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Research Article

Runtime Estimation of the Number of Active Devices in IEEE 802.15.4 Slotted CSMA/CA Networks with Deferred Transmission and No Acknowledgment Using ARMA Filters

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We propose a novel method for estimating the number of active devices in an IEEE 802.15.4 network. Here, we consider an IEEE 802.15.4 network with a star topology where active devices transmit data frames using slotted carrier sense multiple access with collision avoidance (CSMA/CA) medium access control (MAC) protocol without acknowledgment. In our proposed method, a personal area network (PAN) coordinator of a network counts the number of events that a transmission occurs and the number of events that two consecutive slots are idle in a superframe duration, and the PAN coordinator broadcasts the information through a beacon frame. Each device can count the number of slots that each device is in the backoff procedure and the number of the first clear channel assessment (CCA) that each device performs whenever it performs the first CCA after the backoff procedure. Then, each device estimates the number of active devices in the network based on these counted numbers and the information from PAN coordinator with the help of an autoregressive moving average (ARMA) filter. We evaluate the performance of our proposed ARMA-based estimation method via simulations where active devices transmit data frames in IEEE 802.15.4 slotted CSMA/CA networks. Simulation results show that our proposed method gives estimation errors of the number of active devices less than 4.501% when the actual number of active devices is varying from 5 to 80. We compare our proposed method with the conventional method in terms of the average and standard deviation for the estimated number of active devices. The simulation results show that our proposed estimation method is more accurate than the conventional method.

1. Introduction

IEEE 802.15.4 standard [1] was standardized for low-rate wireless personal area networks (LR-WPANs) which require low-power consumption with low cost such as sensor networks. In IEEE 802.15.4 networks, a superframe consists of active and inactive portions, and a superframe duration (SD) is the duration of the active portion of the superframe as $SD = 48 \times 2^{macSuperframeOrder}$ in backoff slots where $0 \le macSuperframeOrder \le macBeaconOrder \le 14$. The beacon starts at the beginning of the superframe in every beacon interval (BI) which is presented as $BI = 48 \times 2^{macBeaconOrder}$ in backoff slots. BI is the length of the superframe including the inactive portion. If there is no inactive portion, SD is equal to BI. The active portion consists of a beacon, a contention access period (CAP) which is focus of this paper, and a contention free period (CFP). The CAP starts after the beacon, and the whole active portion consists of the beacon and the CAP if the length of the CFP is zero. The duration of an active portion is 16 slots, and the duration of a slot is 60 symbols. Since the duration of one backoff slot $aUnitBackoffPeriod$ is 20 symbols, the duration of an active portion is 48 backoff slots. From now on, we can use the term *slot* instead of the backoff slot. To access the medium in the

CAP, devices use slotted carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. In the CAP, a device accesses the medium after random backoff and two CCAs, and if the first or second CCA fails, the device proceeds random backoff and two CCAs again. To reduce energy consumption, each device does not sense the medium during random backoff. The device only senses the medium during CCA procedure only after the random backoff procedure. Each device selects random backoff values between 0 and $2^{BE}-1$. Once a device fails the first or second CCA, the device increases BE by 1 up to $macMaxBe$ and increases NB by 1. The initial values of BE and NB are $macMinBe$ and 0, respectively. If a device fails the first or second CCA when NB is equal to $macMaxCsmaBackoffs$, in other words, if a device fails the first or second CCA $macMaxCsmaBackoffs$ times, the device drops the frame and reset the multiple access control (MAC) parameters, that $BE = macMinBe$ and $NB = 0$ [1].

In IEEE 802.15.4 network, there are two modes, beacon-enabled mode and nonbeacon-enabled mode. If a network uses unslotted CSMA/CA mechanism, the network operates under a nonbeacon-enabled mode. In the nonbeacon-enabled mode, a personal area network (PAN) coordinator does not broadcast a beacon frame which means that the devices cannot be synchronized. The asynchronous channel access may cause more collisions than the synchronous access channel. If the network uses slotted CSMA/CA mechanism, the network operates under a beacon-enabled mode. In the beacon-enabled mode, the PAN coordinator broadcasts a beacon frame at the start of every superframe to synchronize the devices. In this paper, we focus on the beacon-enabled mode [1–3].

In IEEE 802.15.4, the acknowledgment is optional and it is determined by the value of the acknowledgment request (AR) field in a transmitted data frame. If the AR field is set as 1, the acknowledgment for the data frame is required. If the AR field is set as 0, the acknowledgment for the data frame is not required. With no acknowledgment, the transmitter assumes that the transmission of the data frame is successful [1].

In the CAP, data frames are transmitted/received using slotted CSMA/CA MAC protocol. Particularly, the CSMA/CA is one of the widely used contention-based MAC protocols in wireless networks due to its self-managed and noncentralized characteristics. However, the CSMA/CA becomes extremely inefficient; i.e., the throughput performance gets lower when the number of active/contending devices is either relatively *(1)* larger or *(2)* smaller than the backoff period. When the number of active devices is relatively large (e.g., a significant number of sensors simultaneously try associations with a PAN coordinator in a network), then the devices may not successfully transmit frames (e.g., the devices may fail in associating with the PAN coordinator) due to the repeated collisions. On the other hand, when the number of active devices is relatively small (e.g., one or two sensors try to send their data in a network), then the throughput performance gets lower due to the large portion of idle slots coming from contending devices' unnecessary backoffs. To prevent these performance degradations, an accurate method for estimating the number of active devices in a network is highly demanded to maintain the network performance adaptively to the network congestion level. For example, backoff period of each device can be set proportionally to the estimated number of active devices in the network.

There have been studies estimating the number of active devices in CSMA/CA-based networks such as IEEE 802.11 [4, 10] and wireless sensor networks (WSNs) [5–9]. In IEEE 802.15.4 with no acknowledgment, the transmitter assumes that the transmission of the data frame is successful [1]. Since the studies for the estimation of the number of active devices [4–9] need the conditional collision probability, the studies cannot be used in IEEE 802.15.4 slotted CSMA/CA networks with no acknowledgment.

In this paper, we propose an autoregressive moving average- (ARMA-) based method for estimating the number of active devices in an IEEE 802.15.4 slotted CSMA/CA network in runtime. Instead of the conditional collision probability, our proposed method utilizes the conditional probability that at least one device performs the first clear channel assessment (CCA) when active devices are in the backoff procedure and the conditional probability that each device performs the first CCA when the device is in the backoff procedure. A concept of ARMA filter is adopted to estimate the number of active devices based on these probabilities. We evaluate the performance of our proposed estimation method via simulations in terms of the estimation error in the number of active devices.

The remainder of this paper is organized as follows. In Section 2, we introduce the related works. In Section 3, we propose an estimation method for the number of active devices in IEEE 802.15.4 slotted CSMA/CA with no acknowledgment. In Section 4, we propose a runtime estimation method for the number of active devices in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment using ARMA filters. In Section 5, we compare our proposed method with the conventional method in terms of the average and standard deviation for the estimated number of active devices. At the last, conclusions are given in Section 6.

