Applying data fragmentation in IEEE 802.15.4: modeling and analysis under unsaturated traffic

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The IEEE 802.15.4 standard, which is developed for low rate applications, offers low latency and energy consumption for wireless sensor networks. The use of the standardized slotted Carrier Sense Multiple Access (CSMA/CA), as a channel access mechanism, can, however, lead to a wastage of the bandwidth utilization and an additional transmission delay. This drawback is mainly caused by deferred transmission in the CSMA/CA algorithm at the end of the superframe, when there is not sufficient time to complete the frame transmission. We propose in this paper to fragment a data frame into a short frame and attempt its transmission in the current frame and transmit the remaining frame in the next superframe. The data fragmentation mechanism is modeled using a Markov chains. A non-saturated traffic and acknowledgement transmission are considered in our analysis. The analytical results of the normalized throughput demonstrate the improvement of the bandwidth occupation when using the proposed data fragmentation mechanism in the IEEE 802.15.4 slotted CSMA/CA protocol.

IEEE 802.15.4 slotted CSMA/CA, data fragmentation, Markov chains, Modeling and Analysis.

1. INTRODUCTION

Before the development of the IEEE 802.15.4 standard, several standards offering high data rates were proposed for local and personal wireless area networks (IEEE 802.11, IEEE 802.15.1, etc.). Such standards were not, however, adapted to miniature devices with limited energy capacities. The IEEE 802.15.4 (IEEE std 802.15.4 (2006)) standard was developed and proposed for Low-Rate Wireless Personal Area Networks (LR-WPANs) with low energy resources, such as wireless sensor networks. The IEEE 802.15.4 defines the specifications of the physical layer and the Medium Access Control (MAC) sublayer of the ZigBee stack. In the MAC sublayer, the IEEE 802.15.4 standard defines two access modes: non-beacon mode and beacon mode. In the non-beacon mode, unslotted CSMA/CA is used for attempting the channel access. However, slotted CSMA/CA algorithm is used in the beacon mode. In the beacon mode, the mode considered in this work, the coordinator sends regularly beacons frames to delimitate the superframe and to synchronize the wireless sensors in the Personal Area Network (PAN). The superframe contains an active period (for communication) and an inactive period (for energy conservation). The active period includes a Contention Access Period (CAP) and an optional Contention Free Period (CFP) for deterministic channel accesses. During the CAP period, the slotted CSMA/CA algorithm is executed by each node desiring to access the channel.

Several researchers have modeled the slotted CSMA/CA protocol with the Markov chains, by referring generally to the Bianchi's model (Bianchi (2000)). A simple model of the slotted CSMA-CA protocol is given by (Pollin et al (2008)) using Markov chains. A generalized Markov chain of IEEE 802.15.4 slotted CSMA/CA is given by (Park et all (2013)). The deferment of the transmission, when there is not sufficient remaining time in the CAP to complete the transmission, is modeled and evaluated by (Rehman et al (2011)).

In IEEE 802.11 standard, the fragmentation technique is implemented and many studies have mentioned that this technique improves the network throughput (see, the works of IEEE Part 11 (2007), Yazid et al (2013) and Li et al (2009)). The authors, in Yoon, Kim and Ko (2007), have proposed the fragmentation mechanism in IEEE 802.15.4 wireless sensor network to improve the bandwidth utilization. However, in this work, the risk of data collisions is possible when a competitive node pulls a backoff number equal to zero while the transmitter node attempts to send the remaining frame, in the beginning of the superframe.

This paper talk about the problem of the deferred transmission that causes a significant bandwidth loss in IEEE 802.15.4 wireless sensor networks. For this reason, we propose to send a short frame (equal to 18 bytes as defined by IEEE 802.15.4 standard) when a long frame can not be sent due to an insufficient time in the current superframe. The data fragmentation mechanism is modeled, under non saturation traffic with transmission's acknowledgment, using a Markov chain. The analytical results show that the fragmentation mechanism clearly allows improving the network performance in terms of throughput.

