Adjustment Delay Scheme to Improve Performance IEEE 802.15.4 Networks

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Abstract

The challenges of CSMA/CA as following: first, when the device nodes detect the channel in busy condition, the device nodes have to increase the value of backoff exponent which cause range of blind backoff process also increase. Second, the blind backoff process will cause lower channel utilization and more energy consumptions. This article proposes a scheme to improve IEEE 802.15.4 medium access control, called adjustment delay scheme (ADES). This article also presents a comprehensive Markov chain analysis to predict the probability of successful transmission, network goodput, bandwidth utilization and total network energy consumption. The validity of the analytical model is proven by closely matching the simulation experiments. ADES performs better than those of other algorithms in term of the probability of successful packet transmission, network goodput, bandwidth utilization as well as energy consumption in the networks.

Keywords: IEEE 802.15.4, Markov chain, blind backoff, energy consumption

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1. Introduction

The IEEE 802.15.4 is one of candidates for wireless sensor networks. Wireless sensor networks consist of large number of sensors that are densely deployed to some physical phenomena for wide variety applications. The IEEE 802.15.4 standard has been designed to specify the physical layer (PHY) and medium access control (MAC) sublayer for low power consumption, short transmission range, and low-rate wireless personal area network (LR-WPAN) [1].

The problem of CSMA/CA as following: first, when the device nodes detect the channel in busy condition, the device nodes have to increase the value of backoff exponent (BE). However, which cause range of blind backoff process also increase. Second, when the device nodes detect the channel in busy condition, the device nodes have to increase number of backoff stage. However, which cause more energy consumptions for entering next backoff stage. In addition, the blind of backoff process in the slotted carrier sense multiple access with collision avoidance (CSMA/CA) will cause lower channel utilization and more energy consumptions in the networks.

The performance analysis of IEEE 802.15.4 MAC is still one of the important research topics in wireless sensor network. A. N. Alvi at al [2] present an evaluation of the slotted CSMA/CA of IEEE 802.15.4 based on all of its frequency, which only analyze each frequency and compare with each other but not to propose a method. K. Ashrafuzzaman at al [3], the authors use node state and channel state models to analyze the performance of IEEE 802.15.4 MAC that are simple but accurate. The authors also present an analytical model for the slotted CSMA/CA algorithm adopted in the contention access period (CAP) of the beacon-enabled mode in IEEE 802.15.4 MAC, which only considers for the saturated mode. However, they do not consider about acknowledgement (ACK).

