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An Enhanced Analytical Model and Performance Evaluation of the IEEE 802.15.4e TSCH CA

Celia Ouanteur[1] · Louiza Bouallouche-Medjkoune[1] ·
Djamil Aïssani[1]

Abstract The Time Slotted Channel Hopping (TSCH) mechanism is created in the IEEE 802.15.4e amendment, to meet the need of Industrial Wireless Sensor Networks. It combines time slotted access and channel hopping with deterministic behavior. The mechanism offers two types of links: dedicated links and shared links. In order to reduce the probability of repeated collisions in shared links, the mechanism implemented a retransmission backoff algorithm, named TSCH Collision Avoidance (TSCH CA). In this article, we develop a two dimensional Markov chain model for the IEEE 802.15.4e TSCH CA mechanism, we take into account the deterministic behavior of this mechanism. In order to evaluate its performances, we estimate the stationary distribution of this chain. Then, we derive theoretical expressions of: collision probability, data packet loss rate, reliability, energy consumption, throughput, delay and jitter. Then, we analyze the impact of the number of devices sharing the link for a fixed network size under different traffic conditions. Finally, the accuracy of our theoretical analysis is validated by Monte Carlo simulation. It is shown that the performances of the IEEE 802.15.4e TSCH parameters are strongly related to the number of devices sharing the link.

Keywords IWSNs · IEEE 802.15.4e TSCH CA · Modeling · Markov chains · Performances evaluation

1 Introduction

Wireless Sensor Networks (WSNs) were used for the first time by soldiers, in the military domain, to detect intrusions and tracking threats [1]. Since, they were widely extended to other applications, such as: medical [2, 3], and environment applications [4]. Nowadays, by

✉ Celia Ouanteur
  ouanteur.celia@gmail.com

1 Research Unit LaMOS (Modeling and Optimization of Systems) Faculty of Exact Sciences, University of Bejaia, 06000 Bejaïa, Algeria

the development of the sensor devices and the arrival of actuators, WSNs increasingly attract the industrial communities [5, 6]. They are used in factory automation and process control [7, 8].

In order to support the Wireless Local Area Networks (WLAN) requirements, the standardization efforts have led to the development of several technologies, namely: IEEE 802.15.1 [9] (Bluetooth), IEEE 802.11 [12] (WiFi), wireless Hart [10], ISA100a [11] and IEEE 802.15.4 [13] (ZigBee).

Although the IEEE 802.15.4 standard is the most used technology for WLANs, the use of this latter for industrial applications became limited [14]. Since 2012, the need to overcome these limitations has given birth to the new IEEE 802.15.4e standard [15].

The IEEE 802.15.4e standard defines Medium Access Control (MAC) enhancements to better support the critical industrial requirements. It introduces new mechanisms, such as: Low Latency Deterministic Networks (LLDN), Distributed Synchronous Multi-Channel Extension (DSME) and Time Slotted Multi-Channel Extension (TSCH). In order to create the IEEE 802.15.4e TSCH amendment, the IEEE standardization has integrated the existing concept of Time Synchronized Mesh Protocol (TSMP) [16] ratified wireless Hart in the IEEE 802.15.4e amendment. This TSCH amendment combines time slotted access and channel hopping [15], or in other words, it combines the Time Division Multiple Access (TDMA) with Frequency Division Multiple Access (FDMA) [17]. The TDMA scheme [18] appears by dividing the time into slot frames repeating over the time. Whereas, the FDMA scheme [19] appears by the possibility for many couples of devices to exchange their data packets in the same timeslot, using different channel offsets. In addition, in a given timeslot, the TSCH mechanism offers two types of links : dedicated links and shared links. More than one device can be assigned to a link (shared group link). In this case, collisions may occur and result transmission failure detected by no receiving an acknowledgment. To reduce the probability of repeated collisions, the IEEE 802.15.4e standard [15] implemented a retransmission backoff algorithm, named TSCH Collision Avoidance (TSCH CA). The TSCH has a deterministic behavior, i.e., all the actions that will occur at each timeslot are well known, even when the actions are assigned to have occurred in a shared link. This means that the number of devices sharing the link is well known. So, intuitively, it is not the whole number of devices in network that are assigned to transmit in a given shared link, but a restricted number of devices.

Since the apparition of the new IEEE 802.15.4e amendment, various researches have been conducted. Some authors were interested to present the MAC mechanisms of the standard [20]. Other, to enhance the proposed mechanisms [21–28], or to define secure protocols [17]. The rest of the authors were interested to the performance evaluation of the IEEE 802.15.4e standard [29–34]. The performance analysis is based either by mathematical modeling or by simulation. When it is based on mathematical modeling, the Markov chain models are often used, it is inspired from the existing works on IEEE 802.11 [35–41] and IEEE 802.15.4 for both slotted CSMA/CA [42–54] and unslotted CSMA/CA [55, 56]. In [33], authors analyzed the transmission in the shared link using TSCH CA algorithm. However, the authors have not taken into account the deterministic behavior of the TSCH mechanism in a shared link, they supposed that all devices of the network share the given link.

In this paper, we present an enhancement analytical study of the transmission in the shared link using TSCH CA algorithm. We take into account the deterministic behavior of the TSCH mechanism. We study the impact of the number of devices sharing the same link on the performances of the network, under saturated and non saturated conditions. The results are validated by Monte Carlo simulations.

The remainder of this paper is organized as follows. Section 2 presents related works about IEEE 802.15.4e standard. Section 3 describes IEEE 802.15.4e standard and summarizes its main MAC enhancements. Section 4 gives a detailed Markov chain model of TSCH/CA mechanism, and derives the theoretical expressions of collision probability, data packet loss rate, reliability, energy consumption, throughput, delay and jitter. Section 5 presents the impact of the number of devices sharing the link variation on the network performances under different traffic conditions. We validate our analysis by Monte Carlo simulations. Section 6 concludes this paper.

2 Related Works

To meet the need of the industrial applications, the new IEEE 802.15.4e standard has been created. Since, the scientific community were interested in its brought enhancements. Some works addressed the LLDN [24–26, 29, 61] and the DSME mechanisms [23, 30–32]. When others were interested in TSCH. Those works done on TSCH are various.

