods will be

$$G_S = \left(\frac{N_{i,s}^u L}{T_S - T_B - T_I} + \frac{N_{i,s}^d L}{T_I}\right) R$$

where T_I represents the duration time of the inactive period.

The goodput of LAPS consists of the contention period or the contention period and the inactive period, depending on whether collision occurs. To calculate the goodput of LAPS, we illustrate a tree structure, as shown in Fig. 6. The i represents the depth of the tree, and there are $j = 2^{i-1}$ kinds of permutation with the contention period or the contention period and the inactive period. The nodes with label C and C + CF denote the situation of contention periods and contention periods and inactive periods, respectively. Every superframe has either a contention period or a contention period and an inactive period, depending on the collision occurrence. The probability $P_{i,j}$ denotes the probability of the path from the root node to node (i,j). Let $G_{i,j}$ be the goodput when the superframe enters the contention period, i.e., the node with label C, or the contention period and the inactive period, i.e., the node with label C + CF. When the number of superframe periods is sufficiently large, the system goodput will enter a steady state, which easily can be derived by $G_{\mathrm{LAPS}} = P_{i,1}G_{i,1} + P_{i,2}G_{i,2} + \cdots + P_{i,j}G_{i,j}$.

IEEE 802.15.4 transmits a frame to utilize the basic backoff scheme. Nevertheless, due to narrowing, the w_i size, and the inflexibility of backoff adjustment, the transmission of a data frame will consume a longer I_b. Fig. 6 shows a tree structure to calculate the goodput of ACCS based on LAPS. MBS dynamically adjusts the w_i value according to the traffic load. Therefore, the proposed ACCS can obtain a smaller I_b value.

Subsequently, we calculate the goodput of ACCS, which consists of MBS and LAPS, and therefore, the performance of ACCS can be derived by the analytical results of MBS and LAPS. The goodput of ACCS is similar to LAPS, except I_b. The

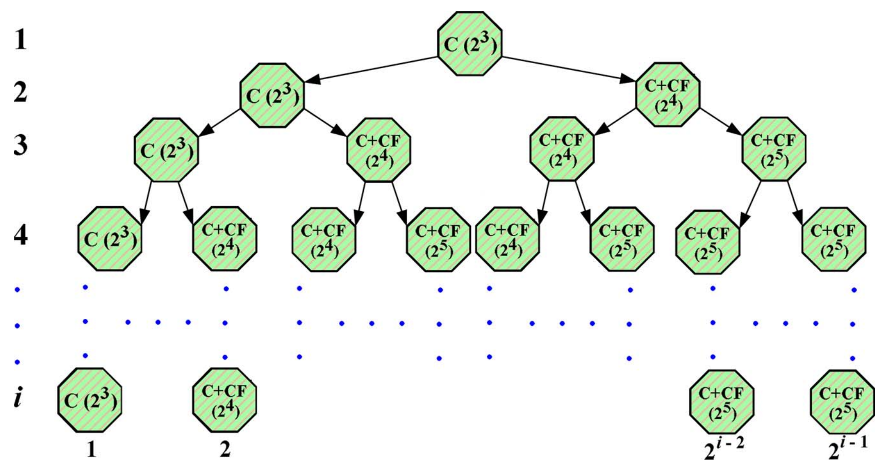

Fig. 6. Goodput calculation of ACCS.

I_b value of ACCS can be obtained from the analysis of MBS and is smaller than that of IEEE 802.15.4. According to MBS, a smaller I_b value can be obtained. This means that a frame spends a smaller backoff time for a successful transmission. In other words, there will be more frames successfully transmitted in every superframe.

To validate the correctness of the analysis, we perform a simple simulation of IEEE 802.15.4 and ACCS to verify the results. We take ten standard IEEE 802.15.4 devices around a coordinator in the simulation. The mean length of data frames is assumed to be 90 B, and the other parameters are given in [5]. From the goodput obtained from the analysis and simulation experiments of IEEE 802.15.4 and ACCS, it is shown that the difference between the analysis and the simulation results is about 5%.

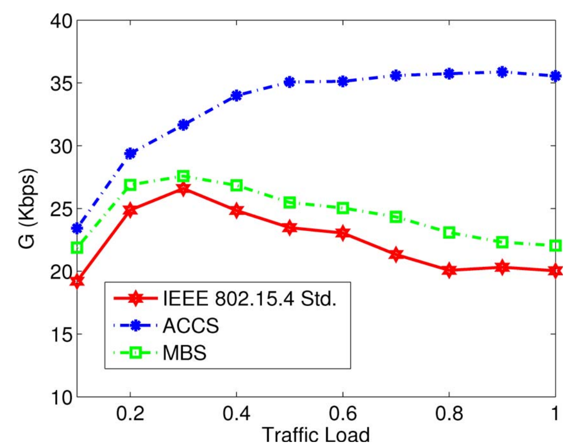

Fig. 7. Effects of traffic load on goodput.