There are several mathematical analyses based on Markov chain models have been proposed to analyze the performance of IEEE 802.15.4, but they do not consider packet retransmissions [4-10]. T.-R Park at al [4] have proposed a new markov chain model of 802.15.4 and analyse throughput and energy consumption in saturation conditions. T.-J Lee at al [5] have presented a new model for the slotted CSMA/CA of IEEE 802.15.4 Medium Access...
Control (MAC) and evaluate its throughput limit in order to grasp the characteristics of IEEE 802.15.4 WPAN. S. Pollin et al [6] have provided a detailed analytical evaluation of its performance in a star topology network, for uplink and acknowledged uplink traffic. Both saturated and unsaturated periodic traffic scenarios are considered. Y. Zhang et al [7] have studied packet size optimization for IEEE 802.15.4 networks. Taking into account of the CSMA/CA contention, protocol overhead, and channel condition, new analytical models are proposed to calculate the goodput and the energy consumption. J. He et al [8] have studied a Markov chain based analytical model to evaluate the slotted CSMA/CA algorithm specified in the MAC layer of IEEE 802.15.4 standard. Z. Xiao et al [9] have proposed a novel queuing model to provide a tool for performance evaluation to IEEE 802.15.4 Medium Access Control (MAC) protocol with sleep mode enabled. C. Buratti et al [10] have presented a mathematical model for the beacon enabled mode of the IEEE 802.15.4 medium-access control (MAC) protocol. A personal area network (PAN) composed of multiple nodes, which transmit data to a PAN coordinator through direct links or multiple hops. Some of the modified Markov chain models have been investigated by considering packet retransmissions but not considering the defer transmission [11-14]. Z. Tao et al [11] have proposed a novel Markov chain for IEEE 802.15.4 MAC, which faithfully captures all the essential features of the protocol, and thus can provide valuable insight into the strengths and weaknesses of this multiple access scheme. P. Park et al [12] have presented a generalized analysis of the IEEE 802.15.4 medium access control (MAC) protocol in terms of reliability, delay and energy consumption. Y.-K Huang et al [13] have studied comprehensively analyzes IEEE 802.15.4 duty-cycle operation. Specifically, a novel analytical model that accommodates a general traffic distribution is developed. M. Khanafar et al [14] have been proposed a modification to the IEEE 802.15.4 standard that achieves efficient power savings for the sensor nodes, better channel utilization, and improved reliability. In [15-19], the authors propose the Markov chain models with considering the postpone transmission. B. Gao et al [15] have proposed an extended Markov-based analytical model for IEEE 802.15.4 slotted carrier sense multiple access/collision avoidance (CSMA/CA) algorithm considering the newly enabled sleep mode. C.-Y. Jung et al [16] have been proposed Markov chain model reflects the characteristics of the IEEE 802.15.4 medium-access control (MAC) protocol, such as a superframe structure, acknowledgements, and retransmissions with and without limit. B. Shrestha et al [17] have presented a general discrete-time Markov chain model for the IEEE 802.15.4 based networks taking into account the slotted CSMA/CA and GTS transmission phenomena together in heterogeneous traffic scenario and non-saturated condition. B.-H. Lee et al [18] have proposed the superframe adjustment and beacon transmission scheme (SABTS) by assigning the accurate values of beacon order and superframe order for the PAN coordinator, cluster coordinators, and device nodes, and deciding the precise time for the beacon transmission of PAN and coordinator nodes. M. Martalo et al [19] have been proposed the analytical model based on Markov chain for multi-hop cluster network has been studied without considering ACK to confirm the successful of data packet transmission. However, all of the abovementioned models only consider for CSMA/CA standard, i.e., not proposed new contention mechanism in CAP.

H.-K Wu et al [20] have proposed a Markov chain model for cluster tree network that is developed with taking into account packet retransmission, acknowledgement, and defer transmission. B.-H. Lee et al [21] also proposed a scheme to improve IEEE 802.15.4 medium access control, called superframe duration adjustment scheme (SUDAS), which analyzes the overall of the IEEE 802.15.4 not only CAP but also CFP. SUDAS is expected to effectively allocate guaranteed time slot to the requested devices, it adjusts the length of the slot in superframe duration based on the length of the packet data.

Several authors have been proposed to improve the slotted CSMA/CA using hybrid MAC protocol integrating CSMA and time division multiple access (TDMA) for wireless sensor network [22-24]. K. Sarvakar et al [22] have been proposed an efficient hybrid MAC layer protocol, utilized ZigBee MAC (EZ-MAC), for sensor networks. Sensor networks have to manage variety of traffics such as real-time traffics and sensor traffics. H. Deng et al [23] have been investigated performance models for CSMA/CA and TDMA systems and compare their performance under both non-saturation and saturation conditions based on the developed performance models. I. Rhee et al [24] have proposed the design, implementation and

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performance evaluation of a hybrid MAC protocol called Z-MAC, for wireless sensor networks that combines the strengths of TDMA and CSMA while offsetting their weaknesses.

R. K Patro et al [25] also presented the analysis correctly for contention access period, but they do not consider about defer transmission if the current superframe is not enough to accommodate transmission. M.B Rasheed et al [26] have proposed an analysis for slotted CSMA/CA for energy consumption, but they only consider about idle condition for the standard and do not propose a new scheme. B-H Lee et al [27] have presented an additional carrier sensing (ACS) for IEEE 802.15.4 in order to improvement performance star networks. However, the authors do not consider about defer transmission and they do not provide retransmission state in Markov chain model. In [29-30], sensor nodes use different mechanisms to reduce the waiting time before they have successfully transmitted packets, which makes it possible to decrease the backoff time between packet transmissions. Ji. Z at al [28] have presented a developed for personal personal area networks (PANS) with low complexity and high reliability which enable PANS to be widely employed in many industrial applications such as E-Healthcare, environmental monitoring and industrial automation. Lu ZQ et al [29] have studied an manage connectivity and detecting nodes or link failures is difficult in unstructured WSN because there is large number of nodes. The sensor nodes are tiny devices with limited constraints and it is not feasible in deployed scenarios to recharging the batteries. Therefore to decrease energy consumption and prolonging the WSN lifetime is main design objective for sensor based applications and mechanisms. B. Bougard et al [30] have evaluated the potential of an 802.15.4 radio for use in an ultra low power sensor node operating in a dense network. They can improve channel utilization. However, fail to alleviate collisions.