2. Related Works

The discrete time Markov chain (DTMC) models to analyze the IEEE 802.15.4 have been studied in [11–15]. Park et al. [11] analyzed the throughput and energy consumption under saturated condition and validated their analysis through comparison with simulations. However, the analysis may be not suitable for the IEEE 802.15.4 standard since the authors assumed that each device starts the backoff procedure at the first slot of waiting for acknowledgment. Pollin et al. [12] analyzed and evaluated the slotted CSMA/CA to validate whether it is suitable for low cost and low-power consumption or not under saturated and unsaturated conditions. Lee et al. [14] presented an additional carrier sensing (ACS) algorithm for IEEE 802.15.4 WSNs which gives the node one more chance that performs CCA if and only if the second CCA of the device is busy. Chong et al. [15] analyzed the performance of throughput and energy consumption of ZigBee sensor networks under wireless local area network (WLAN) interference. However, in [12, 14, 15], the deferred transmission has not been considered when the remaining slots are not enough to transmit a frame. Jung et al. [13] analyzed throughput of the slotted CSMA/CA for IEEE 802.15.4 with considering deferred transmission that occurs when the remaining slots are not enough to transmit a frame and validated the model through simulations.

The MAC protocols for low-power and real-time wireless network have been studied [16–20]. Bartolomeu et al. [16] surveyed and described the studies for wireless low-power technologies and wireless real-time MAC protocols. Jeon and Jeong [17] studied Bluetooth Low Energy (BLE) to enhance the channel access and improve the performance of BLE network. They evaluated the performance of their enhanced channel access scheme through simulations. Chen et al. [18] studied an energy-efficient scheduling algorithm for BLE to minimize the latency without excessive energy consumption. They evaluated the performance of the scheduling algorithm through simulation. Martalo et al. [19] studied clustered sensor networks in IEEE 802.15.4 with data aggregation (DA) and analyzed the probability of decision error and the energy consumption. Simulation results showed that there is a trade-off between the probability of decision error and the energy consumption. Ding and Hong [20] developed a CFP scheduling algorithm to overcome the limitations on the feasibility and the scalability of IEEE 802.15.4 network. They validated that the scheduling algorithm can improve the performance of IEEE 802.15.4 network through simulations.

There have been studies for ultra-wideband- (UWB-) based WPAN [21–23]. Liu et al. [21] analyzed the distributed reservation protocol (DRP) which is specified in WiMedia MAC for UWB-based WPAN. They validated the analysis of DRP by comparing the analytical results with simulation results. Alam et al. [22] analyzed and evaluated the performance of the throughput fairness and energy efficiency with their three approaches for DRP and prioritized channel access (PCA) in WiMedia MAC. Ajorloo et al. [23] analyzed the throughput for UWB and 60 GHz millimeter wave (mmWave). Since DRP may have a fairness problem, they developed a fair DRP (FDPR). They validated the analysis of DRP and FDRP by comparing the analytical results with simulation results.

There have been studies for distributed hash table (DHT) protocol to improve the network performance [24, 25]. Shin et al. [24] developed Motion-MiX-DHT (MX-DHT) for a mobile DHT protocol by extending last encounter routing (LER). They validated that MX-DHT can keep the plausible reliability of the publishing/lookup success ratio and achieve better communication efficiency than other existing protocols through simulations. Tahir et al. [25] developed a 3-dimensional logical cluster-based DHT routing protocol in mobile ad hoc networks (MANETs) to reduce the lookup latency and the overhead of routing to update the mapping information. Simulation results showed that their protocol can reduce the routing overhead and the computation overhead. The simulation results also showed that their protocol has shorter end-to-end delay and higher packet delivery ratio than the existing protocol. Using our proposed estimation method for the number of active devices, the performance of MAC protocol and routing protocol may be improved.

There have been studies estimating the number of devices in IEEE 802.11 and WSNs. In IEEE 802.11, Bianchi and Tinnirello [4] studied the estimation of the number of competing terminals by using conditional collision probability and transmission probability with ARMA filter and extended Kalman filter. Zhao et al. [10] developed a cross-layer estimation mechanism which counts different source addresses in the MAC headers of frames received from neighboring nodes in WLANs. In WSNs, on the other hand, Zhao et al. [5] presented a bandwidth and power efficient MAC protocol which utilizes the estimated number of devices to tune the minimum backoff period in WSNs. Zhao et al. [5] mentioned that the estimation mechanisms [4, 10] can be also valid in IEEE 802.15.4 WSNs. Zhao et al. [6] presented a game-theoretic MAC protocol for WSNs using the estimated number of competing nodes. Zhao et al. [6] mentioned that virtual CSMA/CA [7] can estimate the number of competing nodes. The virtual CSMA/CA [7] estimates the conditional collision probability as if a virtual frame is transmitted when there are no real frames to transmit. Zhao et al. [8] presented a game-theoretic constraint optimization scheme for WSNs using the estimated number of competing nodes as in [6]. However, since the virtual CSMA/CA may not recognize collisions between the virtual frames, the estimation of the number of active devices may have a large error. Chong et al. [9] analyzed and evaluated the association process for the IEEE 802.15.4 wireless network. In [9], efficient association algorithms predict the number of unassociated devices and change CSMA/CA MAC parameters adaptively. Since the studies for the estimation of the number of devices [4–9] need the conditional collision probability, the studies cannot be used in IEEE 802.15.4 slotted CSMA/CA networks with no acknowledgment. To the authors' knowledge, there has been no paper for runtime estimation of the number of active devices in IEEE 802.15.4 slotted CSMA/CA networks with deferred transmission and no acknowledgment using ARMA filters.

3. Estimation of the Number of Active Devices in IEEE 802.15.4 Slotted CSMA/CA with No Acknowledgment

In this section, we propose an estimation method for the number of active devices in IEEE 802.15.4 slotted CSMA/CA with no acknowledgment. Since a transmitter assumes that the transmission of data frame is successful with no acknowledgment mode in IEEE 802.15.4 slotted CSMA/CA, the transmitter cannot obtain the conditional collision probability with no acknowledgment mode. Note that the conditional collision probability is the probability that when a device transmits a data frame, at least one other device transmits a data frame simultaneously. To estimate the number of active devices with no acknowledgment, we use not only a device, but also a PAN coordinator. We consider the star topology without downlink transmissions of data frames from the PAN coordinator. Thus, the PAN coordinator cannot also estimate the conditional collision probability that the downlink transmission of data frame from the PAN coordinator collides.