The remainder of this paper is organized as follows. Section 2 gives an overview of the slotted CSMA/CA. Section 3 presents our motivations for this work and describes the applied data fragmentation mechanism in IEEE 802.15.4 slotted CSMA/CA algorithm. Section 4 presents the proposed mathematical model based on Markov chains of IEEE 802.15.4 standard with the proposed data fragmentation mechanism. Section 5 gives a comprehensive performances analysis of our proposal. Finally, we conclude in Section 6.

2. OVERVIEW OF IEEE 802.15.4 SLOTTED CSMA/CA

In this section, we describe the behavior of the IEEE 802.15.4 slotted CSMA/CA protocol. Each node aiming to transmit a data frame or a control frame, as indicated in IEEE 802.15.4 standard, initializes three variables (NB, BE and CW). The variable NB describes the number of times that the CSMA/CA algorithm is executed for attempting to access the channel (i.e. Number of Backoff). The variable BE is used to generate a random backoff duration that a node shall wait before attempting the first carrier sensing (i.e. Backoff Exponent), its value depend on the value of BLE (Battery Life Extension) sent by the PAN coordinator. The variable CW indicates the number of time that a channel must be clear before beginning the data transmission (i.e. Contention Window). Its value is set to two, as shown in figure 1.

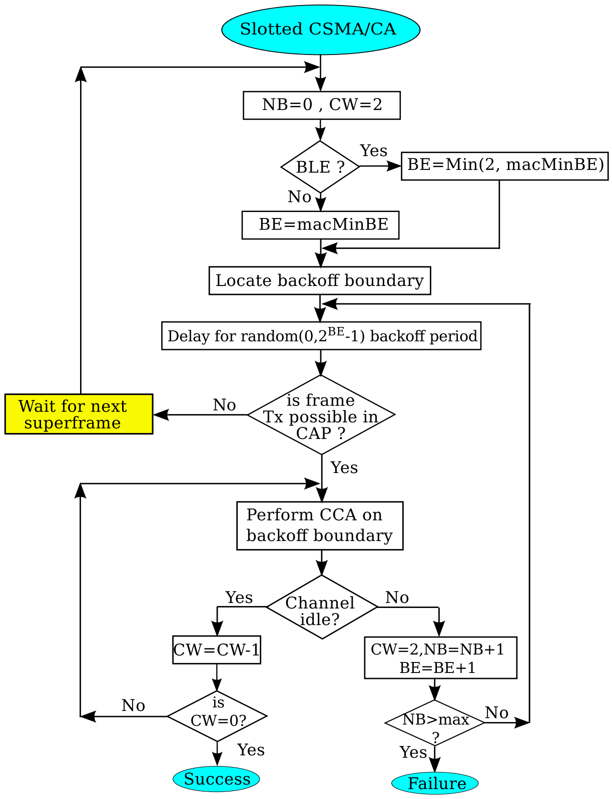

Figure 1: *Flowshart of IEEE 802.15.4 slotted CSMA/CA algorithm*

Once the three variables are initialized, the node waits during a period of backoff randomly chosen in the range $[0, 2^{BE} - 1]$. If the pulled number is greater than the remaining number of backoff periods in the CAP, the MAC sublayer shall pause the backoff countdown at the end of the CAP and resume it at the start of the CAP in the next superframe.

At the expiration of the random backoff delay, the MAC sublayer ensures that the remaining CSMA/CA operations can be undertaken and the entire transaction can be completed before the end of the CAP. Two cases are possible:

Case 1: The remaining time in the CAP is sufficient:

The MAC sublayer requests the physical layer to perform two CCA:

1. The channel is assessed to be busy during one of the CCA: both NB and BE are incremented by one (BE shall be no more than $macMaxBE$), CW is reset to two. If NB is less than or equal to $macMaxCSMABackoffs$, which is equal to 4 by default, a new BE is pulled randomly in the range $[0, 2^{BE} - 1]$. If NB is greater than $macMaxCSMABackoffs$, the CSMA/CA algorithm shall terminate with a channel access failure status.

2. The channel is assessed to be idle during the first CCA: CW is decremented by one and checked whether it is equal to zero.
   The same procedure is considered for the second CCA, If CW is equal to zero, the data frame is transmitted.