This article proposes an adjustment delay scheme (ADES) for IEEE 802.15.4 which is the extended work from [18] and [21]. In [18] the authors focus on how to decrease the collisions between beacons or even between beacon and data packets by adjusting the beacon starting times of PAN and coordinator nodes for cluster tree topology. In [21], the authors focus on assigning adjustable length of GTS slot based on the length of packet and also deciding the precise time for the GTS starting time (GTSstart) and the GTS length (GTSlength) for star topology. However, all of the aforementioned models only consider CSMA/CA standard for contention mechanism. In other words, they did not consider the blind of backoff and probability going to next backoff stage. ADES focuses on adjustment delay if device node detects the channel in busy condition which can reduce probability of going to entering next backoff stage and blind of backoff process. In addition, this scheme also include addition third CCA for reduce collision. The performance of ADES for star topology is analyzed by the Markov chain model modified from [18] for considering packet retransmission, ACK and defer transmission, which is to obtain the probability of success transmissions, network goodput, bandwidth utilization as well as energy consumption for IEEE 802.15.4 networks. The major contribution of this article is to model the channel access for star network that analyze the overall performance of IEEE 802.15.4 MAC to reduce probability of going to next backoff stage which can increase probability success packet transmission with adjustment delay at first CCA and second CCA if channel find in busy condition also including addition third CCA to reduce collision in order for improve performance networks.

2. Research Method
2.1. The Description of ADES
ADES is expected to adjust delay if the device node detects the channel in busy condition. If the device node detects channel in busy condition which cause blind of backoff process. In this case can cause degradation of performance networks not only lower bandwidth utilization but also more energy consumption. Let us denote SD and T delay be the superframe duration in second and the time interval of waiting due to CCA busy in second, which can be obtained by equations (1) and (2), respectively, where aBaseSuperframeDuration and Rs denote the minimum duration of the superframe and symbol data rate are equal to 960 symbols and 62500 symbol/second, respectively.

\[ SD = \text{aBaseSuperframeDuration} \]
\[ T_{\text{delay}} = \frac{Rs}{960} \]

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The format of the superframe is defined by the network coordinator as shown in Figure 1. Furthermore, the active portion of each superframe comprised of three parts: beacon, CAP and CFP, which is divided into 16 equal length slots. The length of one slot is equal to \( aBaseSlotDuration \times 2^{SO} \) symbols, where \( aBaseSlotDuration \) is equal to 60 symbols.

### Figure 1. An example of superframe structure

In this article, each node will communicate with the network coordinator by using the slotted CSMA/CA in CAP. To transmit a packet, a node first will delay a backoff period (BP) determined by randomly choosing from 0 to \((2^{BE} - 1) \ UBP\), where \( BE \) is a backoff exponent and initially set to the value of \( aMinBE \), and then performs the first CCA to detect channel condition. If the channel is founded in busy at the first CCA detection, it will reduce minus one the value of contention window (CW), then continue delay for one slot \( T_{delay} \) and then performs the second CCA to detect the channel again. If the result of second CCA channel is detected by busy condition, the node will reduce again with minus one for value of contention window (CW), then continue delay for two slot \( T_{delay} \) and then perform again for third CCA. If the result of third CCA channel is detected by idle condition, the node will start to transmit its data packet and waits for the acknowledged packet from the coordinator after finishing the data packet transmission. However, if the result of third CCA channel is detected by busy condition, the device node will reassign a backoff period (BP) between 0 and \((2^{(BE + 1)} - 1) \ UBP\) for delay and attempt CCA again, where \( BE \) can be increased to the maximum value of \( macMaxBE \). The transmission will fail if the number of backoff attempts (NB) exceeds the value \( macMaxCSMABackoffs \).