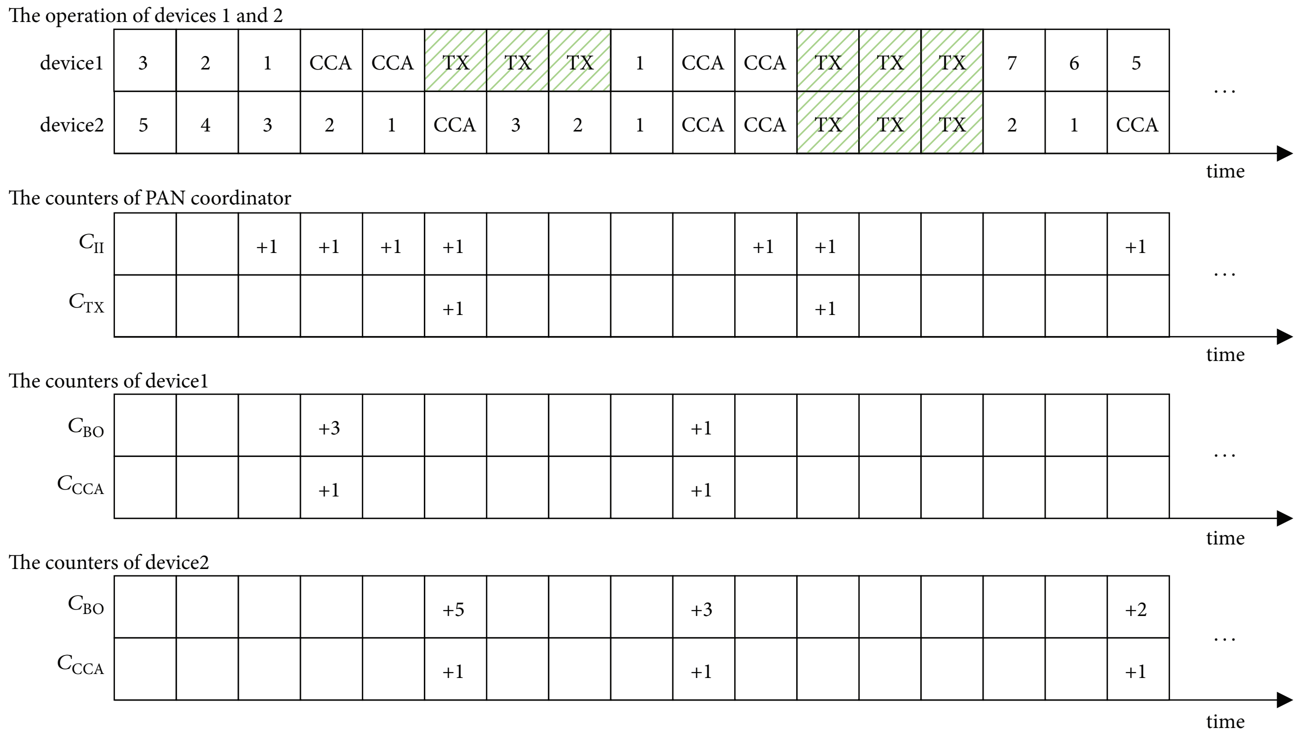


Figure 1: An example of counting C_{II}, C_{TX}, C_{BO}, and C_{CCA}, and backoff procedure for two devices. In each box for the operation of devices 1 and 2, each number means the backoff value, CCA means that the device performs CCA, and three consecutive TXs mean that the device transmits a data frame during three slots.

Denoting by P_{CCA} the conditional probability that at least one device performs the first CCA when active devices are in the backoff procedure, P_{CCA} can be expressed as

$$P_{CCA} = 1 - (1-\tau)^n, \tag{1}$$

where τ is the probability that a device performs the first CCA when the device is in the backoff procedure [11, 15] and n is the number of active devices. Then, from (1), we can calculate n as

$$n = f(\tau, P_{CCA}) = \frac{\log(1-P_{CCA})}{\log(1-\tau)}. \tag{2}$$

Note that τ can be estimated by each device while P_{CCA} can be estimated and broadcasted to each device through a beacon frame by the PAN coordinator. Then, each device can estimate the number of active devices n by utilizing (2).

Denoting by C_{BO} the number of slots that each device is in the backoff procedure and by C_{CCA} the number of the first CCA that each device performs, each device can estimate τ by counting C_{BO} and C_{CCA}. Each device can count C_{BO} and C_{CCA} whenever it performs the first CCA after the backoff procedure.

Denoting by C_{II} the number of events that two consecutive slots before the current slot are idle and by C_{TX} the number of events that the transmission of data frame from at least one device occurs. If the two consecutive slots before the current slot are idle, it means that the transmission of data frame from at least one device may start at the current slot. The PAN coordinator can recognize the transmissions from the devices while it may not recognize CCAs of the devices. If the transmission of data frame from at least one device starts at the current slot, it means that there were two consecutive CCAs during the two consecutive slots before the current slot. Thus, the PAN coordinator can estimate P_{CCA} by counting C_{II} and C_{TX}.

An example of counting these values is shown in Figure 1. In Figure 1, the PAN coordinator increases the value of C_{II} by 1 whenever two consecutive slots before the current slot are idle. If the transmission of data frame from at least one device occurs, the PAN coordinator increases the value of C_{TX} by 1. Each device can count C_{BO} and C_{CCA} whenever it performs the first CCA after the backoff procedure as shown in Figure 1. Each device increases the value of C_{BO} and C_{CCA} by last backoff period of the device and 1, respectively, whenever the device performs the first CCA.

In Figure 1, the PAN coordinator can count C_{II} and C_{TX} by observing the channel status, and each device can count C_{BO} and C_{CCA} from its own status without observing the channel status. Then, the estimated values $\hat{\tau}$ and $\hat{P}_{CCA}$ can be obtained as

$$\hat{\tau} = \frac{C_{CCA}}{C_{BO} + C_{CCA}}, \tag{3}$$

$$\hat{P}_{CCA} = \frac{C_{TX}}{C_{II}}. \tag{4}$$

Note that $\hat{\tau}$, $\hat{P}_{CCA}$, and $\hat{n}$ are the estimated values of τ, P_{CCA}, and n, respectively. Then, by using (2)-(4), the estimated number of active devices $\hat{n}$ can be obtained as

$$\hat{n} = f\left(\hat{\tau}, \hat{P}_{CCA}\right). \quad (5)$$

4. Runtime Estimation of the Number of Active Devices with Deferred Transmission and No Acknowledgment Using ARMA Filters

To estimate the number of active devices in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment in runtime, we use the ARMA filter [4, 9]. We utilize two ARMA filters for $\hat{\tau}$ and $\hat{P}_{CCA}$, which can be expressed as

$$\hat{\tau}^{(t+1)} = \omega \cdot \hat{\tau}^{(t)} + \frac{(1-\omega)}{q} \cdot \sum_{j=0}^{j=q-1} \frac{C_{CCA}^{(t-j+1)}}{C_{BO}^{(t-j+1)} + C_{CCA}^{(t-j+1)}}, \quad (6)$$

$$\hat{P}_{CCA}^{(t+1)} = \omega \cdot \hat{P}_{CCA}^{(t)} + \frac{(1-\omega)}{q} \cdot \sum_{j=0}^{j=q-1} \frac{C_{TX}^{(t-j+1)}}{C_{II}^{(t-j+1)}}, \quad (7)$$

where ω is the smoothing factor of ARMA filters and q is the moving window size of ARMA filters. $C_{BO}^{(t)}$ and $C_{CCA}^{(t)}$ denote C_{BO} and C_{CCA} in the CAP of the t-th superframe, respectively. $C_{TX}^{(t)}$ and $C_{II}^{(t)}$ denote C_{TX} and C_{II} in the CAP of the t-th superframe, respectively. Then, by using (2), (6), and (7), the estimated number of active devices in the CAP of the t-th superframe $\hat{n}^{(t)}$ can be obtained as

$$\hat{n}^{(t)} = f\left(\hat{\tau}^{(t)}, \hat{P}_{CCA}^{(t)}\right). \quad (8)$$

