Performance analysis of the IEEE 802.15.4e TSCH-CA algorithm under a non-ideal channel

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Abstract: The TSCH Collision Avoidance (TSCH-CA) algorithm has been implemented by the IEEE 802.15.4e amendment to decrease the probability of repeated collisions in the packet retransmission in the Industrial Wireless Sensor Networks (IWSNs). This paper proposes a two-dimensional Markov chain model to evaluate the performances of the TSCH-CA algorithm when only shared links are used under non-ideal channel conditions. The accuracy of this model has been verified through Monte Carlo simulations. Based on the proposed model, the expressions of different performance metrics that include retransmission probability, data packet loss rate, reliability, energy consumption, normalised throughput and average access delay have been obtained. Furthermore, a comparative study between TSCH-CA and the unslotted CSMA-CA of IEEE 802.15.4 under a non-ideal channel has been provided. Numerical results reveal that the TSCH-CA performances are clearly affected by channel errors when using only shared links under a noisy environment.

Keywords: IWSNs; IEEE 802.15.4e; TSCH-CA; non-ideal channel; modelling; Markov chains; performances analysis.

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1 Introduction

In recent years, Wireless Sensor Networks (WSNs) have been deployed in critical applications like those in industrial (Gungor and Hancke, 2009) and healthcare (Davenport et al., 2009) domains, thanks to the arrival of actuator devices and the development of sensor devices technology (Ouanteur et al., 2017). Specifically, in the industrial field, an Industrial Wireless Sensor Network (IWSN) is composed of a set of sensor devices which sense the environment and communicate the information collected to controllers (De Guglielmo, 2016b; Alderisi et al., 2015). They include many application domains, namely: factory automation, process control, and real-time monitoring (Alderisi et al., 2015). The IWSNs applications are facing several challenges in terms of latency, robustness and determinism (Gungor and Hancke, 2013). To meet those stringent requirements, several wireless standards, such as Wireless HART (HART, 2007), ISA100.11a (ISA, 2009) and IEEE 802.15.4e (Group et al., 2012) have been released by international bodies.

IEEE 802.15.4e especially is a new amendment developed by the IEEE organisation in 2012, which expands the original 802.15.4 Medium Access Control (MAC) (Group et al., 2011), because the latter did not address the needs of IWSNs applications (De Guglielmo, 2016a; Ouanteur et al., 2017). Indeed, the key feature of this amendment is the creation of interesting new MAC protocols, namely: *Low Latency Deterministic Network* (LLDN), *Deterministic* and *Synchronous Multi-channel Extension* (DSME) and *Time Slotted Channel Hopping* (TSCH). This amendment uses new techniques based on time slotted access, shared and dedicated links, multi-channel communication and frequency hopping. The focus of this paper is principally on the TSCH mode given its importance to the IWSNs. A detailed description of the other IEEE 802.15.4e MAC behaviour modes can be found in Group et al. (2012).

The TSCH mode, as its name implies, is built on two main operations namely, time slotted and channel hopping. The combination of both provides high network throughput, low latency, high reliability and energy efficiency (De Guglielmo et al., 2017). Furthermore, to access the channel, the mode defines both dedicated and shared links. Shared links are allocated to two or more devices to transmit data and as a consequence collisions can occur, leading to a transmission failure detected by not receiving the Acknowledgment (ACK) frame. To reduce the probability of repeated collisions, the TSCH CSMA-CA retransmission back-off algorithm, also known as "TSCH Collision Avoidance (TSCH-CA)" has been developed by the IEEE 802.15.4e standard.

Several analytical models have been published in order to study the behaviour of the CSMA-CA access mechanism used in IEEE 802.15.4. These analytical based studies are often inspired by Bianchi's model (Bianchi, 2000) proposed for the IEEE 802.11 MAC protocol (IEEE Std. 802.11, 1999). Bianchi has depicted the fundamental functionalities of this standard by means of a two-dimensional Markov chain, under the conditions of saturated traffic and ideal channel. Based on Bianchi's model, Jelena Mišić et al. (2005) developed a Markov model for CSMA-CA in order to analyse the impact of the MAC parameters on the IEEE 802.15.4 scheme performances. Then, a Markov model taking into account the Acknowledgment (ACK) mode has been studied in Pollin et al. (2008). Park et al. (2009) and Park et al. (2013) included retransmissions with finite retry limits and have derived a distributed adaptive algorithm for optimising power consumption. Moreover, the same authors have developed a novel analytical model taking into account the multi-path fading channels (Di Marco et al., 2014). Another Markov model has been proposed in Lee et al. (2011) taking into consideration frame dropping. The impact of deferred transmission in the CSMA-CA algorithm for Acknowledged and Unacknowledged Traffic has been modelled in Rehman et al. (2011).

Chen et al. (2013) presented an analytical study of the IEEE 802.15.4e TSCH-CA algorithm used in shared links. We have remarked that the presented work has been investigated under the assumption of an ideal wireless channel conditions. In practice, however, the existence of noise in IWSNs that weakens and disturbs the radio signal and which affects wireless channels quality is unavoidable. As the TSCH mode is one of the most promising technologies for the industrial environment, it is essential to take channel errors under consideration for the study of this mode.

In this work, our goal is to present a performance analysis of the TSCH-CA algorithm under a noisy environment and when only shared links are used. We extend the analytical study proposed in Chen et al. (2013) of the transmission in the shared links using the TSCH-CA algorithm, taking into consideration the non-ideal channel conditions. The major contributions of the work presented in this paper are:

- A Markov chain based model is used for modelling the behaviour of a single node using the TSCH-CA algorithm in shared link under a non-ideal channel conditions;
- Through this analytical model, the theoretical expressions of retransmission probability, data packet loss rate, reliability, energy consumption, normalised throughput and average access delay have been obtained;
- A performance comparison is made between our results and Chen's results (Chen et al., 2013) in order to show the effect of noise on the performance metrics;
- The proposed Markov model is validated using Monte Carlo simulations. In addition, a comparative study between the IEEE 802.15.4e TSCH-CA and the IEEE 802.15.4 Unslotted CSMA-CA mechanisms has been provided.

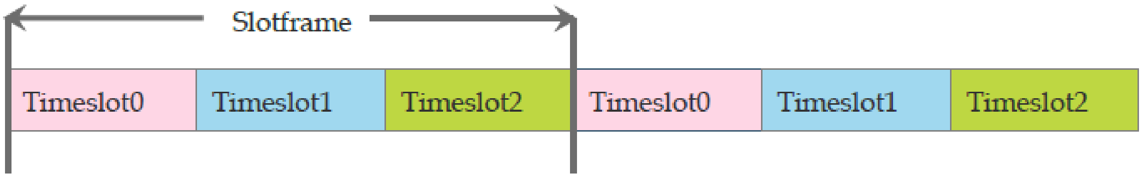
The remainder of this paper is structured as follows: a description of the IEEE 802.15.4e TSCH mode is presented in Section 2. Section 3 gives a review of previous works about the IEEE 802.15.4e standard and especially about the TSCH mode. In Section 4, we present the proposed analytical model of the TSCH-CA algorithm under a non-ideal channel in detail. In Section 5, a performance analysis under a non-ideal channel conditions is conducted. The accuracy of our analysis is validated by means of Monte Carlo simulations. Finally, Section 6 concludes the paper.

2 IEEE 802.15.4e TSCH overview

The TSCH mode was created for wireless devices of IEEE 802.15.4 to support a wide range of industrial applications and, more precisely for the process automation, including oil and gas industry, food and beverage products, pharmaceutical products, chemical products, water/waste water treatments, green energy production and climate control (Group et al., 2012).

TSCH operates in non-beacon mode; it combines time slotted access with channel hopping, that is to say, a hybrid of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) (Accettura and Piro, 2014). TSCH is also an independent topology, it can be used with any network topology from a star to a full mesh (Group et al., 2012).