For more detail about the aforementioned description, we can explain ADES with flowchart as shown in Figure 2. We consider a star topology network having one network coordinator and several device nodes. By using Equation (2), we can get the value of \( T_{delay} \) for each CCA when channel in busy condition.

### Figure 2. ADES algorithm flowchart

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Figure 2. The flowchart of ADES

Figure 3. An example of implementation of ADES
2.2. Analysis of ADES

In this section, the proposed ADES based on the IEEE 802.15.4 use slotted carrier sense multiple access with collision avoidance (CSMA/CA) for active portion, part of CAP only,

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because we only consider about active period, while part of CFP is neglected. This article also taking into account the case of acknowledged uplink data transmission is investigated comprehensively via Markov chain model as shown in figure 5.

Let \( b_{i,j,k} \) be the stationary probability at the stochastic state \((s(t) = i, c(t) = j, \text{ and } r(t) = k)\), where \( s(t) \), \( c(t) \), and \( r(t) \) represent backoff stage, backoff counter, and number of retransmissions, respectively, shown as Equation (4), where \( b_{0,1,k} \), \( b_{1,2,k} \), \( b_{2,3,k} \) and \( b_{3,4,k} \) are the stationary probabilities for the first CCA (CCA1), the second CCA (CCA2), the third CCA (CCA3) and packet transmission, respectively, at the \( i^{th} \) backoff stage and the \( k^{th} \) retransmission. Let \( b_{Si,k} \) and \( b_{CI,k} \) be the stationary probabilities of the successful transmission and collision at the states of \( S_{i,k} \) and \( C_{i,k} \) as shown in Equations (5) and (6), respectively, where \( m \) and \( R \) are the maximum NB stage and retransmissions, i.e., they are equal to 4 and 3, respectively. Let \( b_{DFi,k} \), \( b_{DSA,k} \) and \( b_{DSSi,k} \) be the stationary probabilities of delay one slot at first CCA busy, delay one slot for second CCA busy for first and delay one slot for second CCA busy for second at the states of \( DF_{i,k} \), \( DSA_{i,k} \) and \( DSB_{i,k} \) for the \( i^{th} \) backoff stage and the \( k^{th} \) retransmission as shown in equations. (7) to (9), respectively.

\[
\begin{align*}
    b_{i,j,k} &= \lim_{t \to \infty} P[s(t) = i, c(t) = j, r(t) = k] \text{ for } i \in (0, m), j \in (-4, w_1 - 1), k \in (0, R) \\
    b_{Si,k} &= \lim_{t \to \infty} P[S_{i,k}] = S_i, r(t) = k, i \in (0, m), k \in (0, R) \\
    b_{CI,k} &= \lim_{t \to \infty} P[C_{i,k}] = C_i, r(t) = k, i \in (0, m), k \in (0, R) \\
    b_{DFi,k} &= \lim_{t \to \infty} P[DF_{i,k}] = DF_i, r(t) = k, i \in (0, m), k \in (0, R) \\
    b_{DSA,k} &= \lim_{t \to \infty} P[DSA_{i,k}] = DSA_i, r(t) = k, i \in (0, m), k \in (0, R) \\
    b_{DSSi,k} &= \lim_{t \to \infty} P[DSS_{i,k}] = DSS_i, r(t) = k, i \in (0, m), k \in (0, R)
\end{align*}
\] (4)

Let us explain the parameters used in the Markov chain model as follows. Let \( w_1 = 2^{BE_1} \) be the backoff window at the \( i^{th} \) backoff stage of a device, where the backoff exponent \( BE_i = 3, 4, 5, 5, \) and 5 for \( 0 \leq i \leq m \). An IDLE state means that a device node has no packet to transmit. Let us denote \( q \) be the probability that a packet arrives at a node during the active period.