Case 2: The remaining time in CAP is insufficient:
The transmission will be deferred to the next superframe and a new slotted CSMA/CA is executed at the beginning of the CAP, as depicted on the yellow rectangle of the Figure 1

3. MOTIVATIONS AND PROPOSAL

In this section, we give our motivations behind applying the data fragmentation mechanism in IEEE 802.15.4 slotted CSMA/CA protocol. Then, we describe our solution and we give its main interest in the IEEE 802.15.4 wireless sensor networks.

3.1. Motivations

Given the critical nature of the applications in which the sensor networks are applied, it is important to optimize the use of all resources (bandwidth, battery, ...) together with the time of communication. As explained in the section 2, a node using slotted CSMA/CA to transmit a data frame must estimate the remaining time in the ion, it sends the frame, otherwise it differs the transmission for the new superframe (see figure 2).

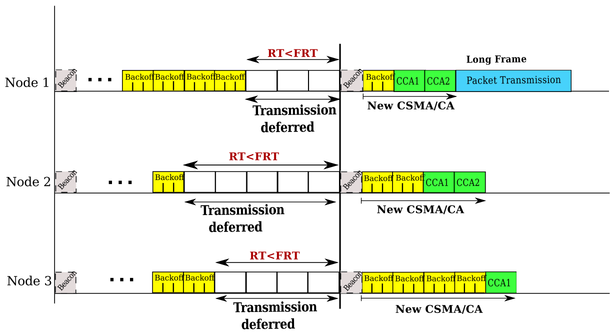

***Figure 2:** Deferred transmission in Slotted CSMA/CA*

The delay caused by the deferred transmission of a data frame increases more when the size of a packet increases. The long frame and the frequent deferments lead to a bandwidth misuse. These problems can be avoided by applying the data fragmentation mechanism. Thus, a rational management of the bandwidth and a minimum time of transmission will be achieved.

3.2. Slotted CSMA/CA with data fragmentation

IEEE 802.15.4 describes two types of data frames: a long frame (greater than 18 bytes) and a short frame (less than or equal to 18 bytes). In our work, we propose to add the following test in the slotted CSMA/CA algorithm: before deferring the transmission of a long frame due to insufficient remaining time in the CAP period, slotted CSMA/CA checks if the remaining time is sufficient to complete the transmission of a short frame. In this case, the rest of the frame will be transmitted in the new superframe.

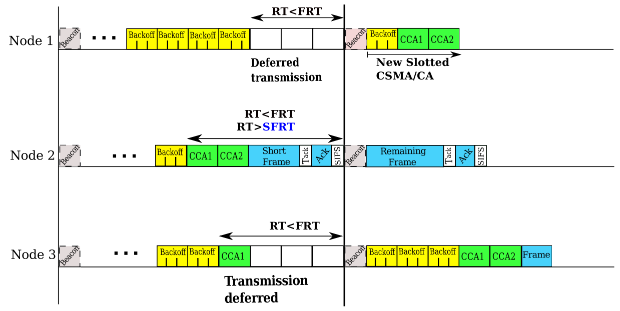

***Figure 3:** Applying data fragmentation in Slotted CSMA/CA*

Figure 3 shows that the data fragmentation increases the bandwidth occupation and reduces the data transmission time. To ensure the transmission of the remaining frame without collision, at the beginning of the superframe, our technique avoids the channel listening (CCA1 2 and CCA) for the node which transmitted a short frame in the previous superframe.

4. ANALYTICAL MODEL

In this section, we model and analyze the proposed data fragmentation mechanism in the IEEE 802.15.4 with acknowledgment of the transmitted data under unsaturated traffic conditions. We assume N nodes connected with a PAN coordinator in a star topology.

4.1. Markov chain model

In the following, we model the behavior of a single node using IEEE 802.15.4 slotted CSMA/CA with the data fragmentation mechanism, using a three dimensional Markov chain in order to analyze the network performances. Three stochastic processes are used to describe the state of the node at each time when executing slotted CSMA/CA with data fragmentation mechanism.