Figure 1 Example of a TSCH slotframe with three timeslots



2.1 *TSCH access mechanism description*

In a TSCH scheme, the notion of the superframe used in IEEE 802.15.4 is substituted by a slotframe. One slotframe consists of defined periods of communications between devices named timeslots. It automatically repeats over time and the beacon is not required to start communications. Figure 1 illustrates an example of a TSCH slotframe structure with three timeslots; each timeslot is sufficiently long for a device to send or receive a maximum length frame and facultatively receive or transmit an acknowledgment (ACK) to that frame. In the TSCH mechanism, when the ACK is required and not received within a predetermined time, the retransmission will only happen in the subsequent timeslot dedicated to the same transmitter-receiver pair of devices on any slotframe (Group et al., 2012).

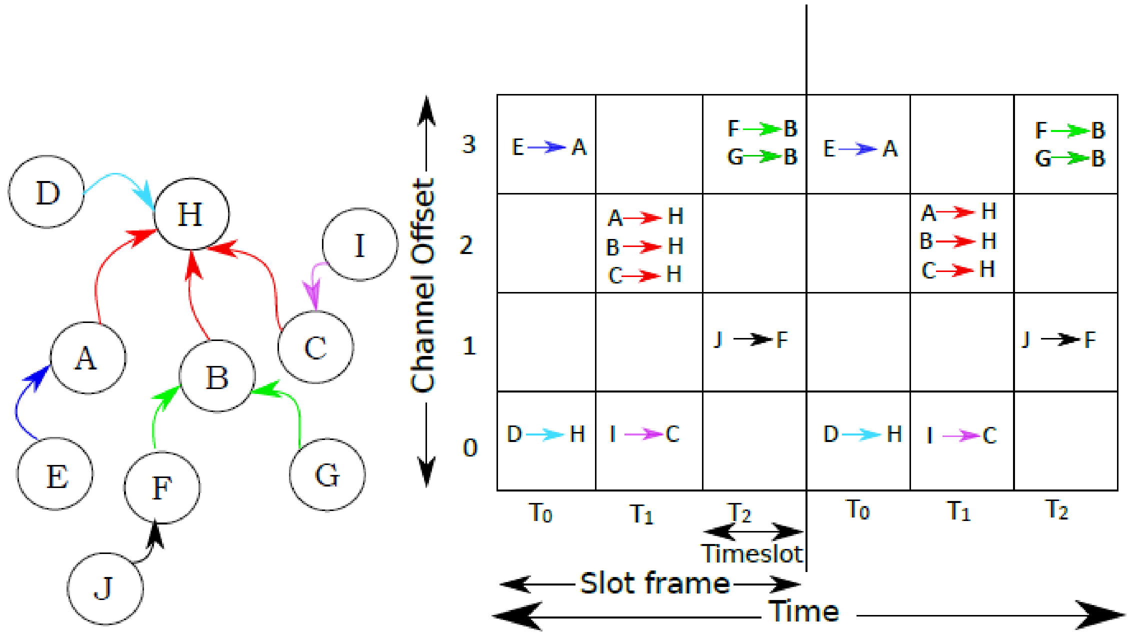
TSCH uses the multi-channel strategy, where multiple communications can occur at the same time (in the same timeslot) using different channels. In addition, TSCH networks may support channel hopping where permitted or when required, and devices may hop between the different frequencies when communicating to mitigate the impact of multi-path fading and interferences (Group et al., 2012).

According to the IEEE 802.15.4e standard, there are 16 channels operating in a 2.4 GHz frequency. Each frequency channel is identified by a channel offset which is an integer value in the range [0; 15] (De Guglielmo et al., 2014). A link is defined in Group et al. (2012) as the pairwise assignment of a directed communication between devices in a certain timeslot, with a given channel offset. So a link in TSCH may be represented by a pair (*Timeslot*, *channelOffset*). The physical channel *CH* in a given link is derived according to the following formula:

$$\mathrm{CH} = F[(ASN + channelOffset) \bmod N_{ch}]; \tag{1}$$

where *ASN* (*Absolute Slot Number*) is a counter which represents the total number of slots elapsed since the deployment of the network. A*SN* is initiated to 0 and increased by 1 for each timeslot. N_{ch} is the length of the table HoppingSequenceList which contains the whole of the available channels; in other words N_{ch} is the number of available frequencies. In TSCH, a link can be dedicated or shared, when it is dedicated, only one pair of devices can communicate. In the case of shared link, several devices can transmit data at the same timeslot, on the same frequency. An example of a TSCH scheduling is given in Figure 2.

Figure 2 Example of a TSCH scheduling with three timeslots and four channel offsets in one slotframe

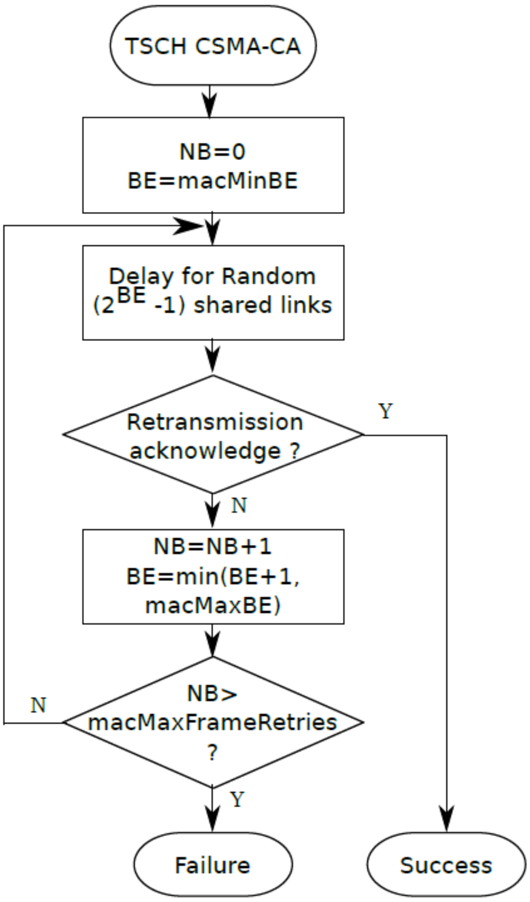


2.2 *TSCH-CA algorithm*

When the data frame is transmitted on a shared link and the acknowledgment is predicted but not received, a collision has probably happened. Thus, the sending device will invoke the TSCH-CA retransmission back-off algorithm in order to decrease the probability of repeated collisions. Knowing that a retransmission will happen in the next link dedicated to the same destination, the subsequent retransmissions can be either on shared or dedicated links. The TSCH-CA algorithm has the following properties:

- The retransmission back-off shall only apply to the transmission on shared links and there is no waiting for transmission on dedicated links;
- The retransmission back-off is calculated in the number of shared transmission links;
- The back-off window increases after each consecutive unsuccessful transmission on shared links;
- The back-off window is reset to the minimum value after a successful transmission on a shared link;
- The back-off window remains unchanged when a transmission is unsuccessful in a dedicated link, and also when a transmission is successful in a dedicated link and the transmission queue is still not empty;
- The back-off window is reset to the minimum value after a successful transmission in a dedicated link and the transmission queue is then empty.

Figure 3 The TSCH-CA algorithm in shared links



2.2.1 TSCH-CA algorithm in shared links

If only shared links are used and a node encounters an unsuccessful transmission, it shall execute the following steps:

1. A set of state variables is initialised: the Back-off Exponent (*BE*=*macMinBE*) and the number of retransmissions (*NB* = 0);
2. The MAC sub-layer delays for a random number of shared link uniformly distributed in the range $[0; 2^{BE} - 1]$;
3. If the retransmission is successful on a shared link, *BE* is reset to *macMinBE* and the algorithm terminates;
4. If the retransmission is unsuccessful in a shared link, MAC sub-layer will increase the value of *NB* by 1 and make *BE* = min (*BE* + 1; *macMaxBE*) respectively;
5. If *NB* exceeds its max value *macMaxFrameRetries*, the MAC sub-layer shall assume that the transmission has failed and will inform the next higher layer of the failure. Otherwise the algorithm returns to step 2. This is illustrated in Figure 3.