The MAC sublayer should transmit its packet if the remaining CSMA/CA steps, i.e., CCA analyses, the frame transmission, and any ACK can be completed before the end of \( \text{CAP}_{\text{ades}} \). Conversely, if the current \( \text{CAP}_{\text{ades}} \) has not enough slots to transmit data packets, it should defer transmission until the beginning of the \( \text{CAP}_{\text{ades}} \) in the next superframe duration. Let \( d \) be the probability of defer transmission that no enough slot is left in the current \( \text{CAP}_{\text{ades}} \) to transmit data packet, which can be obtained by equation (10), where \( T_{\text{CCA}}, T_{\text{data}}, T_{\text{ack}}, T_{\text{Lack}}, T_{\text{LIFS}} \) are the time to transmit CCA, time to transmit data packet, time to waiting for ACK packet, time to transmit ACK packet and time duration of IFS, respectively. The length of \( T_{\text{Lack}} \) is equal to 88 bits, whereas the length of \( L_{\text{IFS}} \) is equal to \( \text{macMinLIFSPeriod} \) (160 bits) if the length of packet is greater than \( a\text{MaxSIFSFrameSize} \) (144 bits), otherwise, it is equal to \( \text{macMinSIFSPeriod} \) (48 bits).

\[
d = \frac{3T_{\text{CCA}} + 3T_{\text{delay}} + T_{\text{data}} + T_{\text{ack}} + T_{\text{Lack}} + T_{\text{LIFS}}}{\text{CAP}_{\text{ades}}}
\] (10)
Let us denote $\alpha$, $\beta$ and $\gamma$ be the probabilities that CCA$_1$, CCA$_2$ and CCA$_3$ are busy, respectively. CCA$_1$ busy means that the device node at one of the CCA$_1$ states while at least one of the other nodes at packet transmission state, while CCA$_2$ busy means that the device node at one of the CCA$_2$ states while at least one of the other nodes at packet transmission state and CCA$_3$ busy means that the device node at one of the CCA$_3$ states while at least one of the other nodes at packet transmission state. Let us also denote $P_{\text{coll}}$ to be the probability of the collision of packet transmission after CCA$_2$ or CCA$_3$, i.e., the device node at packet transmission state while at least one of the other nodes in the packet transmission state at the same time, which can be obtained by equation (11). Let us also denote $P_{\text{fail1}}$ and $P_{\text{fail2}}$ to be the probabilities of fail transmission due to the maximum number of retransmissions after collisions and no channel to use after reaching the maximum backoff stage at the maximum retransmission stage, as shown in Equations (12) to (13), respectively.

$$P_{\text{coll}} = N \tau \left(1 - (1 - \tau)^{(N-1)}\right)$$

$$P_{\text{fail1}} = \sum_{i=0}^{m} b_{c_{i,k}} = b_{0,0,0}(X^R + Z^R)X$$

$$P_{\text{fail2}} = b_{m,0R} (1 - d) \beta \gamma = b_{0,0,0} (Y^m)(X^R + Z^R)(1 - d) \beta \gamma$$

Let denote $P_{\alpha}$ to be the probability of collision transmission after $k$ attempts (Probability of packet being dropped due to collision retransmission), which can be calculated by equation (14). Let $P_{\text{dropcoord}}$ and $P_{\text{succeed}}$ be the probabilities of drop transmission and successful transmission from device node to its coordinator, which can be obtained by Equations (15) and (16), respectively. Let us also denote $N_{\text{recvcoord}}$ and $T_{\text{sim}}$ to be the number of packets are received by the network coordinator and time of simulation, which can be calculated by equation (17). Therefore the goodput of ADES in the network which denoted by $S_{\text{ades}}$, can be calculated by Equation (18).

$$P_{\alpha} = \sum_{k=1}^{R} (P_{\text{coll}})^k$$

$$P_{\text{dropcoord}} = P_{\alpha} + P_{\text{fail1}} + P_{\text{fail2}}$$

$$P_{\text{succeed}} = 1 - P_{\text{dropcoord}}$$

$$N_{\text{recvcoord}} = \frac{\lambda_n \times N \times (1 - P_{\text{dropcoord}}) \times T_{\text{sim}}}{L_{\text{data}}}$$

$$S_{\text{ades}} = \frac{N_{\text{recvcoord}} \times L_{\text{data}}}{T_{\text{sim}}}$$