Let $S(t)$, $B(t)$ and $T(t)$ be the stochastic processes representing the backoff stage, the state of the backoff counter and the packet type to transmit at time t, respectively. Their values are given as follows: $S(t) = (0..m)$, $B(t) = (-2..W_i - 1)$ and $T(t) = \{-1, 0, 1, 2\}$, where $m = macMaxCSMABackoffs$, and $W_i = 2^i W_0$, the initial value of $W_0 = 2^{BE} - 1$, where the value of BE is defined in figure 1. We note that, the backoff counter $B(t)$ is divided into two periods, the backoff period pulled between $\{0, 2^{BE}\}$ and the second period represent the two clear channel assessment (CCA) periods (-2 and -1).

The *Idle* state in figure 4 indicates wether the node has a data frame to transmit. In other words, this state models the queue of a node. To satisfy the condition of non-saturated network (i.e. a node has not always a frame to transmit), we consider that the events arrive to the nodes according to the poisson process with the rate λ. Hence, the probability q that a data packet (event) arrives to a node during one backoff period Ts is given as follows:

$$q = \int_0^{Ts} \lambda e^{-\lambda t} \mathrm{d}x \quad (1)$$

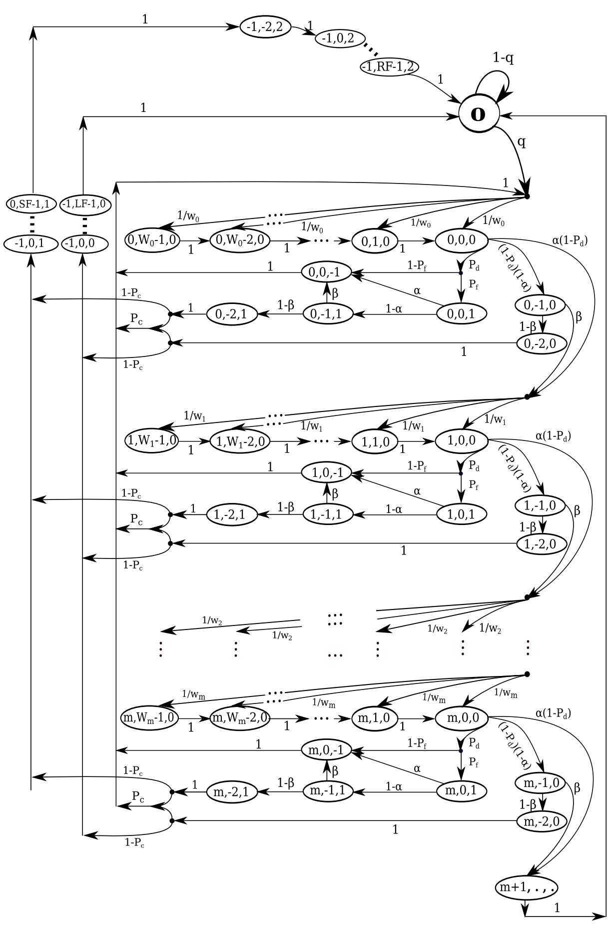

__Figure 4:__ Markov chain model for Slotted CSMA/CA with fragmentation

The transition probabilities associated with the Markov chain of figure 4 are:

$$P(i,k,j|i,k-1,j) = 1, \quad k \geqslant 0 \quad (2)$$

$$P(i,-1,j|i,0,j) = (1-\alpha)\Big[(1-P_d) + P_d P_f\Big], \quad j = \{0,1\}, i \leqslant m \quad (3)$$

$$P(i,-2,j|i,-1,j) = 1-\beta, \quad j = \{0,1\}, \quad i \leqslant m \quad (4)$$

$$P(i,k,j|i-1,0,j) = (1-P_d)\frac{\alpha + (1-\alpha)\beta}{W_i}, \quad i \leqslant m \quad (5)$$

$$P(0,k,0|i,0,0) = \frac{P_d}{W_0}[(1-P_f) + P_f[\alpha + (1-\alpha)\beta]], \quad j = \{0,1\}, i \leqslant m \quad (6)$$