3 Related works

Since the successful advent of the IEEE 802.15.4e standard, several researchers have studied the performances of its three MAC protocols introducing different enhancements: LLDN (Dariz et al., 2013; Berger et al., 2014; Anwar and Xia, 2014; Ouanteur et al., 2017; Sahoo et al., 2017; Willig et al., 2017, DSME (Jeong and Lee, 2012; Lee and Jeong, 2012; Capone et al., 2014; Lee and Chung, 2016; Vallati et al., 2017) and TSCH (Palattella et al., 2012; Accettura et al., 2015; Duy et al., 2017; De Guglielmo et al., 2014b; Vogli et al., 2015, Du and Roussos, 2012; De Guglielmo et al., 2014a; Alves et al., 2016; Vilajosana et al., 2014; Al-Nidawi and Kemp, 2015; Sciancalepore et al., 2017; Ouanteur et al., 2017; Chen et al., 2013; De Guglielmo et al., 2017).

To improve the TSCH mechanism, a lot of research works have been done for which the majority emphasised on the problem of how to construct an optimised schedule that allows assigning timeslots to TSCH devices. Palattella et al. (2012) proposed Traffic-Aware Scheduling Algorithm (TASA) as a centralised approach based on network topology and traffic load. In order to schedule the distribution of slots and channel offsets to the nodes on the whole network topology, TASA exploits matching and colouring methods from graph theory with an innovative approach. Accettura et al. (2015) proposed a Distributed Traffic-Aware Scheduling (DeTAS) mechanism as a distributed approach of TASA. Here, all nodes used a common schedule named macro-schedule, which is the combination of micro-schedules of every routing graph and very micro-schedule is calculated in distributed mode. A simple and novel distributed cell-selection strategy for the scheduling function designed for the industrial internet of things has been proposed in Duy et al. (2017). The proposed strategy is a distributed approach; it defines two main processes, namely: the slotOffset and channelOffset selections, then a new protocol is implemented to plug the proposed strategy directly into the scheduling function. This strategy helps to reduce the scheduling errors and collisions, including the energy consumption and consequently the whole network life is improved. De Guglielmo et al. (2014b) and Vogli et al. (2015) investigated the TSCH network formation phase. In De Guglielmo et al. (2014b), a simple random-based advertisement algorithm has been proposed, it has been analysed in terms of the joining time which is the total time taken by a new node seeking to join the TSCH network. Hence, the authors have shown the impact of channels offsets number used for advertisement on joining time. In Vogli et al. (2015), two novel mechanisms implemented in real motes to speed up joining operations in a TSCH network have been presented. The results have demonstrated that the joining operations can be effectively boosted by increasing the node density. To enhance the reliability of the existing TSCH scheme, Du and Roussos (2012) proposed an Adaptive TSCH (A-TSCH). In this scheme, the blacklisting technic has been exploited; this consists in selecting a subset of channels with less interference, instead of using all 16 channels as in the IEEE 802.15.4e TSCH scheme. In addition, the same authors have introduced mechanisms for learning the spectral condition and blacklisting to the A-TSCH mode (Du and Roussos, 2013).

On the other hand, a lot of research has been realised on the performances analysis of the IEEE 802.15.4e TSCH mode. To the best of our knowledge, those existing works are based on two main approaches: simulation investigation (De Guglielmo et al., 2014; Alves et al., 2016; Vilajosana et al., 2014; Al-Nidawi and Kemp, 2015; Sciancalepore et al., 2017) and analytical models (Chen et al., 2013; Ouanteur et al., 2017; De Guglielmo et al., 2017).

De Guglielmo et al. (2014) analysed the performances of the IEEE 802.15.4e TSCH mode using the NS2 simulation tool (Issariyakul and Hossain, 2011). They have presented some results, such as: latency, delivery ratio and energy per packet. These results have been compared to the existing IEEE 802.15.4 to illustrate the performance improvements approved by the new amendment. Alves et al. (2016) analysed the performances of IEEE 802.15.4e TSCH mode using a real implementation in emulated environment, concerning delivery rate, latency and time to association. They have shown that a proper schedule is crucial to achieve good performances, taking into consideration the traffic pattern. An energy consumption model has been presented in Vilajosana et al. (2014). Watteyne et al. (2012) provided an experimental validation based on real nodes running the OpenWSN protocol stack. The paper emphasises the contribution of each type of slot on the total energy consumed and the experimental validations have been conducted on different hardware platforms. Al-Nidawi and Kemp (2015) addressed the impact of mobility over the TSCH sensor network, they have presented a Markov chain model to determine the parameters that affect mobile node association process, and then, they have proposed a protocol named Mobile Timeslotted Channel Hopping (MTSCH). This protocol simplifies the mobile nodes association, and minimises the latency occasioned by leaving the nodes dissociated from the network. TSCH and the proposed MTSCH mechanisms have been implemented and evaluated by means of Contiki OS (Dunkels et al., 2004). Furthermore, the work presented in Sciancalepore et al. (2017) analysed the security on the link-layer of TSCH, where a full link-layer security on multiple platforms has been implemented using different hardware/software policies.

Regarding the analytical performance analysis of the TSCH mechanism, the existing works have focused on shared links. In Chen et al. (2013), a Markov chain model has been presented for evaluating the performances of the TSCH-CA Algorithm for shared links. The authors have considered the retry limits, the transmission and acknowledgment mechanism in one timeslot under the saturation conditions, and the theoretical expressions of the packet loss rate, normalised throughput, energy consumption, and average access delay have been derived. The performance analysis has shown that the TSCH-CA Algorithm can guarantee low-energy consumption and relative reliability with a reduced number of nodes sharing a link. An enhanced analytical model has been presented in Ouanteur et al. (2017); it has taken into account the deterministic behaviour of the TSCH mechanism in a shared link. It has studied the impact of the number of devices sharing the same link on the performances of the network under saturated and unsaturated conditions. The results have indicated that performances of the IEEE 802.15.4e TSCH protocol are highly related to the number of devices sharing the link and the traffic conditions. Finally, De Guglielmo et al. (2017) developed an analytical model of the TSCH-CA Algorithm in shared links taking into account the capture effect parameter.

Through the analytical models cited above, we note that, there are not many performance evaluation models of the TSCH-CA Algorithm and the proposed models are developed under the assumption of an ideal channel. So, in our work we want to study the performances of the algorithm in a noisy environment, since the IEEE 802.15.4e TSCH mode is dedicated to IWSNs.

4 Analytical model of the TSCH-CA algorithm

To analyse the transmission in the shared link in the TSCH mechanism using the TSCH-CA scheme under a non-ideal channel conditions, we develop a new two-dimensional discrete time Markov chain. Some performance metrics, such as: retransmission probability, data packet loss rate, reliability, energy consumption, normalised throughput and average access delay are derived using the proposed model. The following list represents the principal hypotheses of our analytical model for the TSCH-CA scheme under a non-ideal channel. The list of probabilities is given in Table 1.

1. There are N devices transmitting their data in a shared link;
2. The wireless channel is disturbed and noise errors may happen on the transmitted data packets, this means that the impact of the *Bit Error Rate* (*BER*) is taken into consideration. Therefore, the loss of a packet may be caused by a noisy channel;
3. The devices that encountered collisions and/or errors can only retransmit their packets on shared links, i.e., dedicated links are not taken into account;
4. The Capture effect is ignored;
5. The ACK is considered.

Table 1 IEEE 802.15.4e TSCH-CA analytical model probabilities

Probability	*Definition*
P_c	Data packet collision probability
P_e	Data packet error probability
P_r	Data packet retransmission probability
τ	Data packet transmission probability
δ	The probability of returning to the idle state

4.1 Markov chain model

In this subsection, we study the behaviour of an individual device using the TSCH-CA algorithm under a non-ideal channel with a new two-dimensional discrete time Markov chain model, (illustrated in Figures 4 and 5). We compute the packet transmission probability τ by solving the stationary probabilities equations of this Markov chain model. Finally, we use this probability to develop mathematical models in order to obtain some performance metrics of the TSCH-CA algorithm.