In IEEE 802.15.4, a device defers its transmission to the next superframe when the transmission cannot be completed during the CAP of current superframe [1, 13]. To estimate the number of active devices with deferred transmission and no acknowledgment, the PAN coordinator counts $C_{II}^{(t)}$ and each device counts $C_{BO}^{(t)}$ when the following conditions are satisfied. To count $C_{II}^{(t)}$, we assume that the lengths of data frames are the same and the PAN coordinator knows the length of data frame. Then, the PAN coordinator counts $C_{II}^{(t)}$ when the remaining time in the CAP of the t-th superframe is sufficient to complete the transmission of data frame. Each device counts $C_{BO}^{(t)}$ whenever it performs the first CCA after the backoff procedure. Therefore, if the backoff procedure for device does not end during the CAP of the t-th superframe, the device can add the number of ongoing backoff slots to $C_{BO}^{(t+1)}$ instead of adding them to $C_{BO}^{(t)}$. When a device ends the backoff procedure and defers its transmission to the $(t+1)$-th superframe, the device does not add the number of backoff slots to $C_{BO}^{(t)}$. At this time, the device does not add them to $C_{BO}^{(t+1)}$ since new backoff procedure starts at the beginning of the CAP in the $(t+1)$-th superframe. An example of counting these values is shown in Figure 2. In this example, we consider that there are not ongoing backoff procedures for devices 1 and 2 at the beginning of the CAP in the t-th superframe.

Table 1: Input parameters for the simulations [1].

Parameter	Value
length of data frame [slots]	[3, 7, 13]
length of beacon frame [slots]	3
duration of a CCA [slots]	0.4
macMinBe	4
macMaxBe	6
macMaxCsmaBackoff	4
macSuperframeOrder	3
macBeaconOrder	3
moving window size, q	5

In Figure 2, PAN coordinator does not count the last slot for $C_{II}^{(t)}$ because the remaining time in the CAP of the t-th superframe is insufficient to complete the transmission of data frame. Device 1 adds the last three backoff slots to $C_{BO}^{(t+1)}$ instead of adding them to $C_{BO}^{(t)}$ since the ongoing backoff procedure for device 1 does not end during the CAP of the t-th superframe. Device 2 does not count the last two backoff slots for both $C_{BO}^{(t)}$ and $C_{BO}^{(t+1)}$ because device 2 does not perform CCA at the last slot of the CAP in the t-th superframe due to its deferred transmission.

5. Simulation Results

In this section, we validate our proposed method through simulations using python. The input parameters for the simulations are shown in Table 1 [1].

In the simulations, the duration of a beacon frame is set as $L_{beacon} = 3$ in slots. Then, the duration of a CAP is set as $L_{CAP} = SD - L_{beacon}$ in slots. In the simulations, we assume an ideal channel condition that there is no fading. Since the probabilities in Sections 3 and 4 are obtained under saturated condition, we assume that each device always has a data frame to transmit in the simulations. The pseudocode of our proposed runtime estimation for P_{CCA} and τ is depicted in Algorithm 1. C_{TX} and C_{II} can be calculated by the PAN coordinator, and C_{BO} and C_{CCA} can be calculated by each device.

Figure 3 shows the transmissions of data frames from devices in runtime for the last 100 slots of the first superframe and the first 100 slots of the second superframe with varying the length of data frame L for IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment. The number of devices is changed from 15 in the first superframe to 30 in the second superframe. The second superframe starts at the 385-th slot. Since the duration of a beacon frame is 3 in slots, there is no transmission or backoff procedure for the first 3 slots in the second superframe. In Figure 3, the numbers of transmissions C_{TX} for the last 100 slots of the first superframe for $L = 3$, 7, and 13 are 15, 10, and 6, respectively, while those for the first 100 slots of the second superframe for $L = 3$, 7, and 13 are 19, 11, and 7, respectively. It shows that the number of transmissions C_{TX} increases as the number of active devices n increases. The numbers of events

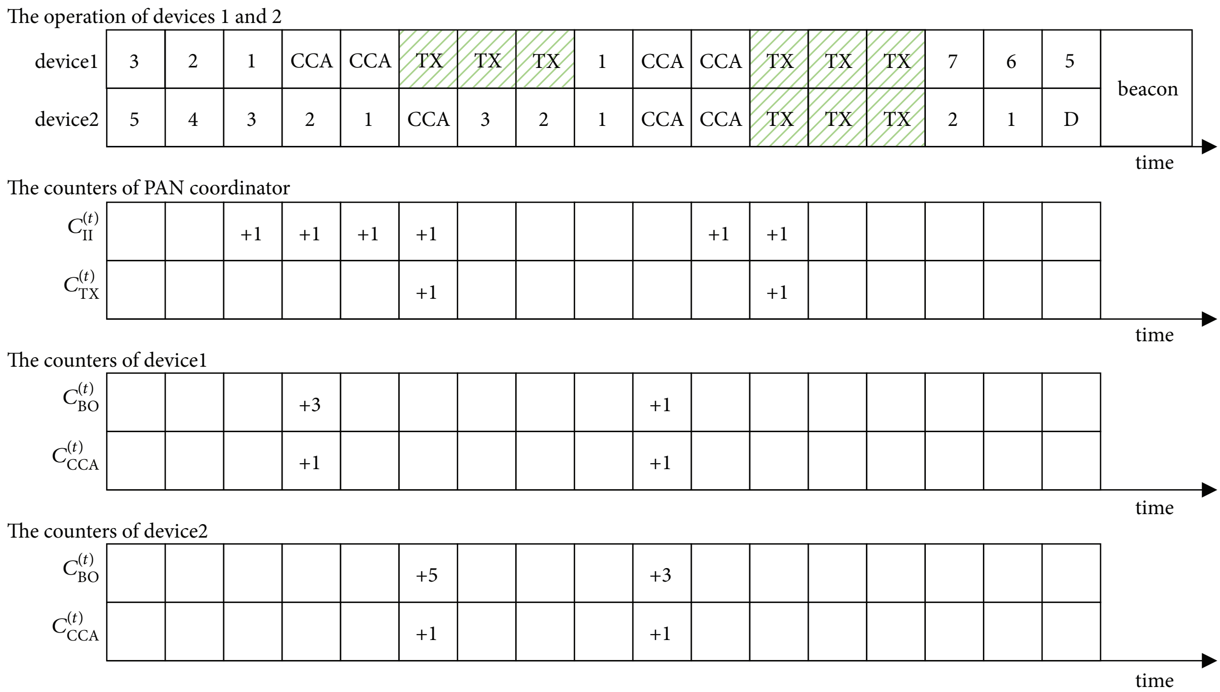


FIGURE 2: An example of counting $C_{II}^{(t)}$, $C_{TX}^{(t)}$, $C_{BO}^{(t)}$, and $C_{CCA}^{(t)}$, and backoff procedure for two devices with deferred transmission. In each box for the operation of devices 1 and 2, each number means the backoff value, CCA means that the device performs CCA, three consecutive TXs mean that the device transmits a data frame during three slots, and D means that the device defers its CCA and transmission.