On the one hand, some of them addressed the enhancement of the TSCH mechanism, where authors proposed scheduling algorithms to allow devices to transmit in their assigned timeslots. In [21] a novel Traffic Aware Scheduling Algorithm for TSCH (TASA) is proposed to support the emerging industrial applications, which require low latency at low duty cycle and power consumption. This algorithm is a centralized algorithm, it extends the theoretically graph theory methods of matching and coloring by means of an innovative approach based on network topology and traffic load. Distributed scheduling algorithms for TSCH are presented in [22, 57]. In [27], authors presented an Adaptive TSCH (A-TSCH) algorithm in order to improve the reliability of the existing TSCH. They proposed to use the blacklisting technic, which consists to use a selected subset of channels considered "Reliable", unlike the IEEE 802.15.4e TSCH which indiscriminately uses all 16 channels in the 2.4 GHz band. In [28], the authors adopted mechanisms for learning the spectral condition and blacklisting to the A-TSCH.

On the other hand, some other works were done on the performances evaluation. The authors of [14] evaluated the performances of the IEEE 802.15.4e TSCH in terms of latency, delivery ratio and energy per packet. They compared their results to the existing IEEE 802.15.4 by simulation. In [34], authors were interested to the formation process of TSCH network. They, firstly, proposed a random advertisement algorithm. Then, they evaluated the joining time performance metric, which is the total time taken by a new device to join the network. Results showed that the parameter depends on the number of channels used for advertisement. In [33], authors analyzed the transmission in the shared link using TSCH CA algorithm. They used the Markov chain modeling to estimate the distribution probability. Then, they derived theoretical expressions of the following performance metrics: data packet loss probability, normalized throughput, delay and energy consumption. Results showed that the TSCH CA can guarantee low energy consumption and relative reliability, for a given device transmitting in a shared timeslot.

In addition, the authors of [17] and [60], presented respectively the new 6TiSCH stack (IPv6 over the TSCH mode of IEEE 802.15.4e) and the 6LoWPAN stack. Both the works addressed the security mechanisms for the IEEE 802.15.4e TSCH. The authors of [59] and [58] were interested to the construction of energy consumption models for IEEE 802.15.4e TSCH. Models are obtained by slot-based "step-by-step" modeling.

3 IEEE 802.15.4e Description

IEEE 802.15.4e [15] amends the IEEE 802.15.4-2011 Standard [13] to specify additional MAC behaviors, that allow devices to better support the industrial and commercial applications. The IEEE 802.15.4e standard defines the following three modes:

- Deterministic and Synchronous Multi-Channel Extension (DSME);
- Low Latency Deterministic Networks (LLDN);
- Time Slotted Channel Hopping (TSCH).

3.1 DSME

The IEEE 802.15.4 supports only up to 7 Guaranteed Timeslots (GTSs) and these GTSs are restricted to use a single channel [13, 15]. The IEEE 802.15.4e DSME enhances the IEEE 802.15.4 standard by extending the number of GTS timeslots, and adopting a channel hopping to ensure that GTSs can be used in more channels. DSME [31, 31] employs a multi-superframes structure defined by coordinators that periodically transmit an Enhanced Beacon (EB). A multi-superframes is a cycle of repeated superframes, each of which consists of a beacon frame, Contention Access Period (CAP) and Contention Free Period (CFP). An example of a multi-superframes structure is shown in Fig. 1. Additional energy-saving is obtained using CAP reduction. When CAP reduction is applied, all CAPs except the one in the first superframe of the multi-superframes are substituted with DSME-GTSs as shown in Fig. 2.

3.2 LLDN

The IEEE 802.15.4e LLDN mechanism [15] operates only in a star topology, and all the devices are connected to the LLDN coordinator. The time is divided in cycles called LLDN superframes, as shown in Fig. 3.

The meaning or the usage of the timeslots in the superframe are as follows:

- Beacon: the first timeslot of each superframe contains a beacon frame. It is used for synchronization with the superframe structure;
- Management timeslots: management timeslots are optional, they provide a mechanism for bidirectional transmission of management data in downlink and uplink direction;
- N and M: are respectively the number of timeslots allowed for data transmission, and retransmission, $N + M$ defines the total number of timeslots available for uplink transmission. IEEE 802.15.4e standard allows a maximum of 254 timeslots excluding the beacon and management timeslots;
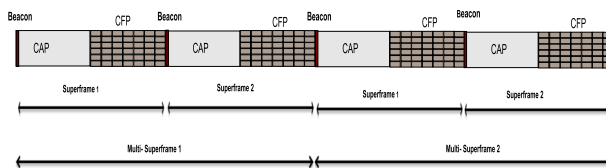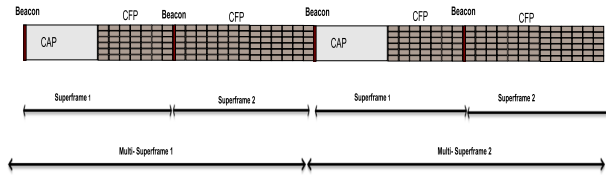

Fig. 1 Multi-superframes structure

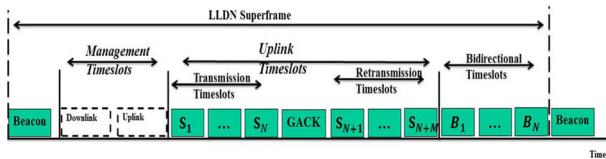**Fig. 2** Multi-superframes structure with CAP reduction

Fig. 3 LLDN superframe structure

- GACK: is the Group ACKnowledgment, it contains N bits bitmap to indicate successful and failed uplink transmissions, in the same order as the uplink transmission. It is used to facilitate retransmission of failed transmission within the same superframe;
- Bidirectional timeslots: used for the transmission of device data to the LLDN PAN coordinator (uplink) as well as of data from the LLDN PAN coordinator to the LLDN device (downlink).

In the LLDN superframe, there are two types of timeslots: dedicated timeslots and shared timeslots. More than one device can be assigned to a timeslot (shared group timeslots). In this case, the devices use simplified CSMA/CA (a contention-based access method).

