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Performance Analysis of IEEE 802.15.4e Time Slotted Channel Hopping for Low-Rate Wireless Networks

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Abstract

The release of IEEE 802.15.4e specification significantly develops IEEE 802.15.4. The most inspiring improvement is the enhancement for medium access control (MAC) sublayer. To study the performance of IEEE 802.15.4e MAC, in this paper we first present an overview of IEEE 802.15.4e and introduce three MAC mechanisms in IEEE 802.15.4e. And the major concern here is the Time Slotted Channel Hopping (TSCH) mode that provides deterministic access and increases network capacity. Then a detailed analytical Markov chain model for TSCH carrier sense multiple access with collision avoidance (CSMA-CA) is presented. Expressions which cover most of the crucial issues in performance analysis such as the packet loss rate, energy consumption, normalized throughput, and average access delay are presented. Finally the performance evaluation for the TSCH mode is given and we make a comprehensive comparison with unslotted CSMA-CA in non-beacon enabled mode of IEEE 802.15.4. It can validate IEEE 802.15.4e network can provide low energy consumption, deterministic access and increase network capacity.

Keyword: IEEE 802.15.4e, TSCH, MAC, Markov chain

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1. Introduction

IEEE 802.15.4 is designed for the low-rate and low-power wireless personal area networks (WPANs) [1]. And the key requirements for Low-Rate Wireless Personal Area Networks (LR-WPANs) are low complexity, low energy consumption, and low cost. Since the first version in 2003, there are lots of applications and analysis based on IEEE 802.15.4. But there are many critical requirements for different applications that can’t be fulfilled using IEEE 802.15.4, such as medical applications, industrial applications and some commercial applications. Considering medical application, references [2][3] introduce the overviews for body area network (BAN) that is a promising technology to provide real-time monitor for human’s body function and the surrounding environment. It can suit the unique features and application requirements for medical applications while not using other protocol and algorithm based on IEEE 802.15.4. Then industrial applications and some commercial applications also have critical requirements such as low latency, low energy consumption, robustness in the harsh industrial RF environment, and deterministic access that are not adequately addressed by IEEE 802.15.4. To allow IEEE 802.15.4 devices to support a wide range of the mission-critical applications, enhancement of the IEEE 802.15.4 medium access control (MAC) specification was started in March 2008.

The first vision of IEEE 802.15.4e [4] was released in February 2012. And there are two categories of MAC enhancements in IEEE 802.15.4e that: general functional improvements and behaviors to support specific applications such as process automation, factory automation. There are already some researches based on IEEE 802.15.4e. But it is still challenging and novel to analyze and research the IEEE 802.15.4e.

In [5], the author introduces three media access control mechanisms of the enhanced MAC specification: Low Latency (LL), Time Slotted Channel Hopping (TSCH), and Distributed Synchronous Multi-Channel Extension (DSME). And this paper gives a calculation method for the basic timeslot length in the superframe structure supported by three media access control mechanisms. References [6][7] give a description for DSME mode which is an improvement to the beacon enabled mode of IEEE 802.15.4. It can resolve beacon conflict and two channel modes to improve the anti-interference ability. In [8], the author gives an account of TSCH mode and focuses on scheduling algorithms for TSCH network. In [9], the IEEE 802.15.4e MAC protocol has been applied to the Machine to Machine (M2M) and works well.

Most of the previous work about IEEE 802.15.4e focused on the description of three media access control mechanisms, and did not have a comprehensive analysis and evaluation to the performance of IEEE 802.15.4e MAC. In this paper, we will consider the IEEE 802.15.4e MAC protocol, with emphasis on the TSCH mode. The Markov chain model for carrier sense multiple access with collision avoidance (CSMA-CA) algorithms of TSCH mode in IEEE 802.15.4e is showed in this paper. And a performance analysis for TSCH MAC in the aspects of the packet loss rate, energy consumption, normalized throughput, and average access delay is presented.

Since the release of IEEE 802.15.4 standard, a lot of researches have been done to evaluate its performance using the Markov chain model. References [10][11][12][13] use the Markov chain models to analyze the slotted CSMA-CA scheme of IEEE 802.15.4 and make a performance evaluation in terms of the reliability, energy consumption, normalized throughput, and average access delay. The Markov chain model for TSCH in this paper will refer to the idea of these references. And the proposed analytical model can be considered to be applied to large scale wireless networks [14][15], because the throughput, delay, and energy computation are the performance metrics of multicast traffic for the wireless network. The tradeoff for different metrics can be discussed using our strategy to obtain the optimal performance for the different wireless networks. And references [16][17][18][19] present a theoretical model and give the performance evaluation for the non-beacon enabled mode of IEEE 802.15.4. In this paper, we will make a comprehensive comparison with unslotted CSMA-CA in non-beacon enabled mode of IEEE 802.15.4, with consulting this theoretical analysis for the non-beacon enabled mode.

The remainder of this paper is organized as follows. Section 2 gives a brief description of IEEE 802.15.4e MAC protocol. Section 3 provides model descriptions and assumptions, details the Markov chain model for CSMA-CA algorithms of TSCH mode in IEEE 802.15.4e, and derives the performance parameters with the Markov chain. Section 4 offers a performance evaluation for this model. The numerical comparison results are given and we have a discussion about the TSCH mode. Section 5 concludes this paper.

2. IEEE 802.15.4e Description

The IEEE 802.15.4e working group was created in 2008 to redesign the IEEE 802.15.4 MAC protocol, toward a low-power multi-hop MAC, better suitable to industrial communication requirements. There are eleven subteams with different improved targets for IEEE 802.15.4e task group (TG). Next we give an introduction for the subteams to support specific applications. Low latency deterministic network (LLDN) group commits itself to support wireless factory automation applications with high determinism and low latency. DSME group is committed to improvement of beacon mode in order to serve the general industrial and commercial applications. TSCH group has the major improvement in non-beacon enabled mode MAC behaviors to better support process automation. It can increase the IEEE 802.15.4 MAC capacity and support deterministic access. The enhanced MAC specification offers three types of medium access control: LL, TSCH, and DSME.

2.1 Low Latency Deterministic Network (LLDN)

LLDN operates in a star topology. LL MAC uses the LLDN superframe based on timeslots. **Fig. 1** shows the superframe for LLDN. One superframe consists of a beacon timeslot, management timeslots if present, and base transmission timeslots of equal length. The base timeslots include uplink timeslots and bidirectional timeslots. Group acknowledgment (GACK) is configured in a superframe in order to promote the retransmission of failed transmission in uplink timeslots. There are two categories of the base timeslot: dedicated timeslot and shared timeslot. The so-called slot owner has access privileges in dedicated timeslots while devices assigned to a shared timeslot use the contention-based access method.