Let also denote $N_{TQ_1}$ and $N_{TQ_2}$ be number of packets received by coordinator using TQ$_1$ and TQ$_2$, respectively. Let us denote $N_{\text{beacon}}$ and $B_{\text{total}}$ be number of beacons and bandwidth utilization in the networks, which can be obtained by equations (19) and (20), respectively.

$$N_{\text{beacon}} = \frac{T_{\text{sim}}}{SD}$$
\[ BU_{total} = \frac{(NT_d \times TQ_i) + (NT_d \times TQ_2)}{N_{beacon} \times \text{CAP}_{ades}} \] (20)

The energy consumption of device can be shown in Equation (21) and the energy consumption of coordinator node can be shown in Equation (22). Finally, the total energy consumption in networks consist of the energy consumption by devices node and coordinator node can be shown in Equation (23).

\[
\begin{align*}
E_{dev} = & \left( PWR_{idle} \sum_{i=0}^{m_s-1} \sum_{j=0}^{w_s-1} \sum_{k=0}^{b_{i,j,k}} \text{SD}_{\text{Coord}} \times \frac{\text{Time}_{\text{bl}}}{B_{\text{Coord}}} \times N \right) + \\
& \left( 3PWR_{tx} \frac{(\lambda_n)}{\text{CAP}_{\text{ades}}} \times \frac{L_{\text{exec}}}{R_b} \sum_{i=0}^{m_s-1} \sum_{k=0}^{b_{i,j,k}} \left( b_{i,j,k} + b_{i-1,j,k} + b_{i-2,j,k} \right) \times T_{\text{sim}} \times \text{D}_{\text{node}} \times N \right) + \\
& \left( PWR_{tx} \frac{(\lambda_n)}{\text{CAP}_{\text{ades}}} \times \frac{L_{\text{delay}}}{R_b} \times P_{\text{succoord}} \times T_{\text{sim}} \times \text{D}_{\text{node}} \times N \right) + \\
& \left( PWR_{tx} \frac{L_{\text{beacon}}}{R_b} \times T_{\text{sim}} \times N \right) + \\
& \left( PWR_{tx} \frac{(\lambda_n)}{\text{CAP}_{\text{ades}}} \times \frac{L_{ack}}{R_b} \times P_{\text{succoord}} \times T_{\text{sim}} \times N \right) + \\
& \left( PWR_{tx} \times Y \times \frac{\text{SD}_{\text{Coord}}}{B_{\text{Coord}}} \times T_{\text{sim}} \times N \right) \\
\end{align*}
\] (21)

\[
\begin{align*}
E_{\text{Coord}} = & \left( PWR_{idle} \times P[\text{IDLE}] \times \text{SD}_{\text{Coord}} \times \frac{T_{\text{sim}}}{B_{\text{Coord}}} \text{D}_{\text{node}} \right) + \\
& \left( PWR_{tx} \times \frac{L_{\text{beacon}}}{R_b} \times T_{\text{sim}} \times \text{D}_{\text{node}} \right) + \\
& \left( PWR_{tx} \frac{(\lambda_n)}{\text{CAP}} \times \frac{L_{\text{data}}}{R_b} \times P_{\text{succoord}} \times T_{\text{sim}} \times N \right) + \\
& \left( PWR_{tx} \frac{(\lambda_n)}{\text{CAP}} \times \frac{L_{ack}}{R_b} \times P_{\text{succoord}} \times T_{\text{sim}} \times \text{D}_{\text{node}} \times N \right) \\
\end{align*}
\] (22)

\[
E_{total} = E_{dev} + E_{\text{Coord}} \] (23)