We introduce the following two stochastic processes:

Let *r(t)* be the stochastic process representing, at a given time *t*, the back-off stage for a given device. Let *b(t)* be the stochastic process representing, at a given time *t*, the back-off time counter. Their values are given as follows: *r(t)* = $(0,\ldots,\mathrm{R})$ and *b(t)* = $(-1,\ldots,w_i-1)$, where $i \in (1,\mathrm{R})$; $R = macMaxFrameRetries$ and $w_i = 2^i w_0$; $w_0 = 2^{MacMinBE} - 1$.

Figure 4 The Markov chain model of the TSCH-CA algorithm under a non-ideal channel

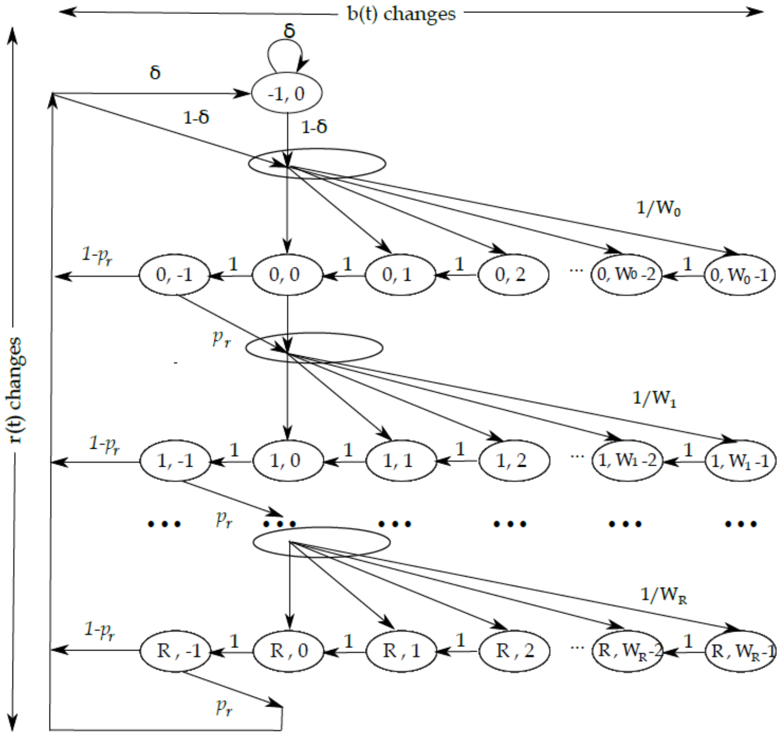
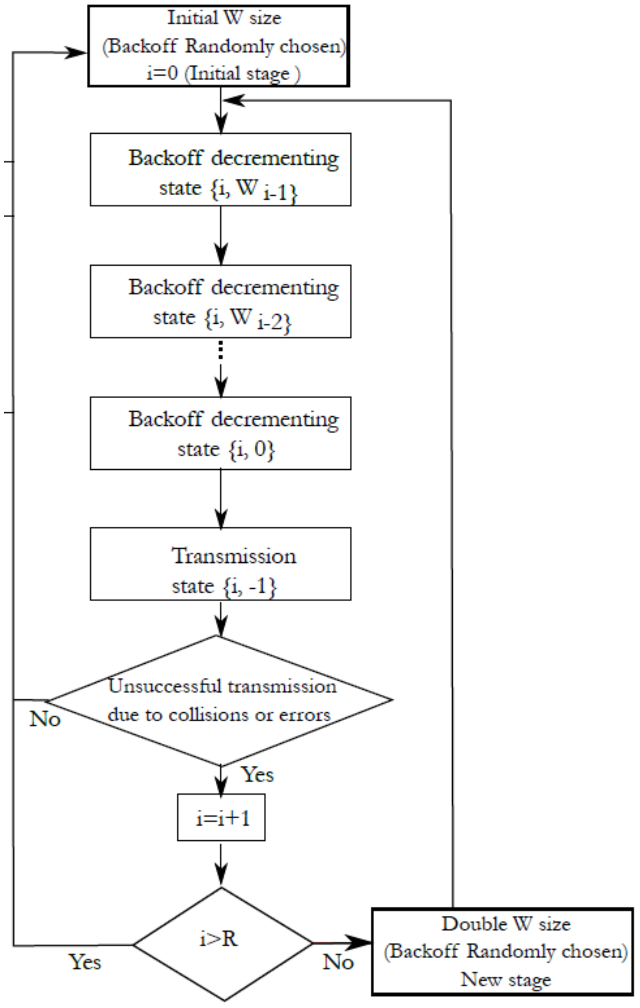


Figure 5 The flow-char for the TSCH-CA model



- The state $\{r(t)=-1,\ b(t)=0\}$ is the idle state;
- The state $\{r(t)=i, b(t)=-1\}$ is the retransmission state.

The back-off window size w_i for a given device in a back-off stage *i* is:

$$w_i = \begin{cases} 2^i w_0, \\ i \le macMaxBE - macMinBE; \\ \\ 2^{macMaxBE - macMinBE} w_0, \\ macMaxBE - macMinBE < i \le R. \end{cases} \tag{2}$$

The transition probabilities of our Markov chain are listed and described as follows:

$$\begin{cases} P\{i,k/i,k+1\} = 1, i \in (0,R), k \in (0, w_i - 2); \\ P\{i,-1/i,0\} = 1, i \in (0,R); \\ P\{i,k/i-1,-1\} = \dfrac{P_r}{w_i}, i \in (0,R), k \in (0, w_i - 1); \\ P\{0,k/i,-1\} = \dfrac{(1-P_r)(1-\delta)}{w_0}, i \in (0,R), k \in (0, w_i - 2); \\ P\{-1,0/i,-1\} = (1-P_r)\delta, i \in (0,R); \\ P\{0,k/-1,0\} = \dfrac{1-\delta}{w_0}, k \in (0, w_i - 2); \\ P\{0,k/R,-1\} = \dfrac{P_r(1-\delta)}{w_0}, k \in (0, w_i - 2); \\ P\{-1,0/R,-1\} = P_r.\delta. \end{cases} \tag{3}$$

The first equation in (3) denotes the decrementing probability of the back-off counter by one unit. The second equation in (3) shows the probability that the device immediately starts its transmission when the back-off counter reaches zero. The third equation in (3) represents the probability of retransmission after an unsuccessful transmission due to a collision and/or errors; in this case, the device uniformly chooses a new back-off delay at the next stage *i* from the range $[0, w_i]$. After a successful transmission, the probability of returning to the first back-off stage if the transmission queue is not empty is expressed in the fourth equation in (3). If the transmission queue is empty, the probability of going back to the idle state is denoted by the fifth equation in (3). The sixth equation in (3) describes the transition probability from the idle state to the transmission state. If the retransmission is unsuccessful at the stage *R*, probabilities of returning to the first stage (the transmission queue is not empty) and to the idle state (the transmission queue is empty) are shown respectively in the last two equations (3).