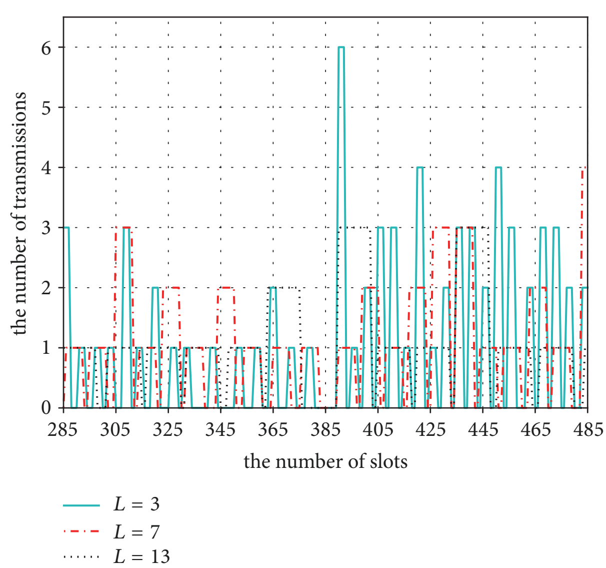


FIGURE 3: The transmissions of data frames from devices in runtime with varying the length of data frame L for IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

that two consecutive slots before the current slot are idle C_{II} for the last 100 slots of the first superframe for $L = 3, 7$, and 13 are 41, 20, and 17, respectively, while those for the first 100 slots of the second superframe for $L = 3$, 7, and 13 are 22, 14, and 11, respectively. It shows that the number of events that two consecutive slots before the current slot are idle C_{II} decreases as the number of active devices n increases.

Figures 4–6 show that the accuracy of our proposed method with varying the number of active devices. Figures 4–6 show $\hat{\tau}$, $\widehat{P}_{CCA}$, and $\hat{n}$ which are obtained from a reference device and a PAN coordinator through simulations with (3)-(5). Each simulation for each number of active devices n from 5 to 80 ran independently for 400 superframes. In Figures 4 and 5, the errors for τ and P_{CCA} are less than 0.0018 and 0.0171, respectively, for each number of active devices n from 5 to 80. More active devices can cause more transmissions that make the channel sensed busy. It can yield that each device is easy to fail the first or second CCA and the backoff value of each device may increase. Thus, τ decreases when the number of active devices increases in Figure 4. In addition, since long data frame can cause long channel occupancy, τ decreases as the length of data frame increases in Figure 4. Due to the same reason for τ, P_{CCA} decreases as the length of data frame increases in Figure 5. In Figure 6, the error of our proposed method for the estimation of the number of active devices is less than 1.3277 for each number of active devices n from 5 to 80. Our proposed method can estimate the number of active devices with errors which are less than 2 when there are up to 80 devices. In Figure 6, simulation results show that our proposed method gives maximum estimation error of 4.5008% in the number of active devices when $n = 5$ and $L = 7$. To obtain the standard deviations for $\hat{\tau}$, $\widehat{P}_{CCA}$, and $\hat{n}$, we ran 9 more simulations for each number of active devices n from 5 to 80. The standard deviations for $\hat{\tau}$, $\widehat{P}_{CCA}$, and $\hat{n}$ are less than 0.0007, 0.0044, and 1.6348, respectively, for each number of active devices n from 5 to 80.

We compare our proposed method with the conventional method [4–9] in terms of the estimated number of active

```
C_BO = (0, 0, ..., 0); C_CCA = (0, 0, ..., 0);
D = {1, 2, ..., n}; T = {}; chBusy = 0;
bv = (0, 0, ..., 0); rbv = bv; cw = (2, 2, ..., 2); defer = (0, 0, ..., 0);
K // number of superframes
L // length of data frame in slots
for each d in D, reset(d);
for k = 1 to K do
   C_TX = 0; C_II = 0; C_BO[1] = 0; C_CCA[1] = 0;
   for each slot in CAP do
      for each d in D, move element d from D to T if cw[d] == 0;
      if new device(s) is(are) ready to transmit (|T| > 0) and chBusy == 0 then
         chBusy = L;
         C_TX = C_TX + 1;
      for each d in D do
         if bv[d] > 0 then
            bv[d] = bv[d] − 1;
         else
            if cw[d] == 2 and remaining time in this CAP< 2 + L then
               defer[d] = 1;
            else if cw[d] > 0 then
               if cw[d] == 2 then
                  C_BO[d] = C_BO[d] + rbv[d];
                  C_CCA[d] = C_CCA[d] + 1;
               if chBusy == 0 then
                  cw[d] = cw[d] − 1;
               else
                  reset(d);
      if remaining time in this CAP ≥ L and two consecutive slots before the current slot are idle then
         C_II = C_II + 1;
      if |T| > 0 then
         chBusy = chBusy − 1;
         if chBusy == 0 then
            for each t in T, reset(t);
            for each t in T, move element t from T to D;
      // end of for each slot in CAP do
   for each d in D do
      if defer[d] == 1 then
         defer[d] = 0;
         reset(d);
   P_CCA[k] = C_TX/C_II;
   τ[k] = C_CCA[1]/(C_CCA[1] + C_BO[1]);
function reset(d)
   cw[d] = 2;
   bv[d] = randombackoff value according to NB and BE;
   rbv[d] = bv[d];
```

Algorithm 1: Pseudocode of the proposed runtime estimation for P_{CCA} and τ in IEEE 802.15.4 slotted CSMA/CA.

devices. In the conventional method, each device estimates the number of active devices as follows:

$$\widehat{p} = \frac{C_{COLL}}{C_{TX,D}}, \tag{9}$$

$$\widehat{n}_{conv} = 1 + \frac{\log(1-\widehat{p})}{\log(1-\widehat{\tau})}, \tag{10}$$

where $\widehat{p}$ is the estimated conditional collision probability that when a device transmits a data frame, at least one other device transmits a data frame simultaneously. $C_{TX,D}$ is the number of events that a device transmits a data frame, and C_{COLL} is the number of events that the transmitted data frames collide. $\widehat{\tau}$ is the estimated probability which can be obtained by (3). To estimate $\widehat{p}$ using (9), each device needs to count $C_{TX,D}$ and C_{COLL}. However, in IEEE 802.15.4 slotted CSMA/CA, each device assumes that the transmission of a data frame from the device is successful with no acknowledgment mode [1]. It may cause that the device estimates the conditional collision probability $\widehat{p}$ in (9) as zero since C_{COLL} is assumed to be zero with no acknowledgment mode. Then, the estimated number of active devices $\widehat{n}_{conv}$ in (10) is one in the conventional method with no acknowledgment mode. The simulation results for the estimated number of active devices using

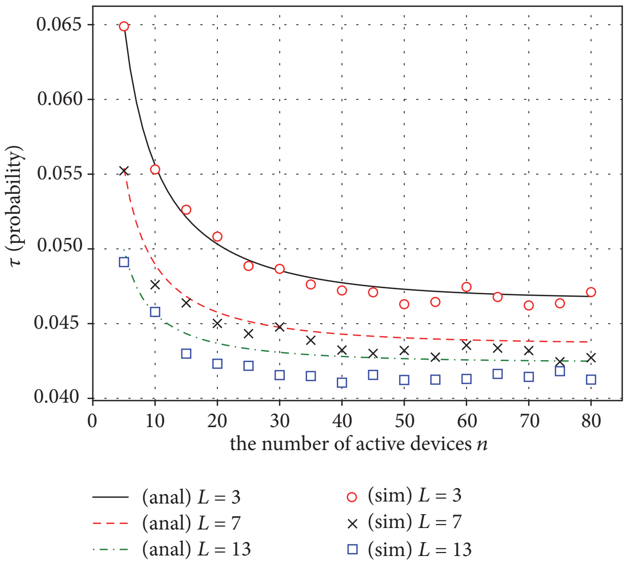


Figure 4: Estimation of τ at a reference device using our proposed method in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