3. Results and Analysis

In this section, simulation experiments for ADES are performed by using the extended Castalia simulator to validate the analysis and performance evaluation. The performance of ADES is compared with the SUDAS and the IEEE 802.15.4 standard, which include the analytical (ana) and simulation (sim) results. We consider a star topology with one PAN coordinator and 20 device nodes, where D_{node} is equal to 10 meters. To simulate the performance of power consumption, we consider the radio parameters of Chipcon’s CC2420 2.4 GHz for the IEEE 802.15.4 RF transceiver [31], where the transmitting power PWR_{tx}, the receiving power PWR_{rx}, and the idle power PWR_{idle} are 31.32 mW, 35.28 mW, and 712 µW, respectively [30]. The BO and SO settings follow the IEEE 802.15.4 standard and the proposed ADES algorithm, which are fixed to be six. We compute the probability of successful packet transmission, network goodput, bandwidth utilization and total network energy consumption,
where traffic load varies from 0.1 to 1 (full loaded). Table 1 summarizes the simulation parameters.

Table 1. The simulation parameters

| Parameter                  | Value       |
|----------------------------|-------------|
| Physical data rate         | 250 kbps    |
| Packet length (L_{data})   | 720 bits    |
| UBP                        | 80 bits     |
| NumSuperframeSlots         | 16          |
| MacPacketOverhead          | 112 bits    |
| ACK length (L_{ack})       | 88 bits     |
| D_{node}                   | 10 m        |
| PWR_{tx}                   | 31.32 mW    |
| PWR_{rx}                   | 35.28 mW    |
| PWR_{idle}                 | 712 µW      |
| BO=SO                      | 6           |
| BE_{min}                   | 3           |
| BE_{max}                   | 5           |

Figure 6 shows the probability of successful transmission arriving at the PAN coordinator against the traffic load by analytical and simulation. The proposed ADES algorithm has higher probability of successful transmissions than those of other algorithms, because adjustment delay and addition third CCA can effectively avoid collision in the network. The average probability of successful transmission of ADES increases by 0.14% and 2.68% compared to SUDAS and IEEE 802.15.4 standard, respectively.

Figure 6. The probability of successful transmission against traffic load

Figure 7. The network goodput against traffic load
Figure 7 shows the network goodput against traffic load. It is obvious the network goodput of ADES is higher than those of the other algorithms. In the light traffic load (i.e., traffic load is equal to 0.1 to 0.6), the network goodput of ADES is almost the same as those of SUDAS and IEEE standard; however, ADES outperforms to the other algorithms as the traffic load increases (i.e., traffic load is equal to 0.6 to 1). The average goodput of ADES increases by 5.2% and 7.6% compared to SUDAS and IEEE 802.15.4 standard, respectively.

Figure 8 shows the bandwidth utilization (BU) against traffic load. The bandwidth utilization of ADES has better efficiency than those of the other algorithms. The average bandwidth utilization of ADES increases by 1.75% and 5.72% compared to SUDAS and IEEE 802.15.4 standard, respectively. ADES can improve the bandwidth utilization because reduce probability going to next backoff stage, which cause blind of backoff process.

Figure 9 shows the network energy consumption against traffic load. The average energy consumption of ADES reduces by 18.2% and 24.2% compared to SUDAS and IEEE standard, respectively. ADES consumes lesser network energy than those of the other algorithms, because the ADES algorithm can adjust the delay when CCA in busy condition which not only reduce probability collision but also probability entering next backoff stage. Moreover, ADES has greater probability of successful transmission than those of the other algorithms, especially in heavy traffic load, which means that ADES minimizes the energy consumption when retransmitting data packet. The energy consumption is obtained by summing the energy consumption of PAN coordinator and all of device nodes in the network.
4. Conclusion

In this article, ADES is proposed to improve performance IEEE 802.15.4 networks in order to reduce collision and blind of backoff process which need more energy consumption for random backoff. The proposed ADES algorithm can adjust delay effectively for CCA when channel find in busy condition. Adjustment delay and addition third CCA not only reduce probability collision but also reduce probability going to next backoff stage.

This article also included a comprehensive Markov chain analysis of IEEE 802.15.4, especially for star topology, to predict the probability of successful transmission, the network goodput, bandwidth utilization as well as the network energy consumption. The validity of the analytical model is shown by closely matching its predictions of the simulation results. The analytical model and simulation experiment results show that the performance of ADES is better than those of the other algorithms in term of the probability of successful transmission, network goodput, bandwidth utilization as well as energy consumption.

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