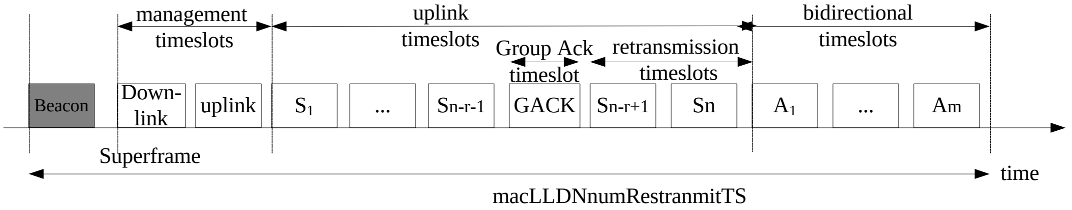


Fig. 1. Usage and order of slots in a LLDN superframe

2.2 Deterministic and Synchronous Multi-channel Extension (DSME)

There are many limitations in advantages about traditional guaranteed time slots (GTSs) of IEEE 802.15.4. Firstly, IEEE 802.15.4 supports GTSs up to 7 which can not support large scale network. Secondly, the GTSs only support the communication between the coordinator and its one hop devices. Finally, GTSs are restricted to use in a single channel. DSME mode can partly solve these problems.

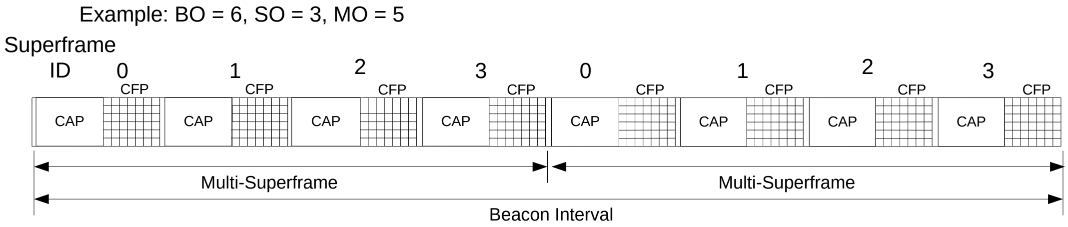


Fig. 2. DSME mutil-superframe structure

DSME employs mutil-superframe defined by a DSME coordinator in **Fig. 2** A multi-superframe is a cycle of repeated superframes. A superframe consists of the beacon, contention access period (CAP), and contention free period (CFP).

DSME MAC supports channel hopping to ensure that a GTS can be used in more channels. In order to save energy, DSME supports CAP reduction. The first superframe in a mutil-superframe has the CAP while other superframes without CAP. For reliability, DSME supports two channel diversity patterns. The channel can be adaptively selected according to some parameters such as the quality of the link. DSME also employs deferred beacon mechanism. If deferred beacon is enabled, the coordinator should perform a clear channel assessment (CCA) to ensure channel free before transmission beacon.

2.3 Timeslotted Channel Hopping (TSCH)

2.3.1. Slotframe structure

In TSCH mode, a slotframe takes the place of the traditional superframe in IEEE 802.15.4. It's an improvement to non-beacon enabled mode and does not need the beacon to initiate communication. The slotframe automatically repeats based on the participating devices' shared notion of time. A timeslot in one slotframe is enough to ensure exchange a frame and an acknowledgment for a set of equipments in **Fig. 3**. The Absolute Slot Number (ASN) is the number of timeslots elapsing from the start of the network or start times defined by the coordinator. ASN increases for every one timeslot and is shared by all devices in the network.

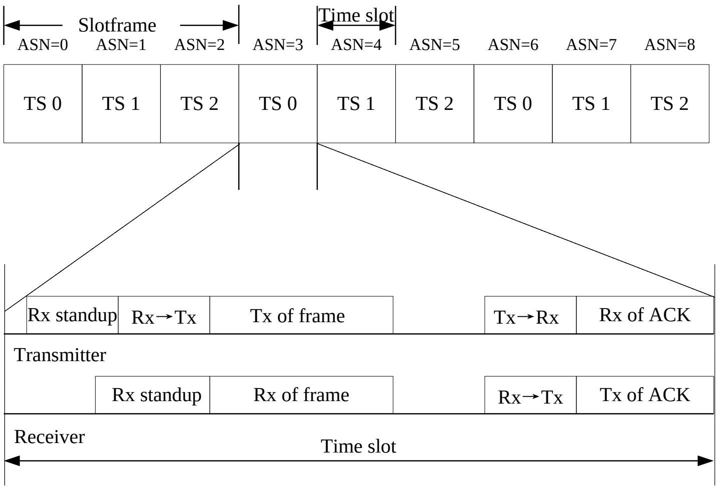


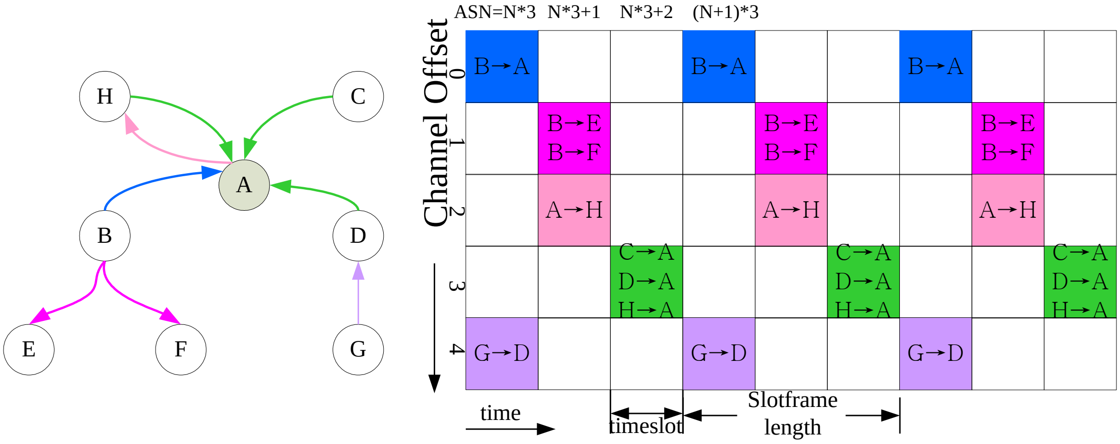
Fig. 3. Example of a three-timeslot slotframe

2.3.2. Channel hopping

TSCH MAC supports channel hopping in timeslots access. Channel hopping adds frequency diversity to mitigate the effects of interference and multipath fading. It can increase network capacity because one timeslot can be used by multiple links at the same time. Then a link in TSCH mode can be represented with timeslot and channel offset. Link = (Timeslot, Channel Offset). Channel in a given link can be got the following:

$$CH = F\left[\left(ASN + channeloffset\right)\%macHoppingSequenceLength\right] \qquad (1)$$

where F is the function of looking up the HoppingSequenceList table which includes the set of available channels in the IEEE 802.15.4e network.



Channel Offset	ASN=N*3	N*3+1	N*3+2	(N+1)*3					
0	B→A			B→A			B→A		
1		B→E B→F			B→E B→F			B→E B→F	
2		A→H			A→H			A→H	
3			C→A D→A H→A			C→A D→A H→A			C→A D→A H→A
4	G→D			G→D			G→D		

Fig. 4. Dedicated links and shared links in one slotframe

Fig. 4 shows an example topology and one example of the slotframe in TSCH mode. Assume that there are three time slots in one slotframe and five channel offsets. Devices in the network are concerned only with network information of its adjacent devices.

