PREDICTING COMMUNICATION DELAY AND ENERGY CONSUMPTION FOR IEEE 802.15.4/ZIGBEE WIRELESS SENSOR NETWORKS

Sofiane Ouni[1] and Zayneb Trabelsi Ayoub[2]

[1] National Institute of Applied Sciences and Technology (INSAT),Tunisia
Sofiane.ouni@insat.rnu.tn
[2] University of Manouba, National School of Computer Science (ENSI), RAMSIS-CRISTAL, Tunisia
trabelsizayneb@yahoo.fr

ABSTRACT

The Wireless Sensor Networks (WSN) particularly for real time applications raise fundamental problems for the scientific community. These problems are related to the limit of energy resource and the real time constraints on the communication delay. The well functioning of such networks depends mainly on the network lifetime result of nodes energies and the communication delay which should meet the required deadlines. Thus, the well design of Real-Time Wireless Sensor Networks must be with the prediction of the energy consumption and the communication delay. Therefore, this paper propose an analytical model to predict the lifetime and the delay in IEEE 802.15.4/ZigBee WSN. Our proposed model is based on realistic assumptions. It considers the most important network features such as idle times from the Backoff, overhearing and interferences by collisions and transmission errors. Compared to simulation results and other analytical approaches, our model gives a reliable lifetime and delay prediction.

KEYWORDS

Wireless Sensor Networks, IEEE 802.15.4, ZigBee, energy consumption, communication delay.

1. INTRODUCTION

Wireless Sensor Network (WSN) is deployed in many fields such as health care, environment control, intelligent, buildings, etc. It consists of a set of small and low-power devices called sensor nodes which interacts with their environment to sense physical phenomena. After being deployed on the area to monitor, these nodes are capable of local processing, communication and self-organization. In fact, they collect environmental information and work together to transmit the data to one or more collection points (sinks) in an autonomous manner. The IEEE 802.15.4/Zigbee standard [14] aims to allow the interconnection of wireless devices with low autonomy (battery powered) and does not require high bit rate, this standard represents an ideal candidate for wireless sensor networks.

WSNs must operate at least for a given mission time, and simultaneously replacing nodes' batteries is often impossible. Hence, the lifetime prediction for WSNs becomes a major concern. For a reliable lifetime prediction, a complete energy consumption analysis is necessary. Accordingly, it should consider the most important sources of energy consumption, namely transmitting and receiving data packets, listening to the channel, transmitting, receiving control packets and receiving packets from neighbours.

DOI : 10.5121/ijcnc.2013.5110

Furthermore, applying Wireless Sensor Networks in real-time context needs to predict the communication delay to meet given real-time constraints.

In this paper, we propose an analytical model based on IEEE 802.15.4 WSNs parameters. The energy consumption and the communication delay analysis are developed to predict the lifetime and the real-time constraints respect. Our model aims to give a realistic analysis in order to predict the network validity.

The reminder of the paper is organized as follows. Section 2 briefly describes IEEE 802.15.4 networks. In Section 3, we present the main related works according to energy consumption and communication delay analysis. Then, our proposed analytical model is presented in Section 4, where we give a complete and detailed energy consumption analysis. In Section 5, we present our analysis to determine the communication delay. The performance evaluation is given in Section 6. In the final section, we present the conclusions.

2. IEEE 802.15.4 NETWORKS

The IEEE 802.15.4 standard [7] was originally designed for personal area networks. Its application fields expand and diversify to touch wireless sensor networks thanks to several features. In fact, the IEEE 802.15.4 defines characteristics of the physical and data link layers for LR-WPAN (Low Rate Wireless Personal Area Network). The standard aims to allow the interconnection of wireless devices with low autonomy (battery powered) and does not require high bit rate.

2.1. Devices

There are essentially two types of device that can participate in IEEE 802.15.4 based networks which are the FFDs (Full-Function Devices) and the RFDs (Reduced-Function Devices). The FFD can operate in three modes serving as a personal area network coordinator (PAN coordinator), a coordinator, or a device. While a RFD can only be terminal equipment because it does not accept the association of other network devices and is usually placed at the end of the network. The PAN coordinator might often be mains powered, while the devices will most likely be battery powered.