Let $\pi_{i,j} = \lim_{t\to\infty}\left(P_r(t) = i, b(t) = k\right)$ be the stationary distribution of our Markov chain model for $i \in (-1, R)$ and $k \in (-1, w_i - 1)$. Hence, the closed-form solution is expressed as follows:

$$\pi_{i,k} = \frac{w_i - k}{w_i}\pi_{i,0}, i \in (0,R), k \in (0, w_i - 1) \tag{4}$$

$$\pi_{i-1,0}.P_r = \pi_{i,0}. \tag{5}$$

$$\pi_{i,0} = P_r^i.\pi_{0,0}, 0 \le i \le R. \tag{6}$$

Since $\pi_{i,-1} = \pi_{i,0}$, $\pi_{i,-1}$ can be presented as:

$$\pi_{i,-1} = P_r^i.\pi_{0,0}, 0 \le i \le R. \tag{7}$$

According to the normalisation condition, we have:

$$1 = \pi_{-1,0} + \sum_{i=0}^{R}\sum_{\mathrm{k}=0}^{w_i-1}\pi_{\mathrm{i,k}} + \sum_{i=0}^{m}\pi\mathrm{i},-1. \tag{8}$$

From equations (4) and (6), $\sum_{i=0}^{R}\sum_{k=0}^{w_i-1}\pi_{i,k}$ can be expressed as functions of $\pi_{0,0}$ and packet retransmission probability P_r, as follows:

$$\begin{aligned} \sum_{i=0}^{R}\sum_{k=0}^{w_i-1}\pi_{i,k} &= \sum_{i=0}^{R}\sum_{k=0}^{w_i-1}\frac{w_i-k}{w_i}\pi_{i,0}, \\ &= \sum_{i=0}^{R}\pi_{i,0}\sum_{k=0}^{w_i-1}\frac{w_i-k}{w_i}, \\ &= 1/2\sum_{k=0}^{w_i-1}\pi_{i,0}\left(1-w_i\right), \\ &= 1/2\left[\sum_{k=0}^{w_i-1}\pi_{i,0} + \sum_{k=0}^{w_i-1}w_i\pi_{i,0}\right] \end{aligned} \tag{9}$$

Then,

$$\sum_{i=0}^{R}\sum_{k=0}^{w_i-1}\pi_{\mathrm{i,k}} = \begin{cases} \dfrac{\pi_{0,0}}{2}\left(w_0\dfrac{1-\left(2.P_r\right)^{(R+1)}}{1-2.P_r} + \dfrac{1-P_r^{(R+1)}}{1-P_r}\right), \\ if\ R \le macMaxBE - macMinBE; \\ \\ \dfrac{\pi_{0,0}}{2}\left(w_0\dfrac{(1-\left(2.P_r\right)^{(h+1)})}{1-2.P_r} + \dfrac{1-P_r^{(R+1)}}{1-P_r}\right), \\ otherwise. \end{cases} \tag{10}$$

where $h = macMaxBE – macMinBE$.

Now, from equation (6), $\sum_{i=0}^{m}\pi i,-1$ can be expressed as functions of $\pi_{0,0}$ and packet retransmission probability P_r as follows:

$$\sum_{i=0}^{R}\pi_{i,-1} = \left(\frac{1-P_r^{R+1}}{1-P_r}\right)\pi_{0,0}. \tag{11}$$

Equation (12) expresses the value $\pi_{-1,0}$ as a function of $\pi_{0,0}$ as follows:

$$\begin{aligned} \pi_{-1,0} &= \delta.\pi_{-1,0} + \delta.P_r.\pi_{R,-1} + \delta\left(1-P_r\right)\sum_{i=0}^{R}\pi_{i,-1} \\ &= \frac{\delta}{1-\delta}\pi_{0,0} \end{aligned} \tag{12}$$

Now, we can derive the expression of $\pi_{0,0}$ by using the normalisation condition expressed in (8):

$$\pi_{0,0}=\begin{cases}\left[\left[\dfrac{\delta}{1-\delta}+1/2\left(w_0\dfrac{1-\left(2.P_r\right)^{(R+1)}}{1-2.P_r}+\dfrac{1-P_r^{(R+1)}}{1-P_r}\right)\right.\right. \\ \left.+\dfrac{1-P_r^{(R+1)}}{1-P_r}\right]^{-1}, \\ if\ R\leq macMaxBE-macMinBE; \\ \left[\dfrac{\delta}{1-\delta}+1/2\left(w_0\dfrac{1-\left(2.P_r\right)^{(h+1)}}{1-2.P_r}+\dfrac{1-P_r^{(R+1)}}{1-P_r}\right)\right. \\ \left.+\dfrac{1-P_r^{(R+1)}}{1-P_r}\right]^{-1}, \\ else.\end{cases} \tag{13}$$

Hence, the probability τ that a device starts transmission when the back-off counter reaches zero can be calculated as:

$$\tau=\sum_{\mathrm{i}=0}^{R}\pi_{\mathrm{i},0}=\sum_{\mathrm{i}=0}^{R}P_r^{\mathrm{i}}\pi_{0,0}=\frac{1-P_r^{R}}{1-P_r}\pi_{0,0}. \tag{14}$$

Nevertheless, the probability τ depends on the following probabilities:

- The collision probability P_c which is the probability that, at the same timeslot, at least one of the remaining (n–1) devices sharing the link transmits. We suppose that the remaining devices transmit with probability τ. Then, the collision probability P_c is expressed as follows:

$$P_c=1-(1-\tau)^{\mathrm{n}-1} \tag{15}$$

- The error probability P_e which is the probability that a transmitted packet experiences a transmission error. P_e is functions of the *Bit Error Rate* (*BER*) parameter and the packet length (*L*). So, we have:

$$P_e=1-(1-BER)^{L} \tag{16}$$

- The retransmission probability P_r which is the probability that a packet is retransmitted if it undergoes a collision or transmission errors. Hence, P_r is expressed as functions of P_c and P_e:

$$\begin{aligned}P_r&=P_c+P_e\\&=1-\left(1-\tau\right)^{n-1}+1-(1-BER\Big)^{L}\end{aligned} \tag{17}$$

The values of τ and P_r can be defined by solving the system of the two non-linear equations (17) and (14), which can be done using numerical technics. Finally, we analyse the Markov chain under saturated conditions, i.e., $\delta=0$.

4.2 Performance metrics

In this subsection, using the previously defined Markov chain, we will determine the expressions of the performance metrics of the TSCH-CA mechanism.

4.2.1 Packet loss probability

In the TSCH-CA scheme under noise conditions, a packet is discarded because of repeated collisions and/or transmission errors. If the data packet retransmission fails after *R* tries, it will be considered to be lost. Hence, the packet loss probability is expressed as follows:

$$\begin{aligned}P_{loss}&=P_r^{R+1}\\&=\left[1-(1-\tau)^{n-1}+1-\left(1-BER\right)^{L}\right]^{R+1}\end{aligned} \tag{18}$$

4.2.2 Reliability

Relying on Park et al. (2009), reliability is set as the probability of successful data packet transmission. It is then given as follows:

$$\begin{aligned}R&=1-P_{loss}\\&=1-P_r^{R+1}\\&=1-\left[1-(1-\tau)^{n-1}+1-\left(1-BER\right)^{L}\right]^{R+1}\end{aligned} \tag{19}$$

4.2.3 Energy consumption

The average energy consumption of one device denoted by E_{avg} is defined by equation (20):

$$E_{\mathrm{avg}}=E_{trans}+E_{recep}+E_{Boff}+E_{idle} \tag{20}$$

where

- E_{trans} is the energy consumption in the transmission state and it is given by:

$$E_{trans}=P_{trans}\sum_{\mathrm{i}=0}^{m}\pi_{i,-1} \tag{21}$$

- E_{recep} is the energy consumption in the reception state, it is given by:

$$E_{recep}=P_{recep}\sum_{\mathrm{i}=0}^{R}\pi_{i,-1}\left(1-P_r\right) \tag{22}$$

- E_{Boff} is the energy consumption in the back-off state. knowing that the device does not listen to the channel in the back-off state, so E_{Boff} is given by:

$$E_{Boff}=P_{idle}\sum_{i=0}^{R}\sum_{\mathrm{k}=0}^{w_i-1}\pi_{i.k} \tag{23}$$

- E_{idle} is the energy consumption in the idle state, it is given by:

$$E_{idle}=P_{idle}\sum_{\mathrm{i}=0}^{R}\pi_{i,-1}P_r \tag{24}$$

The values P_{trans}, P_{recep} and P_{idle} are respectively, the average energy consumption for the data transmission, the data reception and the idle state during back-off stages and the timeout of Ack. Finally, the average energy consumption for a successful transmission of one bit per device is given by the following equation:

$$E = \frac{E_{\text{avg}}}{\tau(1-\tau)^{n-1} * (1-P_e) * 250Kbs} \tag{25}$$

4.2.4 Normalised throughput

Normalised throughput is set as the time of successfully transmitting data with the ratio of the channel time. The channel time includes the channel busy time and the channel free time. We defined the throughput denoted by T_{hr} as a function of the computed value τ.