$$P(i,0,1|i,0,0) = P_d P_f, \quad i \leqslant m \quad (7)$$

$$P(0,k,0|Idle) = \frac{q}{W_0}, k \geqslant 0 \quad (8)$$

Equation (2) defines the decrement probability of the backoff counter. Equation (3) and (4) describes the probability to find the channel idle for the first CCA and second CCA, respectively. Equation (5) denotes that the channel is busy, the node in this case selects a new delay backoff in the new stage. Equation (6) represent the probability to defer the transmission to the next superframe when the remaining time in the CAP is either insufficient to transmit a packet or a fragment, or the fragmentation is possible but the channel is busy. Equation (7) describes the possibility of fragmentation when the remaining delay of CAP is not enough to assure a successful transmission of the original frame. The probability to pull a data frame in the queue of a node to transmit is given in the equation (8).

Let $b_{i,k,j} = \lim_{t\to+\infty} P\{S(t) = i, B(t) = k, T(t) = j\}$, be the stationary distribution of our Markov chain.

Using equation (5), we get the probability to find a node in any stage at the steady state:

$$b_{i,0,0} = \Big[(1-P_d)\Big[\alpha + (1-\alpha)\beta\Big]\Big]^i b_{0,0,0}, \quad for\ 1 \leqslant i \leqslant m \quad (9)$$

The probability to be in any state of the first stage is given as follows:

$$b_{0,k,0} = \frac{W_0 - k}{W_0}\Big[\Big[(1-\alpha)(1-\beta)(1-P_d)\Big]\sum_{i=0}^{m} b_{i,0,0} + (1-P_d)\Big[\alpha + (1-\alpha)\beta\Big] b_{m,0,0}\Big] \quad (10)$$

The probability to be in any backoff state in any stage is given by:

$$b_{i,k,0} = \frac{W_i - k}{W_i} b_{i,0,0}, for 1 \leqslant i \leqslant m, 1 \leqslant k \leqslant W_i - 1 \quad (11)$$

In the normalization conditions, the probabilities must sum to 1. So:

$$\begin{aligned} 1 &= \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k,0} + \sum_{i=0}^{m}\sum_{k=-2}^{-1} b_{i,k,0} + \sum_{i=0}^{m}\sum_{k=-2}^{0} b_{i,k,1} \\ &+ \sum_{i=0}^{m} b_{i,0,-1} + \sum_{k=0}^{LF-1} b_{-1,k,0} + \sum_{k=0}^{SF-1} b_{-1,k,1} \\ &+ \sum_{k=0}^{RF-1} b_{-1,k,2} + b_{Idle}. \end{aligned} \quad (12)$$

Therefore, the formula of $b_{0,0,0}$ is given as follows :

$$ab_{0,0,0} = \frac{1}{\left[\frac{3}{2} + P_d P_f(2-\alpha) + (1-\alpha)(1-P_d) - x \right.} \\ \overline{+(1-P_c)(1-\alpha)(1-\beta)\Big[(1-P_d)(1+LF)} \\ \overline{\left.+P_d P_f(SF + RF + \frac{1}{q})\Big]\right] \frac{1-x^{m+1}}{1-x} + \frac{x^{m+1}}{q}} \\ \overline{+\frac{1-(2x)^{m+1}}{2(1-2x)} w_0}, \quad (13)$$

where, $x = (1-P_d)\big[\alpha + (1-\alpha)\beta\big]$ and LF, SF, and RF represent, respectively, a longue frame, a short frame (fragment) and a remaining frame. The probability that a node attempts to sense the channel for the first time (τ) in any stage of the Markov chain is expressed as follows:

$$\tau = \sum_{i=0}^{m} b_{i,0,0}. \quad (14)$$

To compute the performance of the network, we express all the probabilities in interaction with the probability τ.

A) *Probability* α: is the probability to find the channel busy during CCA1 due to data (or acknowledgment) frame transmission. Similarly to Park et all (2013), we express this probability as follows:

$$\alpha = \big[1-(1-\tau)^{N-1}\big](1-\alpha)(1-\beta)\Big[T + T_{ACK}\frac{N\tau(1-\tau)^{N-1}}{1-(1-\tau)^N}\Big], \quad (15)$$

where T and T_{ACK} represent the number of backoff delay required for the frame transmission and the acknowledgment frame, respectively.