3.3 Time Slotted Channel Hopping (TSCH) Mechanism

The IEEE 802.15.4e TSCH owes its creation to the integration of the existing TSMP into the IEEE 802.15.4e amendment [17]. Unlike DSME and LLDN, TSCH is a non beacon mechanism. It combines time slotted access and channel hopping [15].

3.3.1 Time Slotted Access Synchronization

In TSCH mechanism, like in TDMA scheme, devices are synchronized through a periodic slotframe. A slotframe is a collection of timeslots repeating over the time. Figure 4 shows a slotframe with four timeslots. Multiple slotframes are used for a given network to define different communication schedule for various devices.

3.3.2 Channel Hopping

TSCH supports the use of multi channels based on channel hopping technic. The channel hopping is defined in [15] as the periodically switching of the channel. It uses a known sequence to both sending and receiving devices.

In TSCH a link is defined as the pairwise assignment of a directed communication between devices in a given timeslot, on a certain channel offset [14, 14, 34]. Hence, a link between two devices can be represented by a couple (*ASN*, *channelOffset*), where Absolute Slot Number (ASN) is the total number of timeslots that has elapsed since the start of the
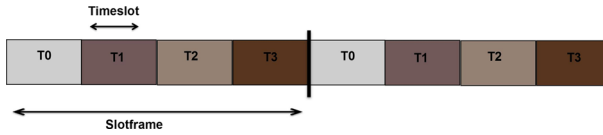
Fig. 4 Example of a four timeslots slotframe

network. It increments globally in the network every tiemslot. In principle 16 different channels are available for communication. Each channel is identified by a channelOffset i.e., an integer value in the range [0…15] [14].

Physical channel, CH, in a link is made according to the following formula:

$$CH = HSL[(ASN + channelOffset)\%HSL]. \tag{1}$$

where HSL is the Hopping Sequence List and HSL is the Hopping Sequence Length.

The channel hopping technic improves the network capacity. However, it is considered as a blind channel hopping [62]. So, a blacklisting technic is proposed in [27, 28] to overcome this problem.

In TSCH, there are two types of links. Dedicated and shared links. We can give an example in Fig. 5 of a possible schedule, supporting dedicated and shared links with four channel offsets. The link (2, 2) is assigned to the device H in order to transmit to the device D, i.e., it's a dedicate link for the device H. Whereas, the link (1, 3) is assigned to devices I and H, i.e., this link is a shared link between devices I and H.

3.3.3 Network Topology

The TSCH mechanism is an independent topology. It can be used to form any topology, from a star to a full mesh [15]. Like in IEEE 802.15.4, the IEEE 802.15.4e TSCH network supports two types of devices:

- Full Function Device (FFD): device that can operate as either a network coordinator or as a simple network device;
- Reduced Function Device (RFD): device that can operate only as a network device.

3.3.4 Transmission Process

When a given device is operating in TSCH mode, Contention Channel Access (CCA) may be used as shown in Fig. 6. So, when a device has a packet to transmit, it shall wait for a
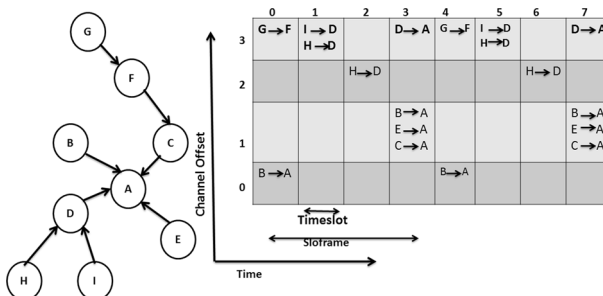

Fig. 5 Example of a possible scheduling with four timeslots in each slotframe and four channel Offsets
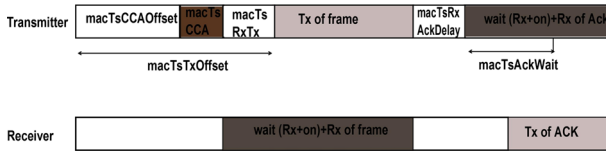
Fig. 6 Timeslot diagram of acknowledged transmission

link to the destination device. Then, the transmitter waits for *macTsCCAOffset*, and performs CCA. At *macTsTxOffset*, the device begins transmitting the frame.

3.3.5 Acknowledgment Process

If an acknowledgment is expected, the device waits for *macTsRxAckDelay*, and then enables the receiver to await the acknowledgment. If the acknowledgment does not arrive within *macTsAckWait*, the device may idle the radio and consider the transmission failed.

The Fig. 6 summarizes the transmission process with expected acknowledgment.

Where the default values of the MAC parameters are given in Table 1.

3.3.6 Retransmission Process in Dedicated Links

In the case where the retransmission is assigned to be in dedicated link, if an acknowledgment is not received within the appropriate time-out, the device shall conclude that the single transmission attempt has failed. So, the device shall repeat the process of transmitting the data and waiting for an acknowledgment, up to a maximum of *macMaxFrameRetries* times. If an acknowledgment is still not received after the number of *macMaxFrameRetries* retransmissions, the MAC sublayer shall assume the transmission has definitively failed and notify the next higher layer of the failure.

3.3.7 TSCH Collision Avoidance Retransmission Algorithm (TSCH CA) in Shared Links

In the case where the transmission was made on a shared link, assigned to more than one device, collisions may occur and result a transmission failure. To reduce the probability of repeated collisions, a retransmission backoff algorithm has been implemented for shared links.

The retransmission backoff is applied only to the transmission on shared links. There is no waiting for transmission on dedicated links. The retransmission backoff is calculated in the number of shared transmission links.

The TSCH CA algorithm has the following characteristics:

- The backoff window increases after each consecutive failed transmission in a shared link;
- The backoff window is reset to the minimum value if the transmission is successful in a shared link;
- The backoff window is reset to the minimum value if the transmission in a dedicated link is successful and the transmit queue is then empty.
- The backoff window does not change when a transmission has failed in a dedicated link;

Table 1 Default values of the IEEE 802.15.4e TSCH MAC parameters

Parameter	Default value (µs)
macTsCCAOffset	1800
macTsTxOffset	2120
macTsRxAckDelay	800
macTsAckWait	400

- The backoff window does not change when a transmission is successful in a dedicated link and the transmission queue is still not empty;

The TSCH CA algorithm presented in IEEE 802.15.4e is analogous to that of CSMA/CA described in IEEE 802.15.4 [13], except that the backoff is calculated in shared links, so the CSMA-CA *aUnitBackoffPeriod* is not used.