There are the dedicated links and shared links in TSCH. The transmission link from device B to device A is a dedicated link. When device B has data to transmit, it can begin transmitting data to device A only until the timeslot 0 and channel offset 0. If the channel quality is good, the transmission on dedicated links is a certain success. If the transmission on the dedicated link is failed, the device B must wait for the next one link to the destination device A.

In TSCH mode, shared link is assigned to more than two devices to transmit data. As shown in **Fig. 4**: timeslot 2 in the N-th cycle of one slotframe and channel offset 3 are assigned to the device C, D, and H for transmitting data to the device A. Because the device does not know whether there are other devices transmitting data to the device A. When one device with data to send reaches its own timeslot, then it will begin transmitting data. If there are more devices simultaneously transmit data to device A on the shared link, a collision will occur. Device A can not receive any data from device and the transmission devices do not receive one acknowledgment (ACK).

Timeslot 1 in one slotframe and channel offset 1 are assigned to the device B to E and F. This is also another kind of shared link. When device B has data to both device E and F, device B can use different time in the same channel offset to transmit data because it know there is a collision.

All the transmissions in TSCH are direct. If a packet needs to go from device G to device A, the packet is first sent to device D, and stored in the buffer area of device D, and then sent form device D to device A. If a single transmission attempt has failed, the device will attempt transmitting the packet and wait for the acknowledgment. The retry time can be up to macMaxFrameRetries.

3. Transmission and acknowledgment in a timeslot

Here is the transmission and acknowledgment process in one timeslot. Shown in **Fig. 5**, the device reaches own timeslot. If CCA is enabled, it waits a certain offset time and executes a CCA to guarantee the channel free. Otherwise device will immediately start to transmit data at the beginning of one timeslot. After the transmission of a packet, device waits an ACK if it is expected. If ACK does not arrive within macTsAckWait μs, device will idle the radio and considers this transmission as failure.

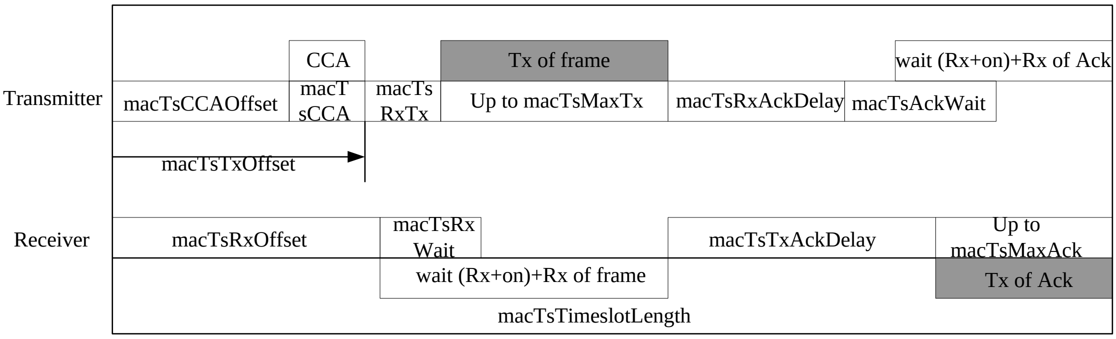


Fig. 5. Timeslot diagram of acknowledged transmission

4. Network information

The IEEE 802.15.4e network supports two types of equipment the same as IEEE 802.15.4 standard: Full-function device (FFD) and Reduced-function device (RFD). A FFD can be a network coordinator. The FFDs that are part of the network can broadcast the frame about the TSCH network information. But the RFD can not be a network coordinator and can only communicate with the network coordinator or FFD.

5. TSCH CSMA-CA Algorithm

TSCH CSMA-CA algorithm, also expressed as Time Slotted Channel Hopping collision avoidance (TSCH-CA), is shown in **Fig. 6** Shared links assigned to more devices may lead to conflict and a transmission failure without receiving the acknowledgment frame. In order to reduce the probability of repeated collisions in the packet retransmission, the shared link should perform retransmission backoff algorithm to decompose the collision.

When a packet is sent in a shared link, an acknowledgment is expected but not received. The transmission device will wake up the TSCH-CA retransmission algorithm. The backoff is applied only on the shared link and the retransmission on a dedicated link does not need to wait. The retransmission backoff is calculated in the number of shared link.

This retransmission backoff algorithm has the following properties:

1) The backoff window increases when there is consecutive failed transmission in a shared link.

2) The backoff window does not change for two cases. One is that a transmission is failed in a dedicated link. In addition, a transmission is successful in a dedicated link and there transmission queue is still not empty.

3) The backoff window is reset to the minimum value if there is a successful transmission in a dedicated link with the transmit queue be then empty or a successful transmission in a shared link.

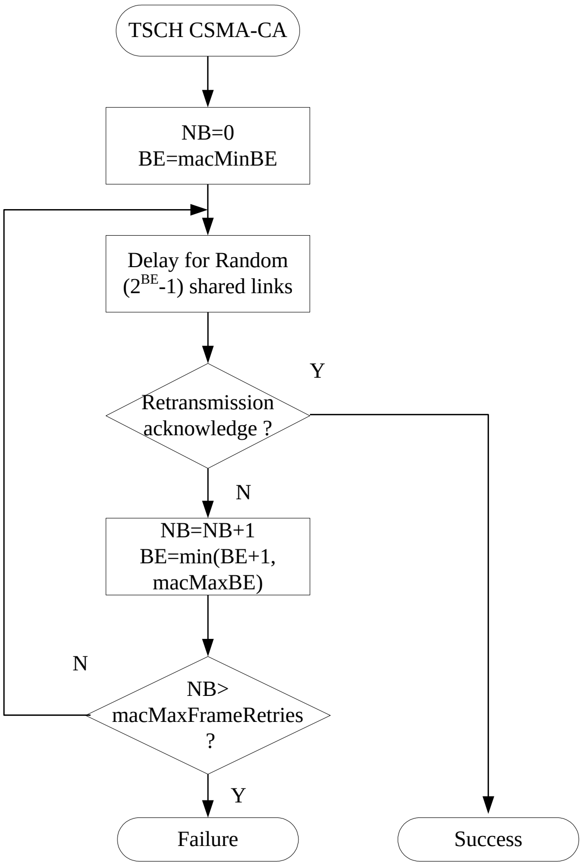


Fig. 6. TSCH CSMA-CA backoff

The device uses an exponential backoff mechanism similar to the traditional CSMA-CA. The device with a transmission failure on shared link initializes the backoff exponent (BE) to macMinBE. When the device is trying a retransmission on a shared link, MAC layer should delay randomly 0 to $2^{BE}-1$ shared links. If the acknowledgment is not still received after macMaxFrameRetries transmissions, the MAC layer will consider that the transmission is failed and inform the higher level of the failure.