2.2. Network topologies

The IEEE 802.15.4 based networks can operate in two topologies: the star topology or peer-to-peer topology. In the star topology, the communication is established between devices and a single central controller, called the PAN coordinator (considered as sink node). In peer-to-peer topology, nodes can communicate directly without going through the PAN coordinator. This topology allows for more complex networks because it allows the interconnection of multiple networks.

An example of the use of the peer-to-peer communications topology is the cluster tree which is used primarily in wireless sensor networks. In a cluster tree network, most devices are FFDs and only the leaf devices at the ends of the network are RFDs. The PAN coordinator forms the first cluster by choosing an unused PAN identifier then starts broadcasting beacon frames to its neighbours. By receiving the beacon frame, a candidate device wishing to join the network sends an association request to the PAN coordinator. If he accepts, he will add the new device as his child in its neighbours list. Therefore, the new device adds the PAN coordinator as his parent in its neighbour list. As the PAN coordinator, the new joined device begins transmitting periodic beacons and receiving association requests to allow other nodes to associate and to join the network.

3. RELATED WORKS: ENERGY CONSUMPTION AND DELAY ANALYSIS

Extending the network lifetime is a common objective of sensor networks research, since a sensor node has usually a limited energy source and is assumed to be disposed once it's out of battery.

The authors in [1, 2, 4, 6] analyzed the network lifetime for wireless sensor networks. The authors in [1, 6] considered that the energy cost of a node is the ratio of the total energy consumed over the initial battery energy. Thus, the total energy consumed by a node during the network lifetime should be less than its initial energy. According to this model, the total energy consumed includes the energy spent in transmission and reception of packets, sleeping and sensing. Thereby, they ignored significant sources of energy waste such as packet control overhead and collisions due to interference. The authors in [2, 4] considered that the lifetime of a node is the ratio of the initial amount of energy over the total consumed energy. Thus, maximizing the network lifetime means maximizing the lifetime of the greediest node in the network in term of energy consumption. However, the model proposed in [2] didn't take into account the amount of energy spent in retransmission of unsuccessful packets, which is a very important source of energy waste especially in the case of heavy traffic. The model proposed in [4] considered the energy waste due to retransmissions but didn't propose an analytical model to calculate the probability of unsuccessful transmission. Furthermore, the above mentioned studies didn't consider neither the amount of energy spent in overhearing nor the specificity of IEEE 802.15.4 sensor networks.

Concerning the communication delay analysis and prediction, most of the works [17, 18] interested on the GTS mode to predict the communication delay. So, in [17] use the (guaranteed time slots) GTS mode to get a stochastic model for guaranteed communication delay. Being optional, it is activated upon request from a node to the PAN Coordinator for allocating Guaranteed Time Slots (GTS) depending on the node's requirements. The inconvenient of this mode is the limit number of slots to reserve and it is a centralized medium access with high latency. For the CSMA/CA medium access, works are incomplete to get realistic context. For example, the paper [16] gives a simple analysis which not considers the interferences and transmission errors. It defines the transmission delay according to the frames lengths without the medium access control latency.

Hence, we are interested to propose a realistic analytical model to predict lifetime and communication delay in IEEE 802.15.4 sensor networks with better consideration to the networks and protocols features.

4. ENERGY ANALYTICAL MODEL

The main sources of energy consumption for a sensor node are:

- Transmitting and receiving packets.
- Overheads due to control packets: since control packets don't contain data, they are considered as overheads.
- Collisions: if a collision occurs, nodes must retransmit the same data so they consume more energy.
- Overhearing: when a node picks up packets that are destined to other nodes, it consumes more energy.
- Idle listening: listening to receive possible traffic can increase energy consumption.
- Depending on these resources, we get the parameters to estimate the delay and the energy.

4.1. Energy consumption and lifetime

Actually, the definition of the network lifetime depends on the application at hand. Indeed, it can be considered as [9]:

- The time until the first node fails (runs out of energy).
- The time until the network is disconnected in two or more partitions.
- The time until 50% of failed nodes.
- The moment when the first time a point in the observed area is no longer covered by at least a sensor node.

In all these cases, the lifetime is strongly dependent on residual energy. Accordingly, we focus on the energy consumption of nodes to evaluate their lifetime and consequently network lifetime. In our model, we assume the following properties:

1) Based on [6], the energy cost $C_i\,(t)$ of a node N_i at time t is the ratio of the total energy consumed at time t over the initial battery energy. It can be expressed as follows:

$$C_i(t) = \frac{Consumed\_Energy(t)}{Initial\_Energy} \tag{1}$$

2) Since energy levels are initially given with different values, we would like to normalize the calculation of the energy cost in the interval [0, 1]:

- $C_i(t) = 0$ means that the battery of the node N_i at time t is full.
- $C_i(t) = 1$ means that the battery of the node N_i at time t is depleted.