A device upon encountering a transmission failure in a shared link shall initialize the Backoff Exponent (*BE*) to *macMinBE* (the minimum value of the *BE* whose default value is one). The MAC sublayer shall delay for a random number in the range $[0, 2^{BE} - 1]$ shared link. For each successive failure on a shared link, the device should increase the backoff exponent until the backoff exponent is equal to *macMaxBE* (which default value is seven). Successful transmission on a shared link resets the backoff exponent to *macMinBE*. If an acknowledgment is still not received after a maximum retransmissions retry limit *macMaxFrameRetries* (which default value is three), the MAC sublayer shall assume that the transmission has definitively failed and notify the next higher layer of the failure.

4 Modeling of the IEEE 802.15.4e TSCH CA Mechanism

In this section, we propose a two dimensional Markov chain model for the IEEE 802.15.4e TSCH CA mechanism. Then, we resolve the stationary probabilities equations, in order to compute the packet transmission probability τ. This probability will be used to develop mathematical models, in order to derive the following performance metrics, namely: data packet loss probability, reliability, energy consumption, throughput, average delay and jitter.

4.1 Hypothesis

The following list depict the considered hypothesis in the construction of our analytical model for IEEE 802.15.4e TSCH CA mechanism.

1. There are *N* devices disposed on a star topology around an FFD device;
2. There are *K* devices sharing their data in a shared link ($K \leq N$);
3. The wireless channel is ideal, the capture effect and noise errors are neglected;
5. The frames which have undergone a collision are retransmitted in shared links using TSCH CA algorithm;
6. The possible retransmission in a dedicated link is not taken into account;
7. The ACK is taken into account.

Table 2 defines the probabilities used in our Markov chain model.

Table 2 Probabilities of the IEEE 802.15.4e TSCH analytical model

Probability	Definition
λ	The probability of going back to the idle state
P_c	The collision probability of transmitted data packet
τ	The transmission probability

4.2 Data Packet Transmission Probability (τ)

In this subsection, in order to study the behavior of a single device transmitting its data packet in a shared link, we use a two dimensional Markov chain model. This modeling allows us to compute the probability τ that a device transmits its data packet in a chosen link.

Our Markov chain of IEEE 802.15.4e TSCH CA mechanism is defined by a graph transition G illustrated in Fig. 7, and its set of states $E = \{s(t), c(t)\}$, where

- $s(t)$ is the stochastic process representing at a given time t the backoff stage;
- $c(t)$ is the stochastic process representing at a given time t the backoff time counter.
- The state $\{s(t) = -1, c(t) = 0\}$ is the idle state;

  - The state $\{s(t) = 0, c(t) = -1\}$ is the transmission state;
  - The state $\{s(t) = i, c(t) = -1\}$ is the retransmission state, where $i \in (1, m)$. m is the *macMaxFrameRetries*.

4.3 Transition Probabilities

The state transition probabilities associated with our Markov chain are given as follows:
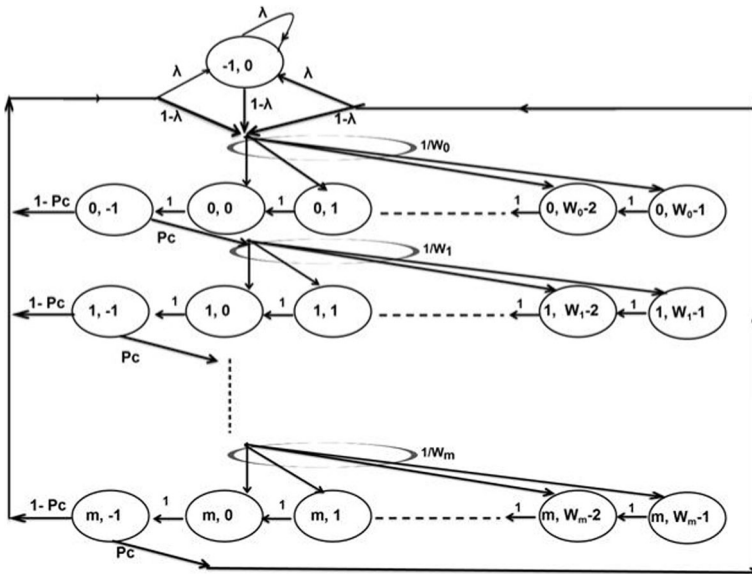

Fig. 7 Transition graph of IEEE 802.15.4e TSCH CA Markov chain model

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

$$P\{i, -1/i, 0\} = 1, \in (0, m). \tag{3}$$

$$P\{i, k, /i - 1, 0\} = \frac{Pc}{W_i}, \quad i \in (1, m), k \in (0, W_i - 1). \tag{4}$$

$$P\{-1, 0/i, -1\} = (1 - Pc)\lambda, i \in (0, m). \tag{5}$$

$$P\{0, k/i, -1\} = \frac{(1 - \lambda)(1 - Pc)}{W_0}, i \in (0, m),$$
$$k \in (0, W_i - 2). \tag{6}$$

$$P\{-1, 0/m, -1\} = Pc\lambda. \tag{7}$$

$$P\{0, k/m, -1\} = \frac{Pc(1 - \lambda)}{W_0}, \quad k \in (0, W_i - 2). \tag{8}$$

- The backoff counter decreases with the probability expressed in Eq. (2).
- When the backoff counter reaches to zeros, the device starts transmission immediately, from where Eq. (3).
- When the transmission has undergone a collision, a new initial backoff value is uniformly chosen at the backoff stage i from the range $[0, W_i]$, as in Eq. (4), where

$$W_i = \begin{cases} 2^i W_0, & i \leq m_b - m_0; \\ 2^{m_b - m_0} W_0, & m_b - m_0 < i \leq m. \end{cases} \tag{9}$$

  where $m_b = macMaxBE$, $m_0 = macMinBE$ and $m = macMaxCSMA$.
- After a succesful transmission:

  - the probability to go back to the idle state (no data packet to transmit) is expressed by Eq. (5).
  - the probability to go back to the backoff stage zero is given by Eq. (6).