B) *Probability* β: is defined as the probability to find the channel busy in the CCA2, given that it is free in the CCA1 period.

$$\beta = \frac{1-(1-\tau)^{N-1} + N\tau(1-\tau)^{N-1}}{2-(1-\tau)^N + N\tau(1-\tau)^{N-1}}. \quad (16)$$

C) *Probability of deferment (P_d)*: is defined as the probability that the remaining time in the CAP is not sufficient to complete the transmission of a data frame and its acknowledgment. Hence, after the completion of the backoff decrementation, the current time of the node must be in the interval $]CAP - T_{LF} + 2 * T_{cca} + T_{ack\_wait} + T_{ACK}, CAP]$ to defer the transmission. This interval is illustrated by the blue stripes part as shown in the figure 5.

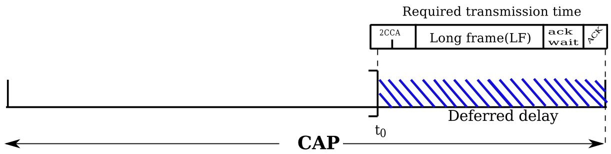

Figure 5: *Insufficient remaining time in CAP for a complete transmission*

The probability of deferment is formulated by the following expression:

$$P_d = \frac{T_{LF} + 2 * T_{cca} + T_{ack\_wait} + T_{ACK} + \varepsilon}{T_{CAP}}, \quad (17)$$

where T_{ack_wait} is the time to wait before beginning the ACK transmission. While ε is introduced in the equation (17) to indicate that the time, in the CAP, to complete the frame transmission is insufficient.

D) *Probability of fragmentation (P_f)*: is the probability to find, in the remaining time of the CAP, sufficient time to transmit a short frame and any acknowledgment. Assuming that when the backoff counter of a sensor is zero its current time is in the interval $]T_{CAP} - T_{LF} + 2 * T_{cca} + T_{ack_wait} + T_{ACK}, T_{CAP} - T_{SF} + 2 * T_{cca} + T_{ack\_wait} + T_{ACK}]$, the blue stripes in figure 6. In this case, the data fragmentation is applied. Otherwise, the fragmentation is not possible and the data transmission will be deferred to the next superframe, as depicted by the red stripes in figure 6.

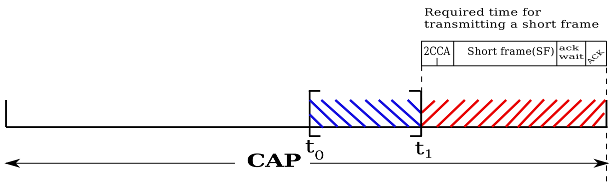

Figure 6: *Possibility of fragmentation in the CAP*

The probability of fragmentation is given in the following expression:

$$P_f = \frac{T_{LF} - T_{SF} + \varepsilon}{T_{CAP}}, \quad (18)$$

where ε is introduced in equation (18) to express the impossibility of transmitting the original frame (LF).

4.2. Throughput

The unsaturation throughput (noted S), as defined in Bianchi (2000), as the fraction of time that the channel is used to successfully transmit the data frame. Therefore, S depends, on the following probabilities:

A) *Transmission probability* (P_{tr}): represents the probability that at least one node (among N nodes) is in the beginning of the first clear sensing (CCA1) with probability τ, the channel sensed free in CCA1 and CCA2 and the transmission will not be deferred.

$$P_{tr} = \left[1 - (1-\tau)^n\right](1-\alpha)(1-\beta)(1-P_d). \quad (19)$$

B) *Successful transmission probability* (P_s): is the probability that exactly one transmission occurred in the channel, conditioned by the transmission probability (as defined in Bianchi (2000)).

$$P_s = \frac{n\tau(1-\tau)^{n-1}(1-\alpha)(1-\beta)(1-P_d)}{P_{tr}}. \quad (20)$$