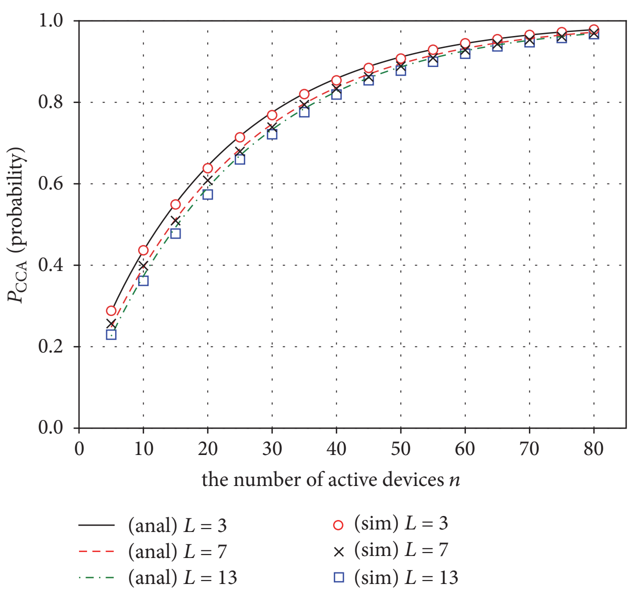


Figure 5: Estimation of P_{CCA} at a PAN coordinator using our proposed method in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

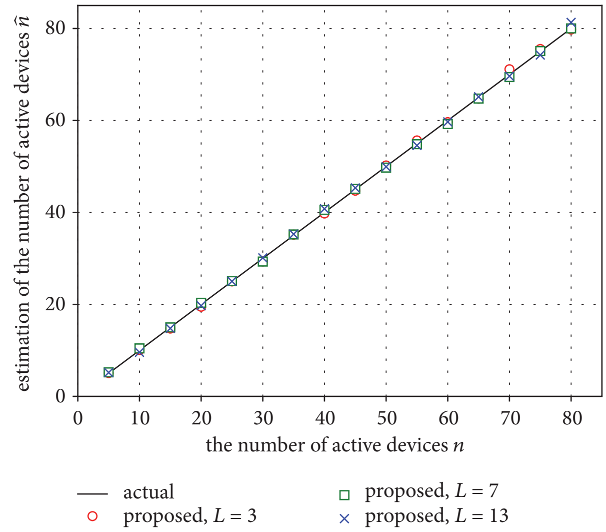


Figure 6: Estimation of the number of active devices at a reference device using our proposed method in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

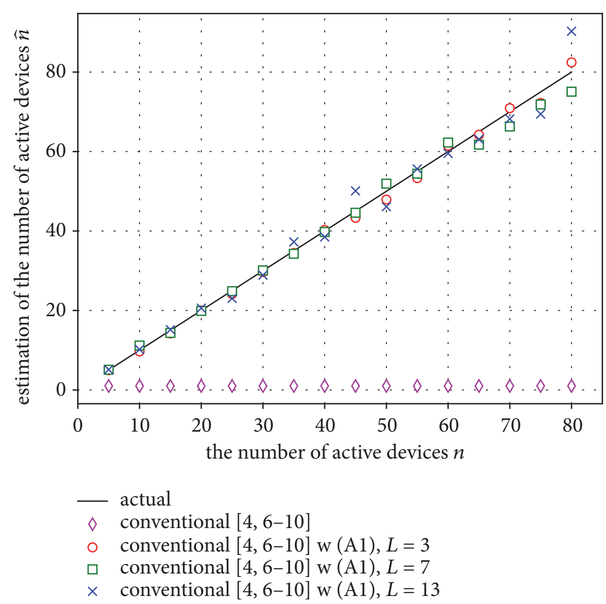
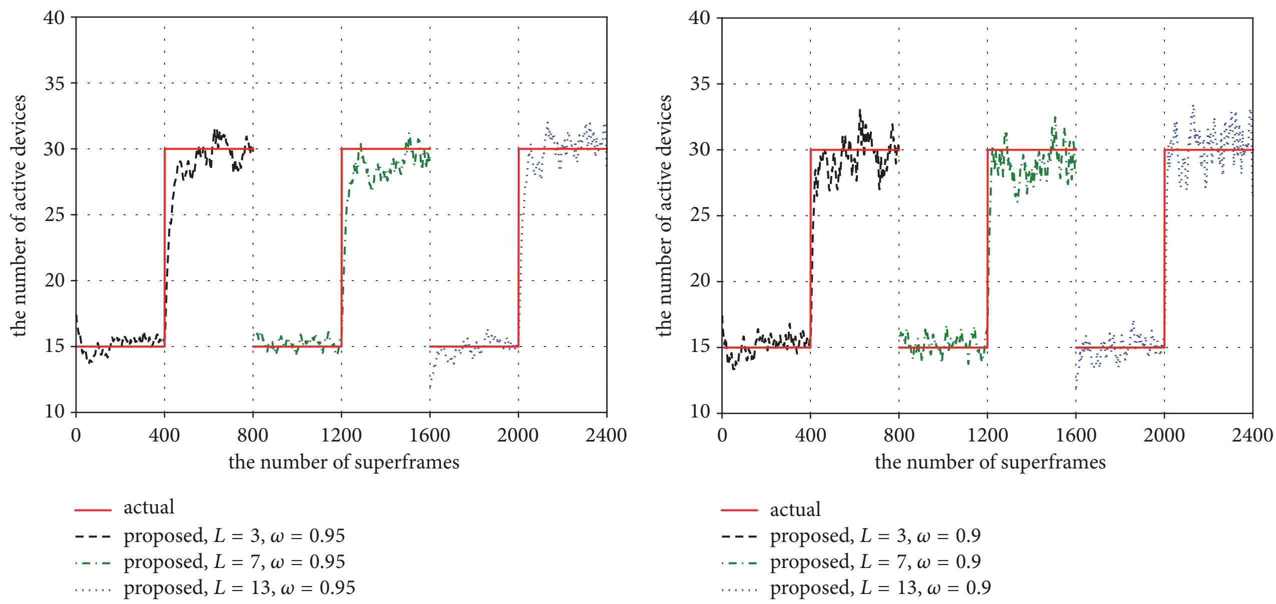


Figure 7: Estimation of the number of active devices at a reference device using the conventional method [4–9] in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

the conventional method are shown in Figure 7. In the conventional method with no acknowledgment mode, the estimated number of active devices is always one. Then, the estimation error of the number of active devices is $n-1$ which may be large. Thus, the conventional method is not appropriate to be utilized with no acknowledgment mode.