V. Simulation Model and Results

The developed simulation model follows the specification of the IEEE 802.15.4 MAC layer [5]. To clearly indicate the power-saving features of the proposed scheme, we adopt a transceiver Chipcon CC2420 model [1]. The lengths of data frames are exponentially distributed with a mean of $1/\mu$ UBP. Mobile devices will transmit data to other mobile devices within the same personal area network. The mobile stations also transmit data to the Internet through the coordinator. When the Internet data transmit into personal area network through the coordinator, the transmission procedure of IEEE 802.15.4 is used. Without loss of generality, several assumptions are described as follows. First, all mobile devices support a 250-kb/s transmission rate. Second, the coordinator is static and located at the center of the simulated area.[6]

In the simulation model, the transmission range of a coordinator is assumed to be 30 m with a transmission rate of 250 kb/s. In the simulation experiments, we simulate a scenario of 20 mobile devices, and their initial locations are randomly assigned within the area. Each simulation run lasts 320 s, and each simulation result is obtained from averaging the results of ten independent simulations. Each mobile device maintains a first-in–first-out waiting buffer of 16 frames, and the mean frame length, i.e., $1/\mu$, is assumed to be 90 B (e.g., 9 UBPs at the 250-kb/s transmission rate, excluding PHY and MAC headers). The network load consists of the uplink transmission (from mobile devices to the coordinator) and the downlink transmission (from the coordinator to mobile devices) traffic. When the network load, i.e., $N\lambda/\mu$, is less than 0.3, it indicates a "light" traffic load. On the contrary, when the network load is greater than 0.7, the situation is defined as "heavy" traffic load.

The primary performance metrics are goodput (G), average queueing delay (D_q), MAC delay (D), and energy consumption. G is defined as the ratio of the expected delivery period of data payload to the totally expected transmission period (excluding control frames, etc.) [11]. D_q/D is defined as the interval between the time that the mobile station creates/serves the frame and the time that the frame is successfully transmitted. The energy consumption is defined as the energy consumption per successfully transmitting a frame to the destination.

Fig. 7 shows the effect of ACCS, MBS, and IEEE 802.15.4 on goodput for different traffic loads. The figure shows that ACCS and MBS outperform IEEE 802.15.4. ACCS, and MBS increases the goodput when the traffic load increases. However, IEEE 802.15.4 decreases its goodput when the traffic load is larger than 0.3. This is because IEEE 802.15.4 adopts a

[6]Note that our simulation model can easily be extended to an accommodation peer-to-peer WPAN.

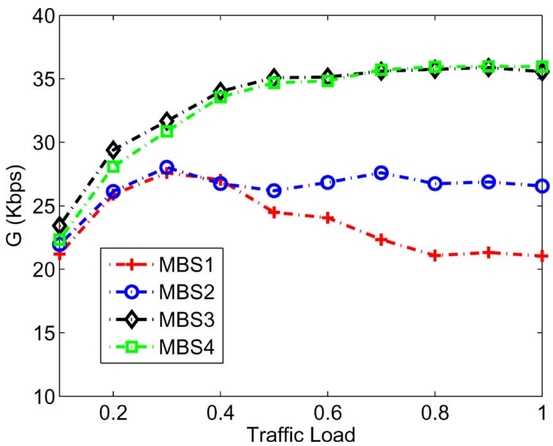

Fig. 8. Effects of traffic load on MBS numbers.

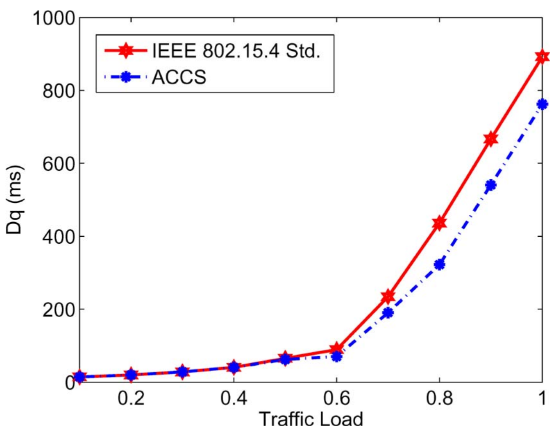

Fig. 9. Effects of traffic load on the average queueing delay.