- If the transmission has undergone a collision at backoff stage m:

  - the probability to go back to the idle state (no data packet to transmit) is expressed by Eq. (7).
  - the probability to go back to the backoff stage zero is given by Eq. (8).

As we can see in the graph transition G illustrated by Fig. (7), our Markov chain is irreducible, so the stationary distribution exists. Particulary, this stationary distribution is unique because our Markov chain is ergodic.

Let $\pi_{i,j} = \lim_{t \to \infty}(P(s(t) = i, c(t) = k)), i \in (-1, m), k \in (-1, W_i - 1)$ be the stationary distribution of the proposed Markov chain model. From Eqs. (2)–(8), the closed-form solution for this Markov chain is given by Eq. (10).

$$\pi_{i,k} = \frac{W_i - k}{W_i} \pi_{i,-1}, i \in (0, m), k \in (0, W_i - 1). \tag{10}$$

According to the normalization condition, we obtain:

$$\pi_{-1,0} + \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \pi_{i,k} + \sum_{i=0}^{m} \pi_{i,-1} = 1. \tag{11}$$

Now, we can express each term of Eq. (11) as a function of $\pi_{0,-1}$.

1. Expression of $\pi_{-1,0}$ as a function of $\pi_{0,-1}$:
   From our Markov chain, we obtain:

$$\pi_{-1,0} = \lambda \cdot \pi_{-1,0} + \lambda(1 - Pc) \sum_{i=0}^{m} \pi_{i,-1} + \lambda \cdot Pc \cdot \pi_{m,-1}$$

$$= \frac{\lambda}{1-\lambda} \cdot \pi_{0,-1} \tag{12}$$

2. Expression of $\sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \pi_{i,k}$ as a function of $\pi_{0,-1}$:
   From Eq. (10), we have:

$$\sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \pi_{i,k} = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} \pi_{i,-1}$$

$$= \begin{cases} \dfrac{\pi_{0,-1}}{2} \left(\dfrac{1 - Pc^{m+1}}{1 - Pc} + W_0 \dfrac{1 - (2 \cdot Pc)^{m+1}}{1 - 2 \cdot Pc} \right), \\ \qquad\qquad if \quad m \le m_b - m_0, \\[2mm] \dfrac{\pi_{0,-1}}{2} \left(\dfrac{1 - Pc^{m+1}}{1 - Pc} + W_0 \dfrac{1 - (2 \cdot Pc)^{\acute{m}+1}}{1 - 2 \cdot Pc} \right), \\ \qquad\qquad else. \end{cases} \tag{13}$$

3. Expression of $\sum_{i=0}^{m} \pi_{i,-1}$ as a function of $\pi_{0,-1}$:
   We use Eq. (10), and we obtain:

$$\sum_{i=0}^{m} \pi_{i,-1} = \pi_{0,-1} \left(\frac{1 - Pc^{m+1}}{1 - Pc} \right). \tag{14}$$

Now, we replace Eqs. (12), (13) and (14) in Eq. (11), and we obtain the following expression of $\pi_{0,-1}$:

$$\pi_{0,-1} = \begin{cases} \left[\dfrac{\lambda}{1-\lambda} + 1/2 \cdot \left(\dfrac{1 - Pc^{m+1}}{1 - Pc} + W_0 \cdot \dfrac{1 - (2Pc)^{m+1}}{1 - 2Pc} \right) + \dfrac{1 - Pc^{m+1}}{1 - Pc} \right]^{-1}; & if\ m \le m_b - m_0; \\[4mm] \left[\dfrac{\lambda}{1-\lambda} + 1/2 \cdot \left(\dfrac{1 - Pc^{m+1}}{1 - Pc} + W_0 \cdot \dfrac{1 - (2Pc)^{m+1}}{1 - 2Pc} \right) + \dfrac{1 - Pc^{\acute{m}+1}}{1 - Pc} \right]^{-1}; & otherwise. \end{cases} \tag{15}$$

The probability τ that a device starts transmission, according to our Markov Chain, is the probability to be in the transmission state. i.e. $\{s(t) = i, c(t) = -1\}, i = 1 - m$. It is given by Eq. (16):

$$\tau = \sum_{i=0}^{m} \pi_{i,-1} = \sum_{i=0}^{m} Pc^{i}\pi_{0,-1} = \frac{1 - Pc^{m+1}}{1 - Pc}\pi_{0,-1}. \tag{16}$$

This probability is the key to derive the expressions of the performances metrics of IEEE 802.15.4e TSCH/ CA mechanism. However, this probability, τ, depends on the collision probability Pc that at least one of the remaining devices among those sharing the given link $(k - 1)$ transmits at the same timeslot. We assume that those devices transmit with probability τ. Then, the collision probability Pc is given as follows:

$$Pc = 1 - (1 - \tau)^{k-1}. \tag{17}$$

The non linear system formed by Eqs. (16) and (17) can be solved using a numerical method.

4.4 Data Packets Loss Probability

The data packets are discarded after the maximum retry limit achievement. If a device tries to transmit after m attempts, the data packet will be lost. Then, the data packet loss probability, P_{loss}, is given as follows:

$$P_{loss} = Pc^{m+1}. \tag{18}$$

4.5 Reliability

The reliability is defined as the probability of successful data packet transmission. It is expressed as the opposite event of data packet loss probability. So, the reliability R is given by Eq. (19).

$$R = 1 - P_{loss} = 1 - Pc^{m+1}. \tag{19}$$

4.6 Energy Consumption

The average energy consumption of a device is given as the sum of the average energies consumption in the idle state E_{idle}, the transmission state E_{trans} and the reception state E_{recep}. It is expressed as follows:

$$E = E_{idle} + E_{trans} + E_{recep}. \tag{20}$$

where

$$E_{idle} = P_{idle}\left(\pi_{-1,0} + \sum_{i=0}^{m} \pi_{i,k}\right). \tag{21}$$

$$E_{trans} = P_{trans} \sum_{i=0}^{m} \pi_{i,-1}. \tag{22}$$

$$E_{recep} = P_{recep} \sum_{i=0}^{m} \pi_{i,-1}. \tag{23}$$

P_{idle}, P_{trans} and P_{recep} are respectively, the average energy consumption in idle, transmission and reception states.