However the first two MAC are still based on the superframe structure of IEEE 802.15.4, TSCH, part of IEEE 802.15.4e standard since 2010, is the latest generation of highly reliable and low-power MAC protocol. The concept of the superframe structure for TSCH is replaced by the slotframe. The TSCH-CA algorithm is different from CSMA-CA in IEEE 802.15.4 and special for TSCH; While LLDN uses the slotted CSMA-CA channel access mechanism, the same to IEEE 802.15.4, for management timeslots and shared group timeslot. The frames transmitted in the CAP for DSME MAC shall use a slotted CSMA-CA mechanism to access the channel. The acknowledgment mechanisms for LLDN, DSME, and TSCH are different. Here we have an emphasis of the introduction and only analyze TSCH MAC in this paper.

3. Theoretical Analysis

In TSCH mode, we have a hypothesis that the wireless channel is ideal and there is no capture effect so that the transmission in the dedicated link must be successful. The channel utilization is 100% and the data transmission delay is a successful transmission delay. More devices simultaneously transmitting data in shared access mode will collide, and then we should use the TSCH-CA algorithm. Next we will analyze the transmission in the shared links in TSCH mode.

3.1 Analytical Model

In this subsection, we propose an analytical model of the TSCH-CA mechanism of IEEE 802.15.4e. It should be noticed as follows. There are n devices sharing a link. When n devices have data to transmit to one device, they must wait until their own timeslot to transmit and there may be a collision. The device can transmit not only retransmission data but also new data in the shared link. The retransmission of one device on the shared link may have a collision with a retransmission or new transmission of other devices. So we treat equally the new packets and retransmission packets using the TSCH-CA algorithm in order to better analyze.

It's worth noting that the backoff is calculated in shared links for TSCH-CA, so the aUnitBackoffPeriod of traditional CSMA-CA is not used. When the backoff counter is decremented to 0, the device immediately starts the transmission.

Here we adopt the worldwide spectrum 2.45 GHz radio and the channel rate is 250 Kbps. All devices contend to send data to one device, which is the data sink. **Fig. 7** shows the Markov chain model of TSCH-CA for a single device and we will study its behaviors. **Table 1** lists some parameters used in the Markov chain model.

Table 1. Parameters used in Markov chain model

$b_{i,j}$	The state in Markov chain model
m	The maximum retry limits, macMaxFrameRetries
σ	Length of timeslot (ms)
α	The probability that a transmitted packet encounters a collision
p_t	The probability of channel busy
τ	The probability of a device starts to transmit
p_{cr}	The probability of discarding a packet
q_1	The probability that there is no packet to be sent after one transmission
q_2	The probability that there are no packets to be sent after one idle period

S	The normalized throughput

We define s(t)and c(t) as the stochastic processes representing the backoff stage and the backoff counter at time t, The backoff window is:

$$W_i = 2^{macMinBE} 2^{\min\{macMaxBE-macMinBE,i\}} \ , \quad i \in (0,m) \tag{2}$$

where macMinBE is the minimum value of the backoff exponent, macMaxBE is the maximum value of the backoff exponent and the value m is macMaxFrameRetries.

The states from (i, W_m-1) to (i, W_0-1) represent the backoff stage. The states from (0, -1) to (m, -1) represent transmission stage. The state (-1, 0) represents idle state when the packet queue is empty. Let α be the probability that a transmitted packet encounters a collision. The state transition probabilities of the Markov chain is shown in **Fig. 7** as follows.

1) The backoff counter decreases one unit with probability 1 in every L timeslots of one slotframe

$$p\{i,k / i,k+1\} = 1 \ , \ i \in (0,m) \ , \ k \in (0,W_i - 2) \tag{3}$$

2) When the backoff counter reaches zero, the probability of starting transmitting a packet is

$$p\{i,-1 / i,0\} = 1 \ , \ i \in (0,m) \tag{4}$$

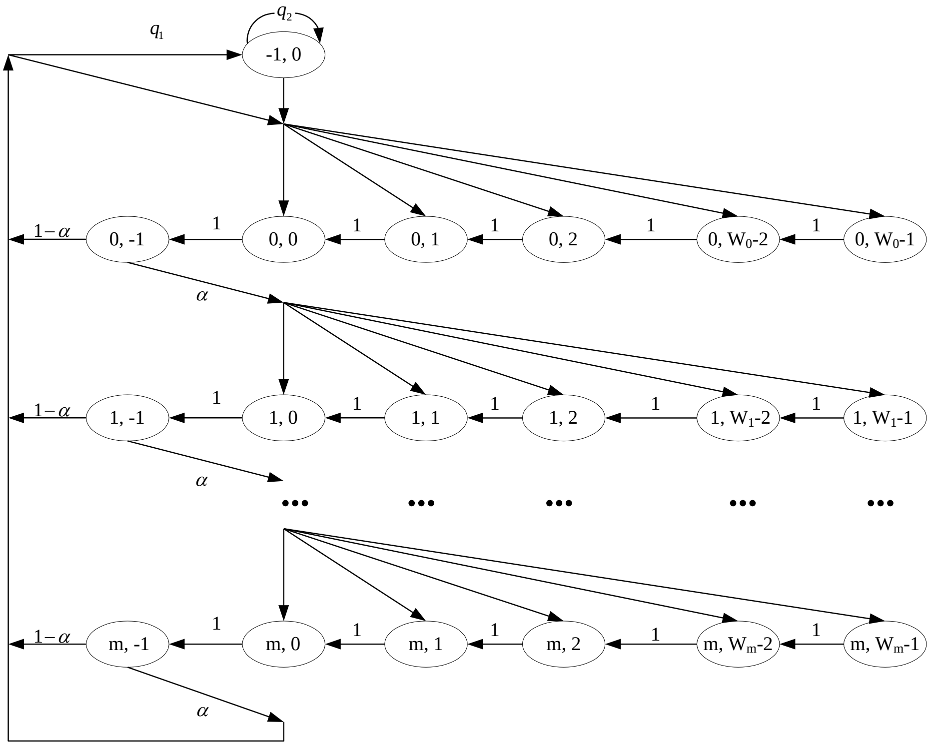


Fig. 7. Markov chain model for TSCH CSMA-CA backoff

3) When the backoff counter reaches zero and the device starts transmitting a packet, but the transmitted packet encounters a collision. The backoff stage increases and the new initial backoff value is chosen as

$$p\{i,k / i\text{-}1,\text{-}1\} = \alpha / W_i \, , \ \ i \in (0,m), \ \ k \in (0,W_i - 1) \tag{5}$$

4) After a transmission, if there are more packets to be sent, the new backoff stage is

initiated and the backoff value is chosen; otherwise, the idle state will be reached

$$p\{0,k/i,\text{-}1\}=1\text{-}q_1/W_0\ ,\ \ i\in(0,m)\ ,\ \ k\in(0,W_0-1) \tag{6}$$

$$p\{-1,0/i,\text{-}1\}=q_1,\ \ i\in(0,m) \tag{7}$$

5) The transition probabilities from the idle state to the transmission state is

$$p\{0,k/-1,0\}=(1-q_2)/W_0,\ \ k\in(0,W_i-1) \tag{8}$$

Let $b_{i,k}=lim_{t\to\infty}\ p\{s(t)=i,c(t)=k\}\ \ (i\in(0,m),k\in(0,W_i-1))$ be the stationary distribution of the Markov chain. Next we show that it is easy to obtain a closed-form solution for this Markov chain.