First, we define the fundamental parameters of T_{hr}:

- P_{tr} is the probability that there is at least one transmission in the given timeslot, i.e., the channel is busy. Given that there are *n* devices competing for the channel, and each device transmits with probability τ, so:

$$P_{tr} = 1-(1-\tau)^n \tag{26}$$

- P_s is the successful data transmission probability, in other words, it is the probability that there is exactly one device that transmits with no noise errors, which is conditioned by the fact that the channel is busy:

$$P_s = \frac{n\tau(1-\tau)^{n-1}(1-P_e)}{P_{tr}} \tag{27}$$

- Let T_s is the time duration for a successful transmission of the data packet:

$$T_s = T_p + T_h + t_{ack} + T_{ack} \tag{28}$$

where T_p, T_h, t_{ack} and T_{ack} are respectively the time duration for the payload transmission, the PHY header and MAC header transmission, the waiting time for an ACK and the time duration of transmitting an ACK.

- Let T_c be the time duration for an unsuccessful transmission of the data packet:

$$T_c = T_p + T_h + t_{ack-to} \tag{29}$$

where t_{ack-to} is the timeout of an ACK.

Finally, the normalised throughput T_{hr} can be computed as follows:

$$T_{hr} = \frac{P_{tr}P_{ts}T_p}{(1-P_{tr})\sigma + P_{tr}P_{ts}T_s + P_{tr}(1-P_{ts})Tc} \tag{30}$$

where σ is the time duration of one timeslot.

4.2.5 Average access delay

The average access delay of a successfully transmitting one data packet is the time interval since a packet is in the MAC queue ready for transmitting, until the reception of the ACK. We only consider the delay of a successful transmission, i.e., the delay of the discarded data packet after reaching the maximum number of retries is not taken into account. The analysis and the development of the delay formula are based on the model of Chen et al. (2013).

Let D_j be the average delay that a device transmits successfully a data packet at *j*-th time. $1-P_r$ is the probability of a successful transmission of a data packet.

Let A_j be the event that a device has transmitted successfully at *j*+1 time after *j* failed transmissions.

Let A_R be the successful data transmission within a maximum number of retransmissions *R*. So, we have:

$$P(A_j / A_R) = \frac{P_r^j}{\sum_{\text{k=0}}^{m} P_r^k} = \frac{(1-P_r)P_r^j}{1-P_r^{R+1}} \tag{31}$$

Then, the total average access delay is given by:

$$E(D) = \sum_{\text{j=0}}^{R} P(A_j / A_R) E(D_j) \tag{32}$$

where

$$E(D_j) = T_s + \text{j} + T_c + \sum_{\text{f=0}}^{j} E(T_f) \tag{33}$$

and $E(T_f)$ is the average back-off delay.

After an unsuccessful transmission, the device resets the back-off counter until it reaches the maximum number of retries.

So, the expression of $E(T_f)$ is:

$$E(T_f) = \sum_{\text{k=0}}^{w_f - 1} \frac{1}{w_f}.k.L.\sigma \tag{34}$$

Hence, the final expression of the average delay is defined as follows:

$$E(D) = \sum_{j=0}^{R} \frac{(1-P_r)P_r^j}{1-P_r^{R+1}} \left(T_s.j.T_c + \sum_{f=0}^{j} \frac{w_f - 1}{2}.\sigma.(L/1-P_e) \right) \tag{35}$$

5 Numerical results and performances evaluation

In this section, the aim is to present an extensive analysis of the TSCH-CA algorithm used in shared links under a non-ideal channel conditions. The main objective of this analysis is to examine the impact of noise on the TSCH-CA Algorithm using only shared links. In other words, we show the effect of the bit error rate parameter on the algorithm performances.

Our proposed analytical model has been validated by means of Monte Carlo simulations using the Matlab programming tool (Gilat, 2010). The list of all parameters used in this analysis is presented in Table 2. We also note that the BER values used in simulations were chosen based on the work done about IWSNs by the authors in Gungor and Hancke (2009).

We present Monte Carlo simulations of the IEEE 802.15.4e TSCH mode and analytical expressions of retransmission probability, data packet loss rate, reliability, energy consumption, normalised throughput and average access delay obtained by both TSCH-CA and Unslotted CSMA-CA algorithms. In all the figures below, we observe that there is a good correlation between the TSCH-CA analytical results and the Monte Carlo simulations ones.

For analysis, we first compare the performances of TSCH-CA between the cases of an ideal and a non-ideal channel. In fact, we will compare the results generated by the analytical model described in Sub-section 4.1 with the Monte Carlo simulations on one hand with the analytical results obtained from Chen's model (Chen et al., 2013), under ideal conditions on the other hand (see Figures 6, 7, 8, 9, 10 and 11). Then, we will give a comparative study between IEEE 802.15.4e TSCH-CA and the IEEE 802.15.4 Unslotted CSMA-CA in non-beacon enable mode (Group et al., 2011), under a noisy environment (see Figures 12, 13, 14, 15, 16 and 17).

Table 2 Analysis parameters

Parameter	*Numerical value*
Channel rate	250 kbps
macMinBE	1
macMaxBE	7
R	3
W_0	2
L	100 B
ACK length	2.4 ms
ACK timeout	0.4 ms
σ	10 ms
P_{trans}	35.5 mw
P_{recep}	41.4 mw
P_{idle}	0.042 mw

In Figure 6, we analyse the retransmission probability variation according to the number of devices sharing the same link, in either case of an ideal channel (BER=0) and a non-ideal channel (BER $=10^{-4}$, $5*10^{-4}$ and 10^{-3}). It is observed that in both cases, as the number of competing devices rises, the retransmission probability rises accordingly. This is explained by the fact that the channel is not ideal and also the range of choosing the back-off number in the TSCH-CA algorithm is smaller, $Backoff \in [0,1], [0,3], [0,7], \dots$ So, with the increase of the number of devices sharing the link, the probability that devices choose the similar back-off grows which increases the collision probability. Consequently, the retransmission probability becomes important. However, as expected, the retransmission probability in an ideal channel is lower than that of a non-ideal channel. This is due to the fact that, when the channel is ideal (BER=0) or slightly noisy (BER$=10^{-4}$), the packets retransmission is mainly due to collisions. We also remark that the curve under high BER value (10^{-3}) is on top of those under moderate BER value $\left(5*10^{-4}\right)$ and lower BER value $\left(10^{-4}\right)$. Hence, the higher the BER value (the channel is very noisy), affecting the transmission, the higher the retransmission probability is.