Now, we can express the unsaturation throughput (S) as follows:

$$S = \frac{P_{tr}P_sT_{pload}}{(1-P_{tr})\sigma + P_{tr}P_sT_s + (1-P_s)T_c + P_d(1-P_f)T_{Def}}. \quad (21)$$

where, T_{pload} is the time occupied by the packet transmission, σ is the duration of an empty time slot, T_s is the time of a successful transmission of a packet, T_c is the time during which the channel is busy due to a collision and T_{Def} is the average time wasted when deferring the current transmission.

$$\begin{cases} T_s = & T_{PHY} + T_{MAC} + T_{pload} + 2T_{CCA} + T_{LIFS}, \\ & +T_{ack} + T_{ACK}. \\ T_c = & T_{PHY} + T_{MAC} + T_{pload} + 2T_{CCA} + T_{LIFS}, \\ & +T_{ack}. \\ T_{Def} = & \dfrac{T_{SF} + T_{PHY} + T_{MAC} + T_{SIFS} + 2T_{cca}}{2} \\ & + \dfrac{T_{ack} + T_{ACK} - \varepsilon}{2}, \end{cases} \quad (22)$$

where ε indicates that there is not sufficient time to complete the short frame transmission in the current superframe.

5. ANALYTICAL RESULTS

In this section, we evaluate the performance of the data fragmentation mechanism in improving the network throughput. The analytical parameters taken into account in the performance analysis are presented in table 1.

Table 1: *Analytical parameters*

Parameters	Initial Value
Max packet length	127 Bytes
Max packet transfert delay	4 ms
Radio transmission power	52.2 mw
Radio reception power	59.1 mw
Radio idle power	1.28 mw
Battery Capacity	2500 mAh
Voltage	3.0 V

Figure 7 shows the results of network throughput for 10 nodes under different traffic load. It illustrates the throughput improvement using the data fragmentation mechanism (IEEE 802.15.4 Frag), comparing it with IEEE 802.15.4 standard (IEEE 802.15.4). We show that when the length of the original frame is just greater than the short frame ($L = 3$ slots and $shortframe = 2$ slots) the gain is not large enough. However, when increasing the frame size, the gain in throughput becomes very important (see the case of $L = 7$ slots).

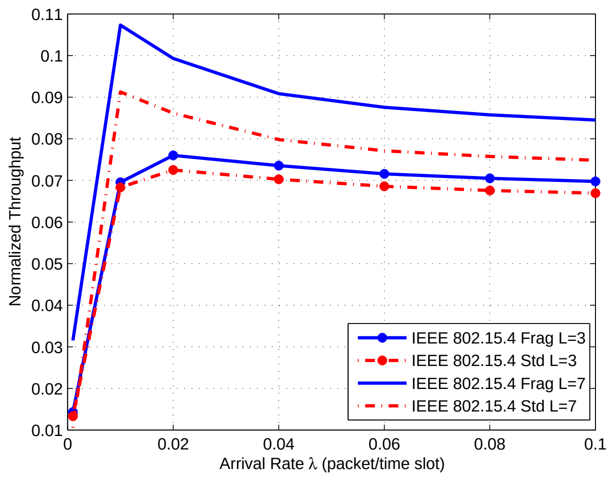

Figure 7: *Throughput versus traffic load with number of nodes = 10*

Figure 8 illustrates the cases of a dense network (number of nodes = 50). When the frame is long ($L = 7$ slots) and the traffic load (λ) is less than $0,01$, the network throughput is better than when using a small frame ($L = 3$ slots), independently from considering or not the fragmentation mechanism. However, when the traffic load increases, it causes frequent collisions and deferred transmissions. That is why, the small frames give better results. In all cases, we show that, the data fragmentation mechanism offers a better throughput.