Firstly, note that for $i\le m$

$$b_{i,-1}=b_{i,0}\ ,\ b_{i,0}=\alpha\times b_{i-1,0} \tag{9}$$

Then $b_{i,0}$ and $b_{i,\text{-}1}$ can be presented as

$$b_{i,0}=\alpha^i b_{0,0},\ \ b_{i,-1}=\alpha^i b_{0,0} \tag{10}$$

Owing to the chain regularities, we can obtain that

$$b_{i,k}=\frac{W_i-k}{W_i}\mathrm{b}_{i,0}\qquad i\in(0,m),k\in(0,W_i-1) \tag{11}$$

$$b_{-1,0}=\frac{q_1}{1-q_2}b_{0,0} \tag{12}$$

Based on the results above and the normalization condition, we can know that

$$b_{-1,0}+\sum_{i=0}^{m}b_{i,-1}+\sum_{i=0}^{m}\sum_{k=0}^{W_i-1}b_{i,k}=1 \tag{13}$$

Next we can derive the expression for each state from Eqs. (10), (11), (12), (13).

When $m\le macMaxBE-macMinBE$, $W_i=2^{macMinBE+i}$. From Eq. (13), we can obtain the formula for $b_{0,0}$

$$\begin{gathered}b_{0,0}=\frac{2(1-\alpha)(1-2\alpha)(1-q_2)}{2^{macMinBE}\left[1-(2\alpha)^{m+1}\right](1-q_2)(1-\alpha)+P_1}\\ P_1=2(1-2\alpha)(1-\alpha)q_1+3\left(1-\alpha^{m+1}\right)(1-2\alpha)(1-q_2)\end{gathered} \tag{14}$$

When $m>macMaxBE-macMinBE$,

$W_i=\begin{cases}2^{macMinBE+i} & i\in(0,macMaxBE-macMinBE)\\ 2^{macMaxBE} & i\in(macMaxBE-macMinBE+1,m)\end{cases}$. The formula for $b_{0,0}$ is

$$\begin{gathered}b_{0,0}=\frac{2(1-\alpha)(1-2\alpha)(1-q_2)}{2^{macMinBE}\left[1-(2\alpha)^{macMaxBE-macMinBE+1}\right](1-q_2)(1-\alpha)+P_2}\\ P_2=(1-2\alpha)2(1-\alpha)q_1+3\left(1-\alpha^{m+1}\right)(1-2\alpha)(1-q_2)\\ +(1\text{-}2\alpha)2^{macMaxBE}\left(\alpha^{macMaxBE-macMinBE+1}-\alpha^{m+1}\right)\end{gathered} \tag{15}$$

Other states can expressed by the $b_{0,0}$. Let $q_1=q_2=0$, we can obtain the results of each state's expression in the saturation condition.

3.2 Performance Parameters Analysis

In this subsection, we will derive the expressions of the packet loss rate, normalized throughput, delay and energy consumption offered by IEEE 802.15.4e by the Markov chain. Devices begin transmitting a packet after the backoff counter reaches zero. The probability of a device starts to transmit is

$$\tau = \sum_{i=0}^{m} b_{i,0} = \sum_{i=0}^{m} \alpha^i b_{0,0} = \frac{1-\alpha^{m+1}}{1-\alpha} b_{0,0} \tag{16}$$

The probability α that a transmitted packet encounters a collision is that at least one of the $n-1$ remaining devices transmits in the same timeslot. In the steady state, each remaining device transmits a packet with probability τ .

$$\alpha = 1-\left(1-\tau\right)^{n-1} \tag{17}$$

A. Packet Loss Rate

In TSCH-CA, packets are discarded due to up to maximum retry limits. A packet is discarded if the transmission fails due to repeated collisions after $m+1$ attempts. The probability of discarding a packet is

$$P_{cr} = \alpha^{m+1} \tag{18}$$

B. Energy Consumption

We know that devices don't listen to the channel in the backoff stage. The average energy consumption of one device is given as follow

$$E_{avg} = P_X \sum_{i=0}^{m} b_{i,-1} + P_R \sum_{i=0}^{m} b_{i,-1} \times \left(1-\alpha\right) + P_i \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} + P_i \sum_{i=0}^{m} b_{i,-1} \times \alpha \tag{19}$$

where P_X , P_R and P_i are the average energy consumption for transmitting data, receiving data, and the idle state during the backoff stages and the timeout of ACK, respectively.

The first and second terms consider the energy consumption of transmitting and receiving state. And the third and forth terms think over the energy consumption during the backoff and idle states.

The average energy consumption for successfully sending one bit per device is:

$$\begin{aligned} E &= \frac{E_{avg}}{250Kpbs \times \tau\left(1-\tau\right)^{n-1}} \\ &= \frac{P_X \sum_{i=0}^{m} b_{i,-1} + P_i \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} + P_R \sum_{i=0}^{m} b_{i,-1} \times \left(1-\alpha\right) + P_i \sum_{i=0}^{m} b_{i,-1} \times \alpha}{250Kpbs \times \tau\left(1-\tau\right)^{n-1}} \end{aligned} \tag{20}$$

C. Normalized Throughput

Let P_t be the probability that the channel is busy. In other word, there is at least one transmission in the considered timeslot. Since there are n devices on the channel, and each device transmits packets with probability τ . The probability P_{ts} is the successful data transmission probability conditioned on the fact that the channel is busy. P_t and P_{ts} are as follow

$$P_t = 1-\left(1-\tau\right)^n,\ P_{ts} = \frac{n\tau\left(1-\tau\right)^{n-1}}{1-\left(1-\tau\right)^n} \tag{21}$$

The normalized throughput is defined as the time for successful transmission of data with the ratio of the channel time. The channel time includes channel free time and channel busy time.

$$S = \frac{P_t P_{ts} t_p}{\gamma} = \frac{P_t P_{ts} t_p}{\left(1-P_t\right)\sigma + P_t P_{ts} t_s + P_t\left(1-P_{ts}\right)t_c} \tag{22}$$

where t_p is the time duration for the payload of the packet; t_s is the time for the successful transmission of one packets and the received of an ACK, $t_s = t_h + t_p + t_{ack} + T_{ack}$; and t_c is the time for a transmission failure of one packet, $t_c = t_h + t_p + t_{ack-to}$. t_h is the time duration that includes PHY header and MAC header; t_{ack} , t_{ack-to} , T_{ack} are time duration for waiting for an ACK, the timeout for waiting an ACK, and transmitting an ACK, respectively.