To obtain the simulation results of the conventional method [4–9] as shown in Figure 7, we simulate the conventional method under the assumption that each device knows whether a data frame transmitted by the device collides with other frames or not even though there is no acknowledgment. We will refer to this assumption as (A1). In the conventional method, each device counts not only C_{BO} and C_{CCA} to estimate $\hat{\tau}$ in (3) but also $C_{\text{TX,D}}$ and C_{COLL} to estimate $\hat{p}$ in (9). In our proposed method, each device counts C_{BO} and C_{CCA} to estimate $\hat{\tau}$ in (3) and the PAN coordinator counts C_{TX} and C_{II} to estimate $\hat{P}_{\text{CCA}}$ in (4). $C_{\text{COLL}} \le C_{\text{TX,D}}$ since data frames can collide when the data frames are transmitted by the devices. $C_{\text{TX,D}} < C_{\text{TX}}$ since $C_{\text{TX,D}}$ is the number of events related to a single active device and C_{TX} is the number of events related to all the active devices. $C_{\text{TX}} \le C_{\text{II}}$ since the transmission of data



(a)

(b)

Figure 8: Runtime estimation of the number of active devices at a reference device using our proposed method in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

frame can occur after two consecutive slots before the current slot is idle. Thus, the following condition can be obtained as

$$C_{COLL} \le C_{TX,D} < C_{TX} \le C_{II}, \quad \text{if } n > 1. \tag{11}$$

By condition (11), C_{COLL} and $C_{TX,D}$ in Equation (9) are smaller than C_{TX} and C_{II} in (4). Thus, the accuracy of the estimation for the number of active devices in the conventional method with (A1) may be lower than that in our proposed method. In Figure 7, the maximum error of the conventional method with (A1) for the estimated number of active devices is 10.2694 (12.8368%) when $n = 80$ and $L = 13$. It shows that the maximum error of the estimated number of active devices for the conventional method with (A1) is larger than that for our proposed method. To obtain the standard deviations for $\hat{n}_{conv}$, we ran 9 more simulations for each number of active devices n from 5 to 80. The maximum standard deviation for $\hat{n}_{conv}$ of the conventional method with (A1) is 5.1114 when $n = 65$ and $L = 13$. It shows that the maximum standard deviation for $\hat{n}_{conv}$ of the conventional method with (A1) is larger than that of our proposed method. The simulation results show that our proposed method is more accurate than the conventional method.

Figure 8 shows the performance of our proposed estimation method in runtime. Each simulation ran independently for 800 superframes with $L = 3$, 7, and 13, respectively. The actual number of active devices n is changed from 15 to 30 at the 401-st superframe for each simulation. The simulation results in Figure 8 are obtained from a reference device through simulations with (6)-(8). The smoothing factors ω for ARMA filters are 0.95 and 0.9 in Figures 8(a) and 8(b), respectively. Figures 8(a) and 8(b) show that the fluctuation for the estimated number of active devices for the case of $\omega = 0.9$ is wider than that for $\omega = 0.95$. However, Figures 8(a) and 8(b) show that the convergence speed for $\omega = 0.9$ is higher than that for $\omega = 0.95$ when the actual number of active devices is changed.

In Figure 8(a) for $\omega = 0.95$, when the actual number of active devices n is 15 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}$ are 15.1738, 15.2945, and 14.8117, respectively, and the standard deviations of the estimated numbers of active devices are 0.6185, 0.4296, and 0.7448, respectively. In Figure 8(a) for $\omega = 0.95$, when the actual number of active devices n is 30 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}$ are 28.6981, 28.2906, and 29.4994, respectively, and the standard deviations of the estimated numbers of active devices are 2.5668, 2.1465, and 2.4719, respectively.

Meanwhile, in Figure 8(b) for $\omega = 0.9$, when the actual number of active devices n is 15 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}$ are 15.1443, 15.2920, and 14.9142, respectively, and the standard deviations of the estimated numbers of active devices are 0.7349, 0.6507, and 0.8437, respectively. In Figure 8(b) for $\omega = 0.9$, when the actual number of active devices n is 30 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}$ are 29.1502, 28.7304, and 29.9887, respectively, and the standard deviations of the estimated numbers of active devices are 2.1475, 1.8218, and 2.1853, respectively.

In Figures 8(a) and 8(b), the averages of the estimation errors of the number of active devices are less than 0.2945 and 1.7094 in runtime when the actual numbers of active devices are 15 and 30, respectively. Figures 8(a) and 8(b) show that when the actual number of active devices n is 30, the standard deviation for $\omega = 0.95$ is larger than that for $\omega = 0.9$ due to the convergence period. For $n = 30$, if the first 50 superframes among 400 superframes are ignored, the standard deviations with $L = 3$, 7, and 13 for $\omega = 0.95$ are 1.0082, 0.9086, and 1.0148, respectively, while those for $\omega = 0.9$ are 1.2728, 1.2733, and 1.5246, respectively. With the simple ARMA filters, our proposed method can estimate the number of active devices in runtime.

Figure 9 shows the performance of the conventional method [4–9] with (A1) in runtime. In Figure 9(a) for $\omega = 0.95$, when the actual number of active devices n is 15 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}_{\text{conv}}$ are 14.5151, 13.8124, and 16.1222, respectively, and the standard deviations of the estimated numbers of active devices are 1.8073, 3.1180, and 4.0573, respectively. In Figure 9(a) for $\omega = 0.95$, when the actual number of active devices n is 30 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}_{\text{conv}}$ are 29.8343, 30.5295, and 31.0181, respectively, and the standard deviations of the estimated numbers of active devices are 3.3373, 4.4264, and 7.9640, respectively. Figures 8(a) and 9(a) show that the conventional method with (A1) using ARMA filter for $\omega = 0.95$ may have a larger error than our proposed method in terms of the average of the estimated number of active devices. They also show that the standard deviation of the estimated number of active devices for the conventional method with (A1) is up to 7.8479 times larger than that for our proposed method.

Meanwhile, in Figure 9(b) for $\omega = 0.9$, when the actual number of active devices n is 15 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}_{\text{conv}}$ are 14.4941, 14.4253, and 16.0413, respectively, and the standard deviations of the estimated numbers of active devices are 2.1441, 3.4977, and 4.9136, respectively. In Figure 9(b) for $\omega = 0.9$, when the actual number of active devices n is 30 with $L = 3$, 7, and 13, the averages of the estimated numbers of active devices $\hat{n}_{\text{conv}}$ are 30.4327, 31.4003, and 32.3743, respectively, and the standard deviations of the estimated numbers of active devices are 4.0542, 5.7494, and 10.5814, respectively. Figures 8(b) and 9(b) show that the conventional method with (A1) using ARMA filter for $\omega = 0.9$ may have a larger error than our proposed method in terms of the average of the estimated number of active devices. They also show that the standard deviation of the estimated number of active devices for the conventional method with (A1) is up to 6.9404 times larger than that for our proposed method.

Figures 8 and 9 show that the conventional method with (A1) may have a larger error than our proposed method in terms of the estimated number of active devices. They also show that the conventional method with (A1) using ARMA filter may have a larger standard deviation of the estimated number of active devices than our proposed method. It means that our proposed method is more stable than the conventional method with (A1).