Figure 6 Retransmission probability for different number of devices sharing the link according to channel conditions

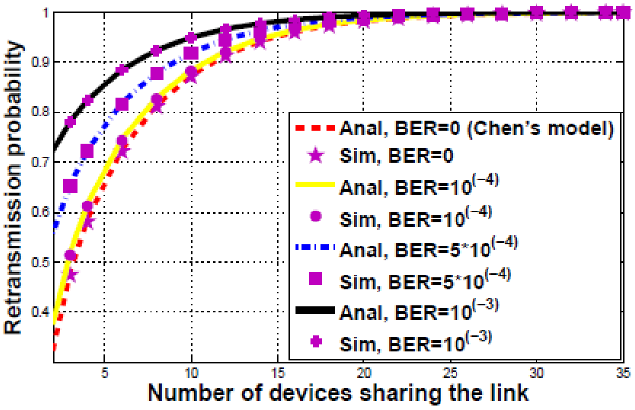
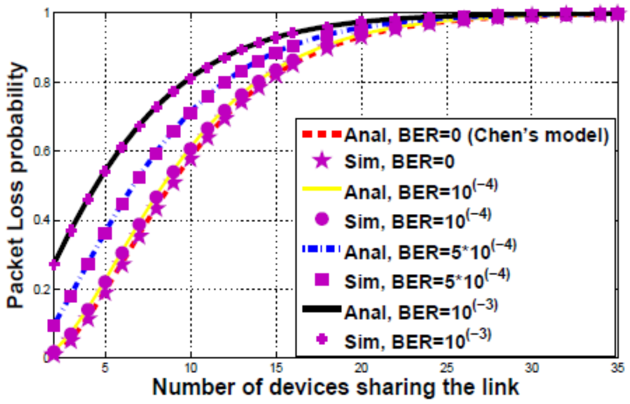


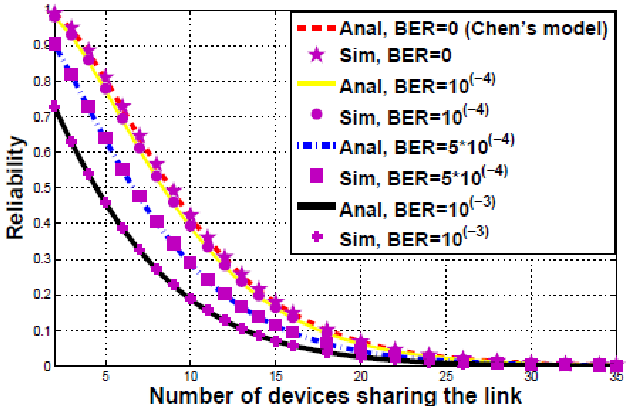
Figure 7 shows the variation of packet loss probability according to the number of devices sharing the link with different BER values. As it is known, packet loss probability is highly linked to collisions and/or errors. In other words, when the retransmission probability caused by collisions and/or errors rises, the probability that packets are discarded due to achieving the maximum retry limit value will rise accordingly. Hence, the behaviour of this figure is similar to that of Figure 6 in either case of an ideal and a non-ideal channel.

Figure 7 Packet loss probability for different number of devices sharing the link according to channel conditions



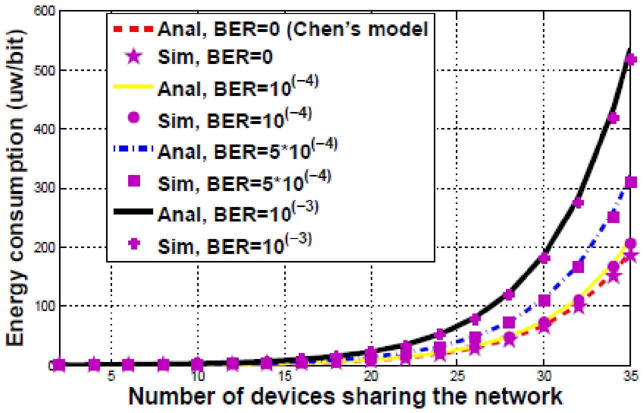
In Figure 8, we observe that the reliability decreases as the number of devices sharing the link increases under an ideal and a non-ideal channel. This is due to the large number of retransmissions which are caused by collisions and/or errors. However, when the channel is in bad conditions (BER$=10^{-3}$, $5*10^{-4}$), the reliability considerately decreases, unlike the case of an ideal channel (BER=0).

Figure 8 Reliability for different number of devices sharing the link according to channel conditions



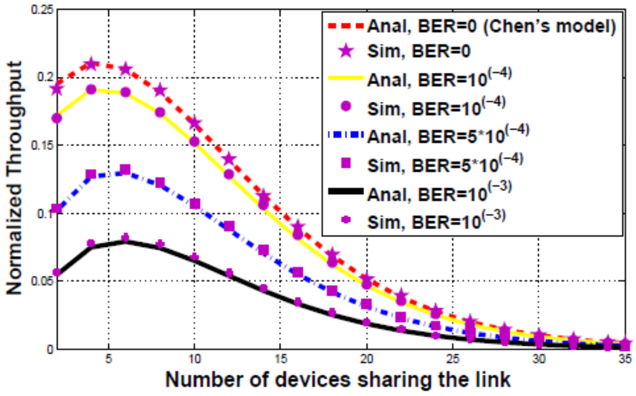
In Figure 9, it can be seen that the energy needed for a successful transmission of one bit per device is small when the number of devices sharing the link is low, in either case of an ideal or a non-ideal channel. On the other hand, we note that as the number of devices grows, more energy is consumed. This is due to the unsuccessful transmissions because of collisions and/or errors. Hence, the device tries more times to transmit the data packet consuming more energy. Nevertheless, when the number of devices is higher, the energy consumption under the higher or moderate BER increases considerably than when BER is low or when the channel conditions are good.

Figure 9 Energy consumption for different number of devices sharing the link according to channel conditions



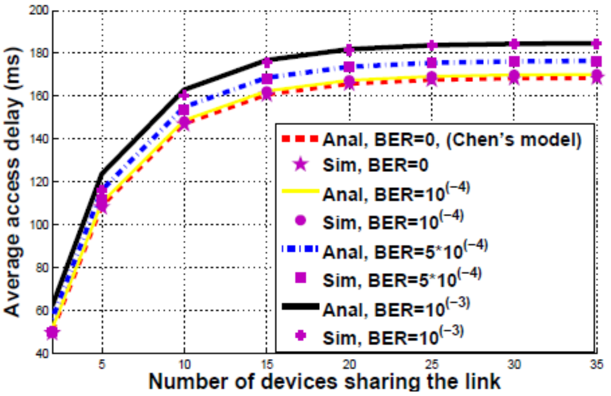
In Figure 10, we report the throughput performance as a function of the number of devices sharing the link under various channel conditions. The curves under the non-ideal channel (BER=10^{-3}, 10^{-4}, $5*10^{-4}$) have the same behaviour as the curve under the ideal channel(BER=0). In other words, with fewer devices sharing the link, the normalised throughput rises under different channel conditions, and then it decreases with the increase of the number of devices. Indeed, as the number of devices sharing the link grows, the retransmission probability rises, so the channel consequently is not used for a successful transmission. However, the normalised throughput in an ideal channel is higher than that of a non-ideal channel. Hence, the impact of channel errors on the throughput is illustrated.

Figure 10 Normalised throughput for different number of devices sharing the link according to channel conditions



We show in Figure 11 that the average access delay is affected by the number of devices sharing the link and the conditions of the channel. In fact, with a rise of the number of devices sharing the link and under a noisy channel, the number of retransmissions rises due to collisions and/or transmission errors. So, the device tries more times to transmit one packet and it spends much time in the back-off state. Nevertheless, the average access delay degrades as the channel conditions become worse; it is significantly greater than that of the ideal channel.

Figure 11 Average access delay for different number of devices sharing the link according to channel conditions

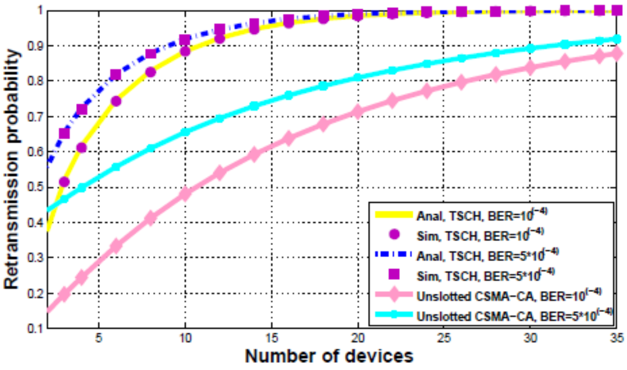


In the following, we compare the performances of the IEEE 802.15.4e TSCH-CA Algorithm with those of the IEEE 802.15.4 Unslotted CSMA-CA algorithm under a noisy environment.