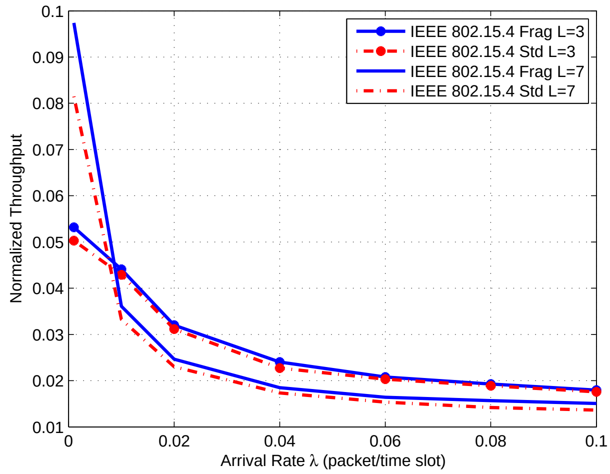

Figure 8: *Throughput versus traffic load with number of nodes = 50*

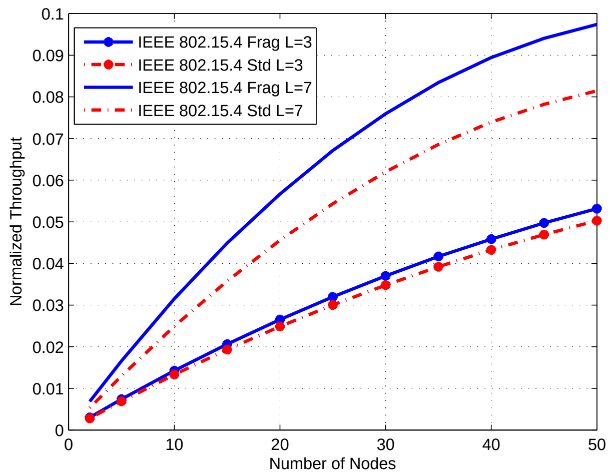

Figure 9: *Throughput versus number of nodes with* $\lambda = 0,001$

Figure 9 clearly shows the contribution of the data fragmentation mechanism, when the network traffic is low ($\lambda = 0,001$). The difference between the throughput of the IEEE 802.15.4 with the proposed fragmentation mechanism and the IEEE 802.15.4 standard becomes clear when the frame length increases.

we presented a Markov chain-based model of the slotted CSMA/CA protocol, which includes data fragmentation mechanism. Using the proposed model, we have evaluated the system performance in term of throughput under non saturated traffic with acknowledgment. The results shows the interests in applying the data fragmentation mechanism in the IEEE 802.15.4 standard.

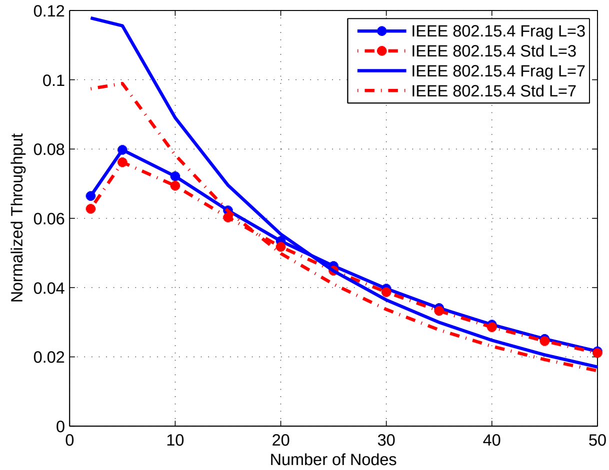

Figure 10: *Throughput versus number of nodes with* $\lambda = 0,05$

In the figure 10, we analyzed an average traffic ($\lambda = 0,05$) to see the contribution of the data fragmentation mechanism when the number of nodes increases. The throughput decreases when the number of nodes increases, due to collisions and frequent transmission deferrement.

6. CONCLUSION

In this paper, the data fragmentation mechanism is proposed to be applied in IEEE 802.15.4 slotted CSMA/CA protocol. The principle of the mechanism is simple to implement, without changing the operating principles of IEEE 802.15.4 slotted CSMA/CA. The data fragmentation is applied when the transmission of a long frame is impossible due to insufficient remaining time in the contention access period. Our proposal privileges the transmission of the remaining frame in the new superframe and avoid its collision. In our future works, we will evaluate the impact of other parameters on the overall network performance and we will analyze how to improve the energy consumption using the data fragmentation mechanism.

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