D. Average Access Delay

Here we will focus on the average access delay to evaluate the performance of TSCH-CA. The average access delay of a successfully sending one packet is the time interval from a packet into the MAC queue ready for transmission, until to the successful reception of the ACK. The delay of discarded packet after a maximum number of retries isn't contained into the average delay.

Let D_i be that the device has a successful transmission of a data packet at the i-th time. The probability of successful transmission of a data packet is $1-\alpha$. Let A_i be the event that the device has a successful transmission at the $i+1$ time after the failure of the previous i transmission. A_m denotes the successful packet transmission within m transmission. The probability of the event A_i is normalized by the probability of the event A_m .

$$Pr\left(A_i / A_m\right) = \frac{\alpha^i}{\sum_{k=0}^{m}\alpha^k} = \frac{\left(1-\alpha\right)\alpha^i}{1-\alpha^{m+1}} \tag{23}$$

So the total average access delay is

$$E\left(D\right) = \sum_{i=0}^{m} Pr\left(A_i / A_m\right) E\left(D_i\right) \tag{24}$$

where $E\left(D_i\right) = t_s + i \times t_c + \sum_{h=0}^{i} E\left(t_h\right)$, $E\left(t_h\right)$ is the average backoff delay.

Now we should calculate the average backoff delay. The device should restart the backoff counter after an unsuccessful transmission until the maximum number of retries. The average backoff delay

$$E\left(t_h\right) = \sum_{k=0}^{W_h-1} \frac{1}{W_h} \times k \times L \times \sigma \tag{25}$$

From Eqs. (22), (23), (24), we can rewrite the average access delay as

$$E(D)=\sum_{i=0}^{m}\frac{(1-\alpha)\alpha^{i}}{1-\alpha^{r+1}}\left[t_s+i\times t_c+\sum_{h=0}^{i}\left(\frac{W_h-1}{2}L\sigma\right)\right] \tag{26}$$

4. Numerical Results

4.1 Protocol Parameters

As is shown above, more devices can share a link to the same one device in IEEE 802.15.4e. This particular device can be a FFD. The links to destination are assigned by the higher layer when the device joins in the network. When the devices have packets to send and reach their own timeslots, they will begin transmitting packets. We know that it’s an improvement to non-beacon enabled mode in IEEE 802.15.4 that devices can support the TSCH mode in IEEE 802.15.4e.

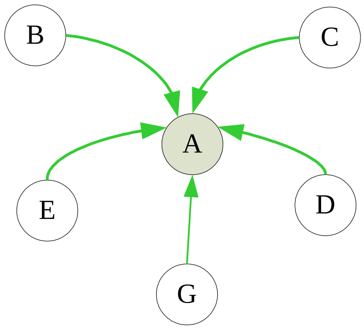


Fig. 8. Star topology structure

Next we will make a comparative analysis between unslotted CSMA-CA algorithm in non-beacon enabled mode and TSCH-CA algorithm for shared links in TSCH mode. The topology is a star that more devices have data sent to a device in non-beacon enabled mode. It is similar to that more devices share a channel in the same timeslot in IEEE 802.15.4e. **Fig. 8** shows the star topology of non-beacon enabled mode in IEEE 802.15.4. When there are data to send to the coordinator, the devices use contention-access (unslotted CSMA-CA access mechanism) to get the channel. If one device successfully obtains the channel, it will begin transmitting data to destination device. If there is a successful transmission of the packet, the device will end the usage of the channel. Otherwise device should transmit its data once again, using unslotted CSMA-CA, to the coordinator. **Table 2** lists some parameters for the comparative analysis between TSCH-CA and unslotted CSMA-CA.

Remarks: It is specified in IEEE 802.15.4 that the Frame Length field in a PHY header (PHR) is 7 bits and specifies the total number of bytes in the PHY service data unit (PSDU) (i.e., PHY payload), up to aMaxPHYPacketSize. The constant for aMaxPHYPacketSize that defines the characteristics of the PHY is 127. These constant is hardware dependent and cannot be changed during operation. And IEEE 802.15.4e is only a MAC protocol change, which does not require any change to the hardware and PHY. The aMaxMACPayloadSize, which is the maximum number of bytes that can be transmitted in the MAC Payload, equals aMaxPHYPacketSize minus aMinMPDUOverhead. The aMinMPDUOverhead is the minimum number of bytes added by the MAC sublayer to the PSDU and has a constant of 9. So the maximum number of bytes that can be transmitted in the MAC Payload, i.e. maximum data payload, is 118 bytes for IEEE 802.15.4 and IEEE 802.15.4e. In the following numerical analysis, the different data payload is considered for the normalized throughput and average access delay and the maximum payload is 118 bytes. In the following numerical analysis, the different data payload is considered for the normalized throughput and average access delay and the maximum payload is 118 bytes.

Table 2. The analytical parameters

Parameter		Value
Channel Rate		250 kbps
P_X		36.5 mw
P_R		41.4 mw
P_i		0.042 mw
MAC Header		9 B
PHY Header		6 B
PHY symbol per byte		2
macMaxFrameRetries		3
IEEE 802.15.4	ACK	11 B
	LIFS Period	40 symbols
	ACK timeout	54 symbols
	aUnitBackoffPeriod	20 symbols
	macMinBE	0~3, default 3
	macMaxBE	5
	macMaxCSMABackoffs	0~5, default 4
IEEE 802.15.4e (TSCH)	ACK Period	2.4 ms
	ACK timeout	0.4 ms
	macMinBE	0~ macMaxBE, default 1
	macMaxBE	3~8, default 7

4.2 Numerical Results and Analysis

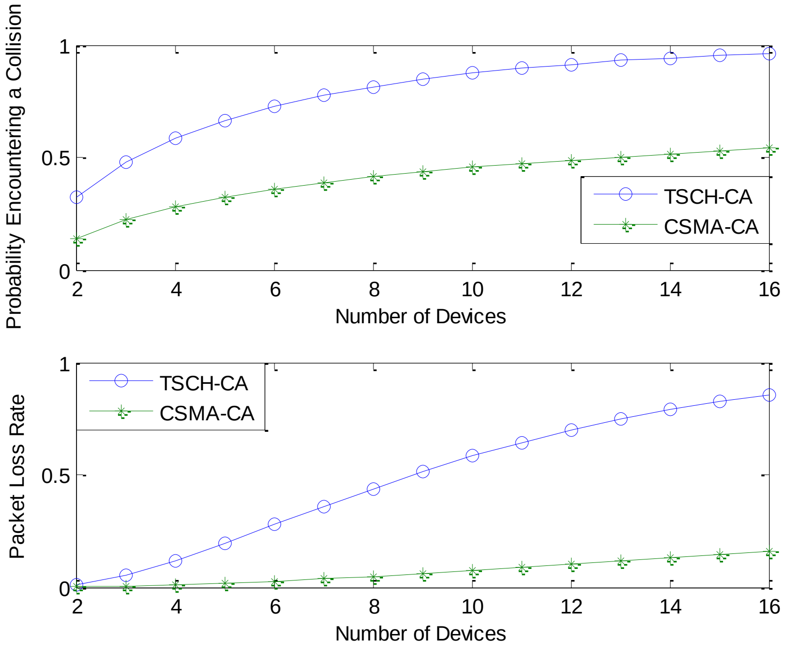


Fig. 9. The probability encountering a collision and packet loss rate versus number of devices