To show the performance of our proposed method in an IEEE 802.15.4 two-hop network, we ran more simulations with varying the number of active devices n as shown in Figure 10. For the IEEE 802.15.4 two-hop network, we consider that a base station and a PAN coordinator constitute a parent PAN and the PAN coordinator and n devices constitute a child PAN. To simulate our proposed method in the two-hop network with the superframe structure, we consider the active portion for the parent PAN and the active portion for the child PAN. In Figure 10, the duration of the active portion for the parent PAN is set equal to that for the child PAN as 384 slots in each superframe. In the active portion for the child PAN, the devices transmit data frames to the PAN coordinator. In the active portion for the parent PAN, the PAN coordinator transmits the data frames to the base station. To show the effect of our proposed method in the two-hop network, we additionally consider the optimal backoff period W_{opt} which depends on the number of

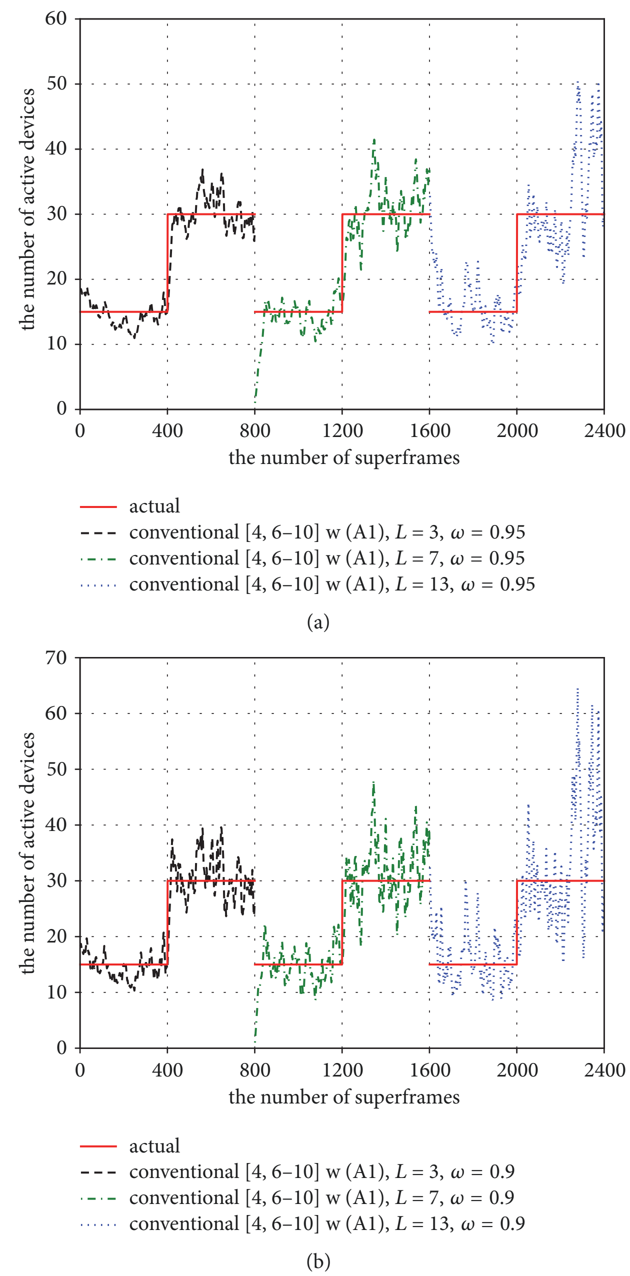


FIGURE 9: Runtime estimation of the number of active devices at a reference device using the conventional method [4–9] with (A1) in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

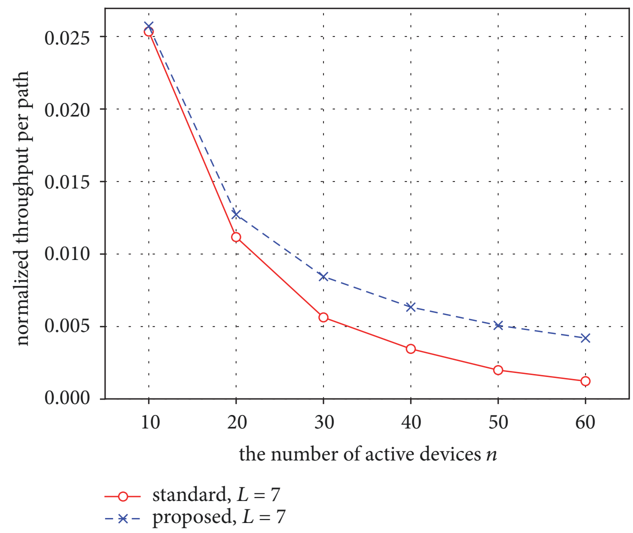


Figure 10: Normalized throughput per path in the two-hop network with varying the number of active devices using IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment.

active devices n. Since our proposed method can estimate the number of active devices in the two-hop network, the optimal backoff period W_{opt} can be utilized via our proposed method.

Figure 10 shows the normalized throughput per path in the two-hop network with varying the number of active devices n. The devices transmit data frames to the PAN coordinator using IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment. The normalized throughput per path can be obtained as $S_{path} = (N_s \cdot L)/(n \cdot T_{sim})$ where N_s is the number of successful transmissions from the devices during T_{sim}, L is the length of data frame in slots, n is the number of active devices, and T_{sim} is the total number of slots during the simulation. In the two-hop network, we compare the throughput performance of our proposed method with that of the IEEE 802.15.4 standard method which may not use the optimal backoff period W_{opt}. Figure 10 shows that the two-hop network using our proposed method can get higher throughput than that using the standard method. In a similar way, the multihop network using our proposed method may get better performance than that using the standard method.

The simulation results show that our proposed method accurately estimates the number of active devices in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment. The simulation results also show that our proposed method is more accurate and stable than the conventional method with (A1) in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment. The simulation results also show that the throughput performance of the two-hop network can be improved using our proposed method.

6. Conclusions

In this paper, we have proposed the method that estimates the number of active devices in IEEE 802.15.4 slotted CSMA/CA networks with deferred transmission and no acknowledgment. We have considered a star topology and assumed that there are uplink transmissions of data frames from the devices in the networks. Since the devices cannot estimate the conditional collision probability with no acknowledgment, our proposed method utilizes the conditional probability that at least one device performs the first CCA when active devices are in the backoff procedure and the conditional probability that each device performs the first CCA when the device is in the backoff procedure. Our proposed method estimates these probabilities based on the concept of ARMA model. We validated our proposed method with varying the length of data frame and the actual number of active devices through simulations. As a performance metric, we measured estimation error in the number of active devices. The simulation results have shown that our proposed method gives errors of the number of active devices less than 4.501% when the actual number of active devices is varying from 5 to 80. Meanwhile, our proposed method gives estimation errors of the number of active devices less than 0.2945 and 1.7094 in runtime when the actual numbers of active devices are 15 and 30, respectively, in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment. We compared our proposed method with the conventional method in terms of the average and standard deviation for the estimated number of active devices. The simulation results show that our proposed estimation method is more accurate and stable than the conventional method in IEEE 802.15.4 slotted CSMA/CA with deferred transmission and no acknowledgment. The simulation results also show that the throughput performance of the two-hop network can be improved using our proposed method.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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