4.7 Throughput

The throughput is defined as the quantity of successful data packet transmission with the ratio of channel time. The channel time includes channel free time σ and channel busy time.

- Let Pr be the probability that the channel is busy (there is at least one transmission in the considered timeslot):

$$Pr = 1 - (1 - \tau)^N. \tag{24}$$

- Let Ps be the probability of successful data transmission probability conditioned by the fact that the channel is busy:

$$Ps = \frac{N \cdot \tau (1 - \tau)^{N-1}}{Pr}. \tag{25}$$

- Let Ts be time duration for successful data packet transmission:

$$Ts = L + t_{ack} + T_{ack}. \tag{26}$$

- Let Tc be the time duration for collided data packet transmission:

$$Tc = L + timeout_{ack}. \tag{27}$$

where L, t_{ack}, T_{ack} and $timeout_{ack}$ are respectively the time duration for the data packet transmission (including payload, PHY header and MAC header), waiting time for an ACK, time duration of transmitting an ACK and the timeout of an ACK.

Now, we can give the theoretical expression of throughput as follows:

$$S = \frac{L \cdot Pr \cdot Ps}{(1 - Pr)\sigma + Ts \cdot Pr \cdot Ps + Tc(1 - Ps)Pr}. \tag{28}$$

4.8 Delay

The average delay, $E(D)$, of a successfully sending data packet is the time interval from the data packet is ready to be transmitted, until an ACK is received. Without loss of generalities, we only consider the delay of successful transmission.

- Let D_i be the average delay that the device transmits a successfully data packet at the ith stage:

$$E(D_i) = t_s + i \cdot t_c + \sum_{k=0}^{i} \frac{W_k - 1}{2} \sigma. \tag{29}$$

where $\frac{W_k - 1}{2}$ is the average number of timeslots that a station decrements in the stage i.

- Let Q_i be the probability that a data packet is successfully transmitted from the stage i:

$$Q_i = \frac{(1 - Pc)Pc^i}{1 - Pc^{m+1}}. \tag{30}$$

where $(1 - Pc)$ is the probability that a data packet is successfully transmitted after previous i failed attempts (Pc^i), provided that the packet is not dropped $(1 - Pc^{m+1})$.

The expression of average delay is given as follows:

$$
\begin{aligned}
E(D) &= \sum_{i=0}^{m} \frac{(1 - Pc)Pc^i}{1 - Pc^{m+1}} E(D_i) \\
&= \sum_{i=0}^{m} \frac{(1 - Pc)Pc^i}{1 - Pc^{m+1}} \left(t_s + i \cdot t_c + \sum_{k=0}^{i} \frac{W_k - 1}{2} \sigma \right).
\end{aligned}
\tag{31}
$$

4.9 Jitter

The delay jitter, J, is defined as the possible variation of the data packet delay values from the mean value. We compute the jitter of the data packet as follows:

$$
J = \sqrt{E(D^2) - (E(D))^2}.
\tag{32}
$$

where the average squared delays $E(D^2)$ is calculated by Eq. (33).

$$
E(D^2) = \sum_{i=0}^{m} \frac{(1 - Pc)Pc^i}{(1 - Pc)^{m+1}} E(D_i)^2.
\tag{33}
$$

5 Performance Evaluation

In this section, we will analyze the IEEE 802.15.4e TSCH in a shared link, under saturated and non saturated conditions $\lambda = 0, 0.5, 0.9$. To see the impact of the number of devices sharing the same link on the performances of the network, we will variate the number of devices sharing the link, at a fixed network size. A Monte Carlo simulations of IEEE 802.15.4e TSCH are presented to complete our analysis. The list of parameters used in our analysis is depicted in Table 3.

Table 3 Parameters of analysis

Parameters	TSCH
W_0	2
m_b	7
m_0	1
m	3
ACK length	2.4 ms
ACK timeout	0.4 ms
σ	10 ms
L	100 B
P_{idle}	0.8 mW
P_{trans}	30 mW
P_{rec}	40 mW

Fig. 8 Collision probability
versus number of devices sharing
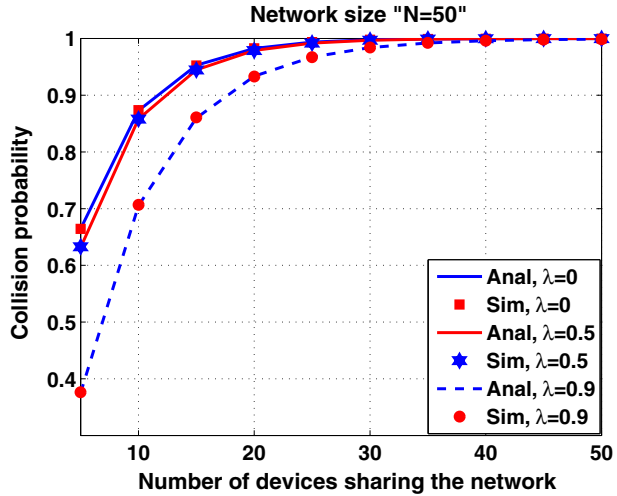the link variation, for network
size = 50

Fig. 9 Packet loss rate versus
number of devices sharing the
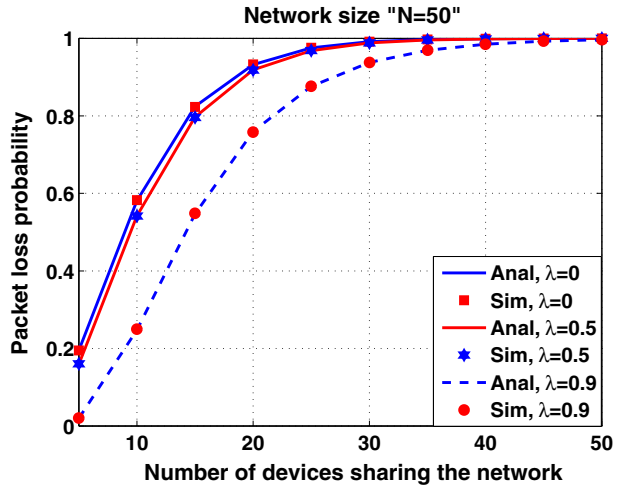link variation, for network
size = 50