Fig. 9 illustrates the probability that a transmitted packet encounters a collision and the packet loss rate of TSCH-CA and unslotted CSMA-CA versus the number of devices, N_d. There is a sharp deterioration of packet loss rate with increasing the number of devices in TSCH mode. The reasons is that the choice of the number of the shared link in TSCH-CA is (0,1), (0,3), (0,7), ..., while the random backoff number of slots of unslotted CSMA-CA is (0,7), (0,15), (0,31), (0,31), ... And we assume there are three timeslots in one slotframe. With the same choice space and the increasing of the devices, the probability that devices choose the same backoff number increases in TSCH mode. Devices trend to choose the same backoff number and the probability with a collision on the same busy channel becomes large. As shown in **Fig. 9** The collision probability for TSCH-CA is approximately as 2 times as unslotted CSMA-CA.

Device needs to attempt more times to send the packet with the increasing collision probability, and the probability that packets are discarded due to up to maximum retry limits will increase. As shown in **Fig. 9** When N_d = 3, the collision probability and packet loss rate for TSCH-CA are 48.1% and 5.3% while 22.3% and 0.32% for unslotted CSMA-CA. When N_d = 5, the collision probability and packet loss rate for TSCH-CA are 66.5% and 19.4% while 32.3% and 1.6% for unslotted CSMA-CA. The packet loss rate for TSCH-CA is poor with more devices, for example 69.8% when N_d =12.

As we know, the packet loss rate is thought as one of the measures of the network dependability. If we consider the maximum allowable packet loss rate as 10%, we can know there are not too many devices to share a link in TSCH mode, for example, 3 or 4 devices. It can ensure that the packet loss rate is small to guarantee the reliability of a packet.

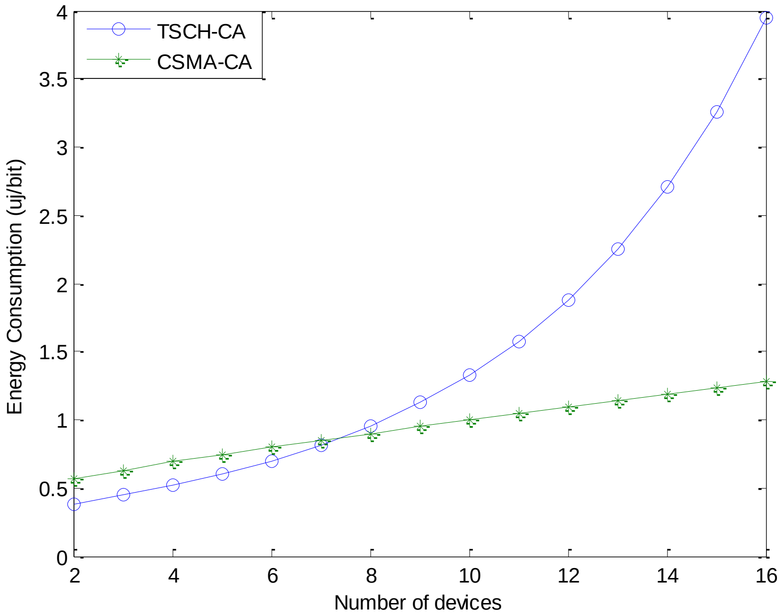


Fig. 10. Energy consumption of successfully sending one bit per device

Fig. 10 shows the energy consumption of successfully transmitting one bit per device in the saturation condition. Firstly, it is observed from two curves that as the number of devices increases, a successful transmission of one bit per device requires more energy. It is due to increasing collision probability and retry times. Secondly, It can be seen that the energy consumption for a single device in TSCH mode is relatively small as N_d <7. For instance, the energy consumption of TSCH-CA are 0.449 $\mu j/bit$, 0.520 $\mu j/bit$, and 0.603 $\mu j/bit$ while 0.630 $\mu j/bit$, 0.690 $\mu j/bit$, and 0.746 $\mu j/bit$ for unslotted CSMA-CA when N_d = 3, 4, and 5. Finally, the energy consumption of a single device in TSCH mode has a rapid trend to increase compared with unslotted CSMA-CA. For example, the energy consumption for TSCH-CA are 0.955 $\mu j/bit$, 1.327 $\mu j/bit$ and 1.879 $\mu j/bit$ while 0.900 $\mu j/bit$, 0.997 $\mu j/bit$ and 1.090 $\mu j/bit$ for unslotted CSMA-CA when N_d =8, 10 and 12, separately. It is due to the fact that as the number of devices increases, the larger collision probability deteriorates the transmission process and results in the increase of energy consumption.

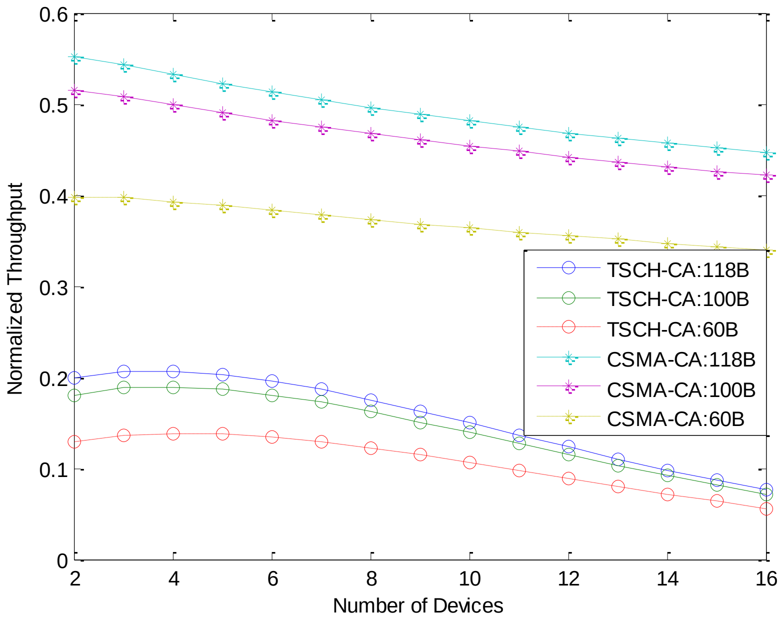


Fig. 11. Normalized throughput versus number of devices

Fig. 11 shows the normalized throughput versus the number of devices and different payload sizes. As a whole, the normalized throughput in TSCH mode is a marked decrease over the unslotted CSMA-CA. In **Fig. 11**, the normalized throughput for TSCH-CA and unslotted CSMA-CA is 0.206 and 0.543, separately, when N_d = 3 and the payload is 118 bytes. The reason is that TSCH-CA backoff is calculated in the number of shared link while unslotted CSMA-CA is the aUnitBackoffPeriod. The backoff unit in TSCH-CA is a timeslot of the slotframe. The backoff unit in unslotted CSMA-CA is constant and is far less than that in TSCH mode. If the device does not access this channel at own timeslot in a slotframe, i.e. the backoff counter does not reach zero at the own timeslot, there is long channel vacancy duration and the channel cannot be made full use of. And as the payload of a packet decreases, the normalized throughput decreases.