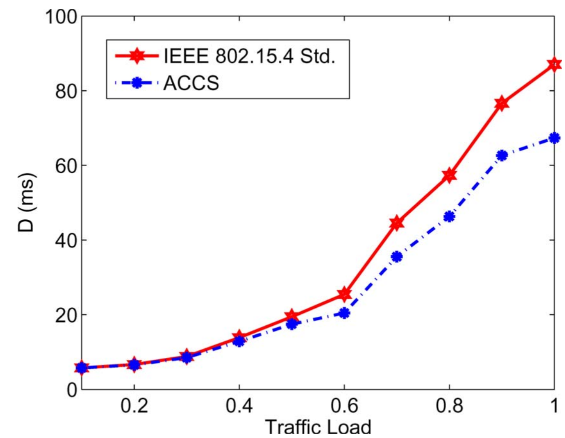

Fig. 10. Effects of traffic load on the average MAC delay.

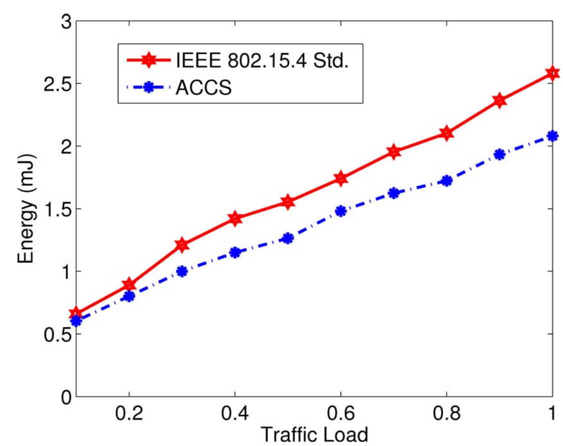

Fig. 11. Effects of traffic load on the power consumption for each data frame.

contention-based mechanism, and more serious collisions will occur when the traffic load is relatively heavy. Here, we find that the goodput of MBS obtains a better performance than that of IEEE 802.15.4 because the accurate CW size can decrease the collision opportunity. This implies that MBS can efficiently predict the network condition and further reduces the occurrence of collisions. In other words, by using MBS, the backoff overhead is significantly reduced, and the goodput improves. However, MBS does not fully solve the collision, particularly in a heavy traffic load. Further, ACCS uses the scheduling mechanism to avoid unnecessary collisions and efficiently decreases redundant transmission steps.

Fig. 8 shows the goodput effects for the number of consecutively successful data transmissions (MBS number) for ACCS. From this figure, we observe that when the MBS number is set as 3, the performance is the best. When the MBS number is set as 1 and 2, we have worse performance because it is not easy to accurately predict the network condition. Contrarily, when the MBS number is set as 4, it does not obtain good performance, particularly in a light traffic load. The reason is that the mobile devices do not frequently transmit a data frame. Therefore, the coordinator keeps out-of-date information, which does not reflect the present network condition. Hence, the MBS number is set as 3 to obtain good performance generality.

Figs. 9 and 10 show the effects of the traffic load on the average queueing delay D_q and the average MAC delay D, respectively. These figures show that the intuitive results for D_q/D of ACCS and IEEE 802.15.4 increase as the traffic load increases. These figures also indicate that when the traffic load is light, the curves for all schemes are insensitive to the traffic load. On the other hand, in the heavy traffic load, the average delays significantly increase as the traffic load increases, particularly for IEEE 802.15.4. A serious collision under a heavy traffic load results in longer delays in IEEE 802.15.4. The D and D_q of ACCS are less than those of IEEE 802.15.4 because the CW under the ACCS schemes can more appropriately be adapted. Furthermore, the redundant transmission steps extend transmission time and then cause longer delays.

Fig. 11 shows the energy consumption for each data frame prior to being successfully transmitted. In wireless sensor networks, the energy consumption is a very important problem. Our proposed scheme can extend the battery life of mobile devices. In Fig. 11, energy more significantly increases for the heavy traffic load than for the light traffic load, particularly in IEEE 802.15.4. For IEEE 802.15.4, the collisions for medium contention under the heavy traffic load become severe. In addition, the redundant transmission steps also increase the energy consumption of IEEE 802.15.4. By using ACCS, the energy consumption is significantly reduced.

VI. Conclusion

In this paper, we have proposed an ACCS based on a two-stage approach. In the first stage of our ACCS, we present an MBS to detect the traffic load of IEEE 802.15.4 networks and to dynamically adjust the size of the backoff window based on the network load. Once the network load is considered-to be a heavy state by MBS, the second stage of our ACCS distributes the tremendous amount of downlink packet transmission to the inactive period. Our proposed scheme can be implemented in the IEEE 802.15.4 MAC protocol standard without adding any new message type. An analytic model was developed to evaluate the performance of IEEE 802.15.4 and ACCS, which has been validated against simulation experiments. The simulation results demonstrate that the proposed scheme significantly improves the goodput, the average queuing delay, the average MAC delay, and the energy consumption.

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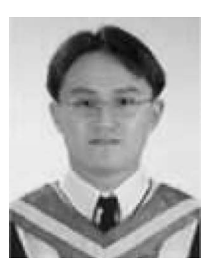

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