Figure 8 shows the collision probability obtained by our analytical expression in Eq. (17) and Monte Carlo simulation. On the one hand, we variate the number of devices sharing the link (*K*) at a given number of devices in the network (fixed at *N* = 50). On the other hand, we variate the traffic conditions $\lambda = 0, 0.5, 0.9$. We observe that the analytical results match the simulation results well whatever the traffic conditions and the number of devices sharing the link in the network are. The collision probability grows up as a function of the number of devices in the network. And, for a given network size, it also grows up as a function of the number of devices sharing the link. For example, for the network size equal to 50, the collisions are lower when the number of devices sharing the network is equal to 10, it grows up until the number of devices sharing the link is equal to 50. The reason is that when the number of devices increases the number of devices trying to transmit becomes important and then causes collisions. In addition, we remark that the curves under saturated traffic condition ($\lambda = 0$) are above those under non saturated traffic

Fig. 10 Reliability versus number of devices sharing the link variation, for network size = 50
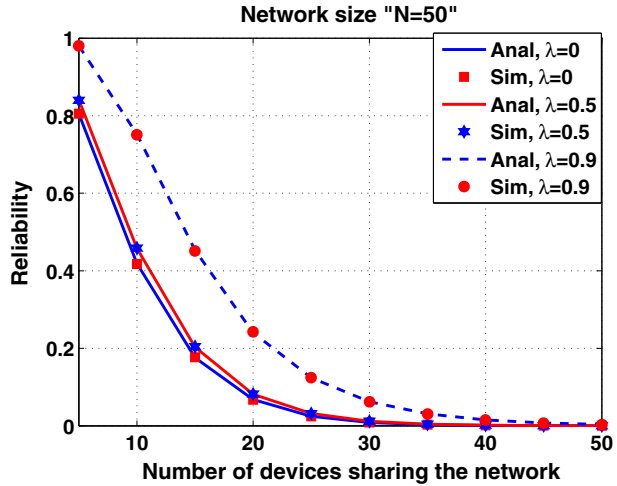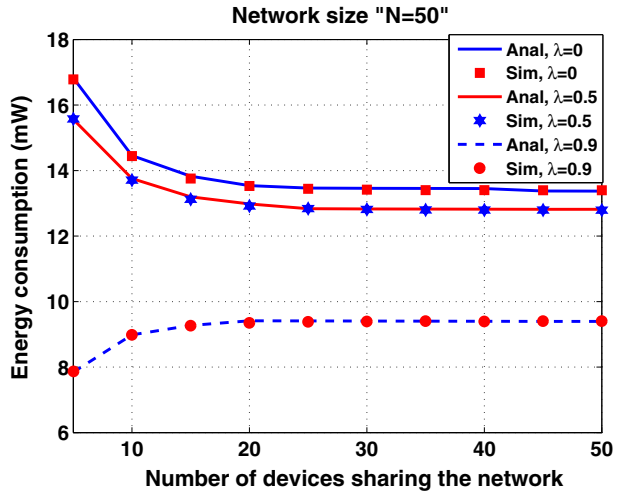

Fig. 11 Energy consumption versus number of devices sharing the link variation, for network size = 50

condition ($\lambda = 0.9$) and medium traffic condition ($\lambda = 0.5$). Moreover, when $\lambda = 0$ means that the transmission queue is not empty, at each time there is a data packet to transmit. This engenders a higher collision probability.

Figure 9 illustrates the data packet loss rate as a function of the number of devices sharing the link, this figure follows the same behavior of Fig. 8, because the data packet loss rate is strongly related to collisions. So, similarly to collisions, both results of analytical expression in Eq. (18) and simulation are close.

In Fig. 10, we report the reliability as a function of the number of devices sharing the link for $N = 50$ under saturated ($\lambda = 0$), non saturated ($\lambda = 0.9$) and medium traffic conditions ($\lambda = 0.5$) for both analytical expression given in Eq. (19) and simulation. As we have described in previous section, the reliability is the opposite event of the data packet loss rate. So, the curves in Fig. 10 are symmetrical to the curves in Fig. 9 by the asymptote $x = y$. Simulation results and analytical expression are well matched.

Fig. 12 Throughput versus number of devices sharing the link variation, for network size = 50
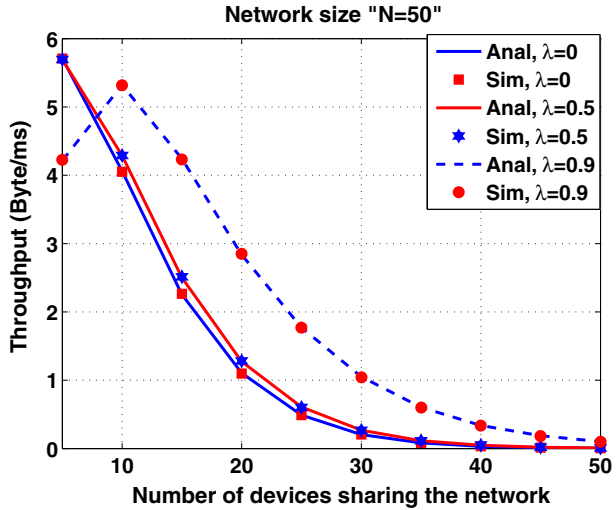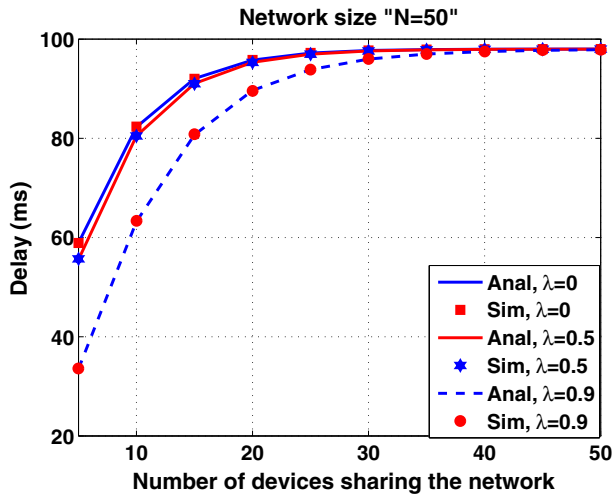