Locally, it can be seen that the normalized throughput for TSCH-CA increases till the maximum value and then falls down with the number of devices in a shared link. The maximum throughput value is 0.207, 0.189 and 0.138 when N_d =4 and the payload is equal to

118 bytes, 100 bytes, and 60 bytes, respectively. As the number of devices increases, the larger collision probability deteriorates the transmission process and the channel cannot be made full use for a successful transmission. The normalized throughput with a larger number of devices has a clear deterioration as shown in the **Fig. 11**.

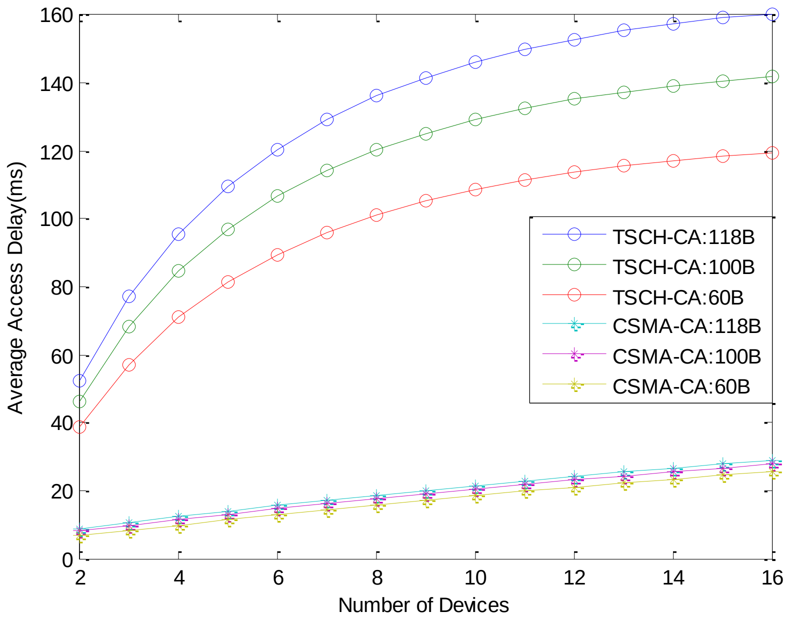


Fig. 12. Average delay for successfully transmitting a packet

Fig. 12 shows the average access delay for successfully transmitting one packet in the saturation condition. It can be seen that the average access delay of TSCH-CA algorithm is far greater than the unslotted CSMA-CA and that the average access delay for TSCH-CA is deteriorated. Some factors, such as the higher busy channel probability, higher collision probability with the increasing devices, and different backoff units, have an influence on the average access delay. The higher collision probability deteriorates the transmission process and results in many transmissions for one packet with greater delay. For example, when N_d =4, the collision probability for TSCH-CA and unslotted CSMA-CA is 0.481 and 0.223 from **Fig. 9**. The backoff unit is 10 ms and 0.32 ms with the maximum payload 118 bytes, separately. The average access delay is 95 ms and 12 ms, separately.

From the analysis for the **Figs. 9-12** above, we can obtain that low energy consumption and relative reliability can be guaranteed with less number of devices sharing a link. It can be seen from these figures that the performance becomes very bad with more devices and that the packet loss rate, normalized throughput and energy consumption are sharp variation. So we can know there are not too many devices to share a link in TSCH mode, for example, 4 or 5 devices. But a larger TSCH network can be supported. The capacity of the TSCH network depends on the factors: the number of available channel, the number of timeslots in a slotframe, and the proportion of dedicated links to all links. There are 16 available channels at 2.45 GHz in IEEE 802.15.4e network. A TSCH network can contain 29+17*4=97 devices in a network; in the condition of N_d =4 with relatively good performance and that the proportion of dedicated links to all links is 60%. A TSCH network can contain 24+24*4=120 devices in a network; in the condition of N_d =4 and that the proportion of dedicated links to all links is 50%. If there are 5 timeslots in a slotframe, a TSCH network can contain 48+32*4=176 devices to increase the capacity of the network, in the condition of N_d =4 that the proportion of dedicated links to all links is 50%. The TSCH network can contain more devices with more timeslots in a slotframe and the appropriate proportion of dedicated links to all links according to the real applications.

4.3 Discussion

From the above analysis, there is a good performance with less devices and the performance deteriorates with a large number of devices. And the performance for the transmission in a shared link is going bad with a comparison to CSMA-CA in IEEE 802.15.4. We have a hypothesis that the wireless channel is ideal and there is no capture effect so that the transmission in the dedicated link must be successful. The channel utilization is 100% and the data transmission delay is a successful transmission delay.

There are shared links and dedicated links in the TSCH mode. Then we have known the properties of the shared links and dedicated links. Timeslot communication links in TSCH can increase potential throughput by minimizing unwanted collisions that can lead to catastrophic failure. So we can use the dedicated links to deducing the unwanted collision and the shared links to access the channel adaptively. Considering the relative poor performance of the transmission in a shared link and the boundedness of the dedicated links number, in order to guarantee a certain network capacity and performance in the practical applications of TSCH mode, the proportion of the dedicated links to shared links can be obtained by analyzing the real applications, such as 60%, 50% etc, and the number of a slotframe can be decided by considering the real applications in the future.

5. Conclusions

In this paper, firstly we described three MAC access mechanisms of IEEE 802.15.4e and focused on the TSCH mode. We introduced the slotframe structure, channel hopping, transmission and acknowledgment in one timeslot, and the CSMA-CA algorithm for TSCH mode. Then we presented an analytical model for evaluating the performance of TSCH-CA mechanism. The analytical model was based on a Markov chain that considered the retry limits, the transmission and acknowledgment mechanism in one timeslot, under the saturation condition. Then we derived the expressions of the packet loss rate, normalized throughput, energy consumption, and average access delay. Finally we made a performance evaluation to TSCH-CA algorithm for shared links and a comprehensive comparison with the unslotted CSMA-CA in IEEE 802.15.4.

We can know that the cyclicity of one slotframe in TSCH mode ensure the automation process. It can increase network capacity because one timeslot can be used by multiple links at the same time and there are more devices sharing a link. The transmission in dedicated links can ensure deterministic access while the transmission in the shared link can guarantee low energy consumption and relative reliability, with less number of nodes sharing a link.

Here we only offer a theoretical analysis to the TSCH mode and will make a comparison with the simulation results. In the future, a schedule for the distribution between dedicated links and shared links will be proposed.

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