In Figure 12, we analyse the retransmission probability according to the number of devices under different BER values (BER=10^{-4}, $5*10^{-4}$). It is observed that the curves of TSCH-CA and the curves of Unslotted CSMA-CA grow with the increase of the number of devices and the increase of the BER values. It is clear that Unslotted CSMA-CA is also impacted by channel errors; however, the retransmission probability of TSCH-CA is more important than that of Unslotted

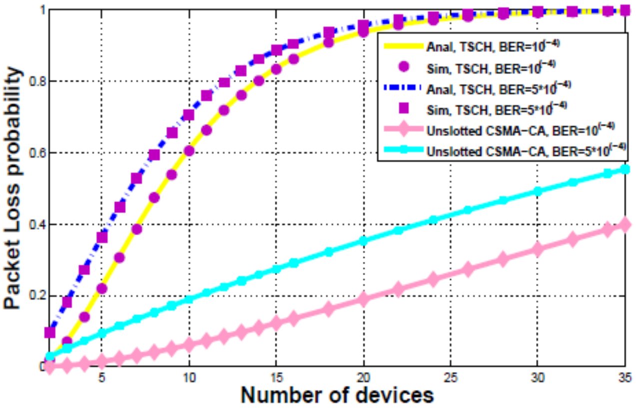
CSMA-CA. The reason is that, in Unslotted CSMA-CA, the range of choosing the back-off number is [0,7], [0,15], [0,31],..., which reduces the collision probability. Whereas in TSCH-CA, Back-off $\in [0,1],[0,3],[0,7],...$

Figure 12 Retransmission probability versus network size according to channel conditions



In Figure 13, we analyse the packet loss probability according to the number of devices under different BER values. As we have mentioned in Figure 6, packet loss probability is highly related to collisions and/or errors. Hence, this figure has the same behaviour as Figure 12.

Figure 13 Packet loss probability versus network size according to channel conditions



In Figure 14, we note that the reliability of TSCH-CA is less important than that of the Unslotted CSMA-CA. This is due to the packet loss probability which is greater in TSCH-CA compared with that of Unslotted CSMA-CA.

In Figure 15, we remark that the energy consumption is small for both TSCH-CA and Unslotted CSMA-CA when the number of devices and the BER values are lower and increases with the increase of these latter. Because, as explained previously, when the retransmission probability grows due to collisions and/or errors, the device tries more times for the transmission of a data packet, thus consuming more energy. In addition, we notice that the curves obtained by TSCH-CA are above those obtained by Unslotted CSMA-CA, that is because the retransmission probability of TSCH-CA is greater than that of Unslotted CSMA-CA.

Figure 14 Reliability versus network size according to channel conditions

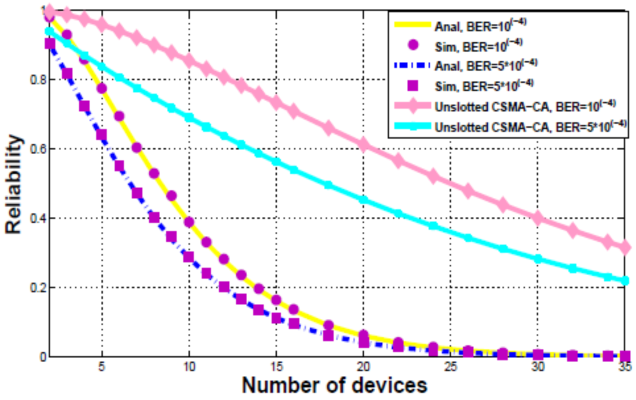
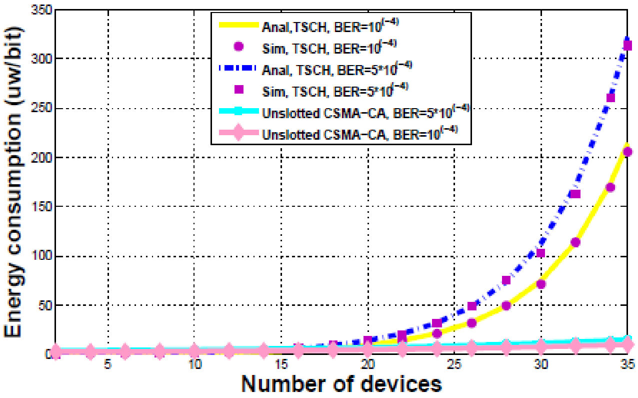
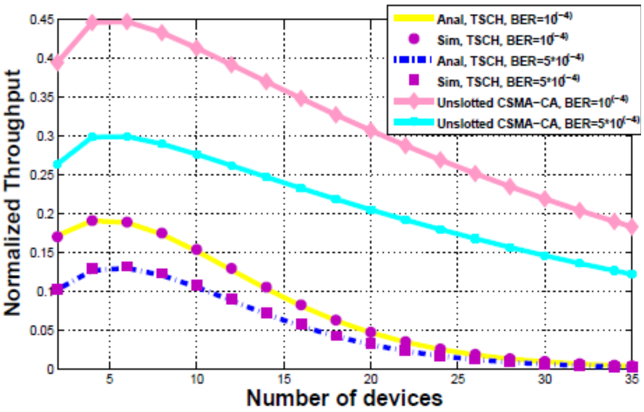


Figure 15 Energy consumption versus network size according to channel conditions



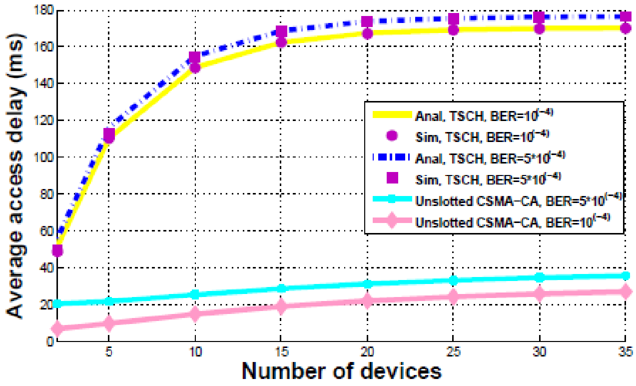
In Figure 16, we analyse the throughput variation as functions of the network size and different BER values. We observe that the throughput of TSCH-CA and Unslotted CSMA-CA increases with less number of devices and lower BER value and decreases with the increase of these latter. From this, we can conclude that the throughput is affected by collisions and errors and this is why, the throughput achieved by TSCH-CA is lower than that achieved by Unslotted CSMA-CA.

Figure 16 Normalised throughput versus network size according to channel conditions



In Figure 17, the average access delay of both TSCH-CA and Unslotted CSMA-CA increases with the increase of the number of devices and BER values. Nevertheless, the average access delay is significantly smaller in Unslotted CSMA-CA, because the retransmission probability is lower.

Figure 17 Average access delay versus network size according to channel conditions



6 Conclusion

The main objective of this work is to develop an analytical model based on discrete time Markov chain for modelling the behaviour of the IEEE 802.15.4e TSCH-CA Algorithm, taking into account the channel errors in the industrial wireless sensor networks. We have studied the case where only shared links are used, i.e., the worst case. Therefore, based on the proposed model, we have derived the expressions for some performance metrics, such as: retransmission probability, data packet loss rate, reliability, normalised throughput, energy consumption, and average access delay; and we have analysed their variation for different number of devices sharing the link according to channel conditions. We have also provided a comparative study between IEEE 802.15.4 Unslotted CSMA-CA and IEEE 802.15.4e TSCH-CA under a non-ideal channel. Our results have shown that the considered performance metrics are clearly affected by the channel errors. Finally, the accuracy of this model has been validated using the Monte Carlo simulations. As future work, we aim to extend our proposed model by taking into account the dedicated links and other rules of the algorithm, under an ideal and a non-ideal channel. It is also important to propose an enhancement of the TSCH-CA algorithm in order to achieve better performances when using only shared links.

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