Fig. 13 Delay variation versus number of devices sharing the link variation, for network size = 50

In Fig. 11, we observe the energy consumption according to the number of devices sharing the link for $N = 50$, under saturated ($\lambda = 0$), non saturated ($\lambda = 0.9$) and medium traffic conditions ($\lambda = 0.5$). On the one hand, we notice that the energy consumption decreases under saturated and medium traffic condition as the number of devices sharing the link increases at a given network size. Because, the more the number of devices sharing the link increases under saturated and medium traffic condition, the more collisions are important. So, the more time the device stays in the backoff state than in other states (transmitting and receiving states) and consumes less energy. On the other hand, we remark that the energy consumption increases under non saturated condition ($\lambda = 0.9$) as the number of devices sharing the link increases at a given network size. Because, under no saturated condition collisions are lower, and the device has more chance to be in a transmitting or receiving state, so it consumes more energy.

Fig. 14 Jitter variation versus number of devices sharing the link variation, for network size = 50
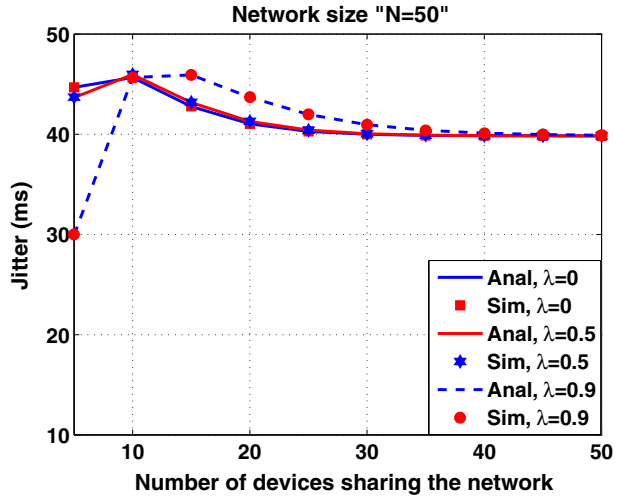
It is important to observe that the energy consumption is really dependent on the number of devices sharing the link and the traffic conditions. Like previous curves, the simulations results and analytical expression in Eq. (21) of energy consumption are very close.

Figure 12 illustrates the Throughput as achieved by analytical expression in Eq. (28) and Monte Carlo simulation. We variate the number of devices sharing the link when the network size is 50. We remark that the throughput under non saturated condition increases from 5 to 10 devices and then it decreases until 50 devices. For saturated and medium traffic conditions, the throughput decreases. It is clear that the throughput is affected by collisions. The throughput is higher when the collisions are lower.

Figure 13 shows the delay variation according to the number of devices sharing the link. We notice that the delay increases with the increase of the devices sharing the link. Because, when the number of devices increases, the given device undergoes more collisions, then it spends much time in backoff state and causes long delay.

In Fig. 14, the jitter increases when the size of the network becomes increasingly important meaning that the variation of the data packet delay values from the mean value grows up when the number of devices is greater. The analytical expressions of both delay in Eq. (31) and jitter in Eq. (32) well match with Monte Carlo simulations.

6 Conclusion

In this article, we have modeled and analyzed the performances of IEEE 802.15.4e TSCH. We have derived theoretical expressions of collision probability, data packet loss rate, reliability, energy consumption, throughput, delay and jitter. We have seen that the performances of the TSCH mechanism are strongly related to the number of devices sharing the link and the traffic conditions. The Monte Carlo simulations well matches with our analytical results.

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Celia Ouanteur is currently a member of the research unit LaMOS (Modeling and Optimization of Systems), Algeria. She received the License degree in 2010 in Applied Mathematics (Decision-making aid option) from the Operation Research Department of University of Bejaia (Algeria), the Master degree in 2012 in Applied Mathematics (Reliability and Performance Evaluation of Networks option) from the Operation Research Department of University of Bejaia (Algeria), and the doctorate degree in 2016 in Applied Mathematics from the Operation Research Department of University of Bejaia (Algeria). Her research interests are in: Modeling, Simulation, Performance evaluation and Analysis of wireless networks (IEEE 802.15.4 Standard) and Industrial networks (Real-time MAC protocols).

Louiza Bouallouche-Medjkoune received the engineer degree in Computer Science from University of Sétif (Algeria), the Magister degree in Applied Mathematics from University of Bejaia (Algeria), the doctorate degree in Computer Science from University of Sétif (Algeria) in 2006 and, the HDR (Habilitation à Diriger des Recherches) from the University of Constantine (Algeria) in 2009. Bouallouche-Medjkoune works as a teacher at the Department of Computer Science of University of Bejaia and as a researcher at the research unit LaMOS (Modeling and Optimization of Systems). She is head of the research team EPSIRT (Evaluation de Performances des Systèmes Informatiques et Réseaux de Télécommunication) since 2005 and head of department of Operation Research since January 2010. Her publications have appeared in various publishing houses: Taylor Francis, Elsevier, Springer, AMS, BCS,… Her research interests are: Performance evaluation of Computer Systems and Telecommunication Networks (Markov chains, Queuing networks, Simulation,…), stability of systems, Quality of service, Routing and Protocols of systems and networks (mobiles, ad hoc, sensors,…).

Djamil Aïssani was born in 1956 in Biarritz (Basque Country, France). He started his career at the University of Constantine (Algeria) in 1978. He received his Ph.D. in November 1983 from Azerbaidjan State University (Bakou) and Kiev State University (Soviet Union). He is at the University of Bejaia since its opening in 1983/1984. Director of Research, Head of the Faculty of Science and Engineering Science (1999–2000), Director of the research unit LaMOS (Modeling and Optimization of Systems), Scientific Head of the Computer Science Doctorate School ReSyD, he has taught in many universities (USTHB Algiers, Annaba, Rouen, Dijon, ENITA, INPS Ben Aknoun, Boumerdes, Tizi Ouzou, Sétif, EHESS Paris,…). He has supervised more than 20 Ph.D. Thesis. He has published many papers on Markov chains, Queuing systems, Reliability theory, Performance evaluation and their applications in such industrial areas as Electrical, Telecommunication Networks and Computer Systems.