Performance modeling of the IEEE 802.15.4e TSCH CSMA-CA algorithm under non-ideal channel

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Introduction

The TSCH mode was created by IEEE 802.15.4e for wireless devices of IEEE 802.15.4 to support a wide range of industrial applications and, more precisely for the process automation [1]. TSCH operates in non beacon mode, it combines time slotted access with channel hopping, that is to say, an hybrid of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) [2]. TSCH is also an independent topology, it can be used with any network topology from a star to a full mesh. In a TSCH scheme, the notion of the superframe used in IEEE 802.15.4 is substituted by a slotframe (Fig.1) and a Link is defined as a pairwise assignment of a directed communication between devices in a specific slot, with a given channel offset [3].

- -> **t** slot in the slotframe.
- -> **chOf** channel offset.

Furthermore, the 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 TSCH scheduling is given in Fig.(2).

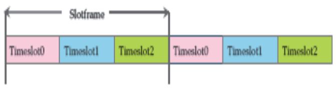

Figure 1. Example of a TSCH Slotframe with three timeslots.

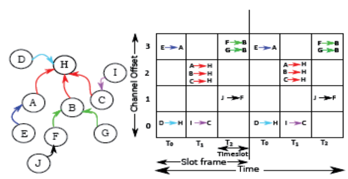

Figure 2. Example of a TSCH scheduling with three timeslots and four channel Offsets in one slotframe.

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 no receiving the acknowledgment (ACK) frame. To reduce the probability of repeated collisions, the TSCH CSMA-CA retransmission backoff algorithm, also known as "TSCH Collision Avoidance (TSCH-CA)" has been developed by IEEE 802.15.4e standard.

Since the successful advent of the IEEE 802.15.4e standard, several researchers have evaluated the performances of the TSCH mode. We have remarked that the presented works have been investigated under the assumption of ideal wireless channel. In practice, however, the existence of noise in IWSNs that weakens and disturbs the radio signal and which affects wireless channels quality is unavoidable.

In this work, our objective is to present a performance analysis of the TSCH CSMA-CA algorithm under a noisy environment and when only shared links are used.

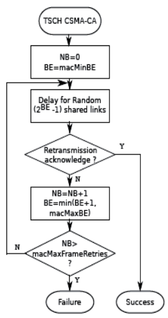

Figure 3. TSCH CSMA-CA Algorithm in shared links

Markov Chain Model

We study the behavior of an individual device using TSCH-CA algorithm, under non ideal channel with a new two-dimensional discrete time Markov chain model, Fig.(4). We compute the Packet transmission probability 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.

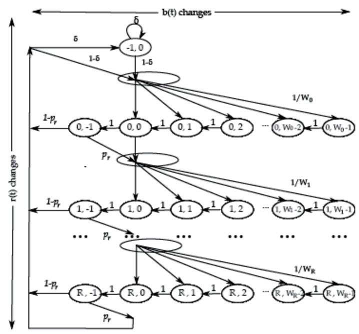

Figure 4. Markov chain model of the TSCH-CA algorithm under non-ideal channel

We introduce the following two stochastic processes:
Let **r(t)** be the stochastic process representing, at a given time t, the backoff stage for a given device. Let **b(t)** be the stochastic process representing, at a given time t, the backoff time counter. Their values are given as follows:
r(t) = (0.. R) and b(t) = (-1..W_i-1), where i ∈(1.. R)
R = macMaxFrameRetries $W_i = 2^i W_0$ and $W_0 = 2^{MacMinBE} - 1$.

- 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 transition probabilities of our Markov chain are
Listed as follows:

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

Let $\pi_{i,j} = \lim_{t\to\infty}(P(r(t)=i, b(t)=k)$ be the stationary distribution of our Markov chain model for $i \in (-1,R)$

The stationary probabilities are expressed as follow:

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

$$\pi_{i-1,0}.P_r = \pi_{i,0}. \quad (5)$$

$$\pi_{i,0} = P_r^i.\pi_{0,0}, 0 \le i \le R. \quad (6)$$

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

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

According to the normalization condition, we have:

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

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

Throughput

First, we give the fundamental parameters of throughput, Thr:
- The transmission probability:

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

- The successful data transmission probability:

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

- The time duration for a successful transmission of the data packet:

$$T_s = T_p + T_h + t_{ack} + T_{ack}.$$

- The time duration for an unsuccessful of the data packet:

$$T_c = T_p + T_h + t_{ack-to}.$$

Finally, the normalized throughput **Thr** can be computed as follows:

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

Conclusion

The main objective of this work is to develop an analytical model based on discrete time Markov chain for modeling the behavior 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, e.i., the worst case scenario. Therefore, based on the proposed model, we have derived the expression of the throughput.

References

[1] IPW Group et al. Part 15.4: Lowrate wireless personal area networks (LRWPANs) amendment 1: Mac sublayer. IEEE Standard for Local and metropolitan area networks IEEE Std 802.15. 4e-2012, 2012.

[2] Celia Ouanteur, Djamil A□ssani, Louiza Bouallouche-Medjkoune, Mohand Yazid, and Hind Castel-Taleb. Modeling and performance evaluation of the IEEE 802.15. 4e LLDN mechanism designed for industrial applications in WSNs. Wireless Networks, 23(5):1343-1358, 2017.

[3] D.De Guglielmo, B. Al Nahas, S. Duquennoy, T. Voigt, and G. Anastasi. Analysis and experimental evaluation of IEEE 802.15.4e TSCH CSMA-CA algorithm. IEEE Transactions on Vehicular Technology, 66(2):1573-1588, Feb 2017.