3) If the energy cost of the greediest node in term of energy reaches the value 1 at time t, we note that its battery is exhausted and this moment represents the network lifetime:

$$Lifetime = \left\{ t \,/ \underset{i \in network\_nodes}{Max} (C_i(t)) = 1 \right\} \tag{2}$$

In what follows, we will present our analytical model to predict the network lifetime. First, we will give energy consumption basic equations. Second, to propose a more realistic analytical model, we will consider an unreliable network. Third, we will consider, in our analysis, the main sources of energy consumption, namely overheads, idle-listening and overhearing.

4.2. Energy consumption basic equations

We consider that total energy consumed in unit time (equation 3) includes the energy spent in transmission (noted: *Etx*) and reception (noted: *Erx*) of data packets, in transmission and reception of control packets (noted: *Eoverhead*), in listening to the channel (noted: *Eidle*) and in reception of neighbours' packets (noted: *Eoverhearing*).

$$Consumed\_Energy = Etx + Erx + Eoverhead + Eidle + Eoverhrearing \tag{3}$$

Since each sensor node can generate its own traffic and forward traffic of other nodes, the energy spent by a node N_i in packet transmission in time interval [0, t] can be computed as the sum of the amount of energy consumed in sending its own traffic, in forwarding traffic of other nodes and in sending acknowledgements related to received packets to be forwarded (4).

$$Etx_i(t) = t \cdot P_{tx} \cdot \Big(\big(TtransPkt \cdot (g_i + f_i) \big) + \big(TtransAck \cdot f_i \big) \Big) \tag{4}$$

where P_{tx} is the power consumption in transmitting one packet, $TtransPkt$ is the transmission time of a data packet, $TtransAck$ is the transmission time of an acknowledgement, g_i is the packet generation rate (packet/second) for a node N_i and f_i is the packet forwarding rate (packet/second) by a node N_i. Similarly, the energy spent by a node N_i in packet reception in time interval [0, t] can be expressed as follows:

$$Erx_i(t) = t \cdot P_{rx} \cdot \left(\left(TtransPkt \cdot f_i \right) + \left(TtransAck \cdot \left(g_i + f_i \right) \right) \right) \quad (5)$$

where P_{tx} is the power consumption in receiving one packet, $TtransPkt$ is the transmission time of a data packet, $TtransAck$ is the transmission time of an acknowledgement, g_i is the packet generation rate (packet/second) for a node N_i and f_i is the packet forwarding rate (packet/second) by a node N_i.

4.3. Unreliable network issue

In CSMA/CA based networks, the packet transmission may fail due to several factors such as collisions, channel errors, etc. Therefore, we assume that we have $\overline{Nc}$ which is the average number of failed transmissions of a packet before being successfully transmitted. For IEEE 802.15.4, a maximum of retransmission is defined to be under aMaxFrameRetries after which the protocol terminates and a communications failure is issued [7]**.** Based on [4], the number $\overline{Nc}$ for a node N_i can be expressed as follows:

$$\overline{Nc}(N_i) = \frac{\beta(N_i)}{1 - \beta(N_i)} \quad (6)$$

Where $\beta(N_i)$ denotes the probability of unsuccessful transmission for a node N_i. To compute $\beta(N_i)$, we should consider the collision probability noted $P_{collision}(N_i)$ and the packet error probability noted $P_{error}(N_i)$ for a node N_i (7).

$$\beta(N_i) = P_{collision}(N_i) + P_{error}(N_i) \quad (7)$$

The collision probability for a node N_i is essentially due to interference from other nodes. If we define by $H(N_i)$ the set of nodes located in the neighbourhood of the node N_i. We prove that the interference probability for this node N_i with its neighbours is:

$$p_{collision}(N_i) = 1 - (1 - TtransPkt_i \cdot (g_i + f_i) + \sum_{j \in H(i)} TtransPkt_j \cdot (g_j + f_j))^2 \quad (8)$$

Where $TtransPkt_i$ is the transmission time of a data packet sent by a node N_i, g_i is the packet generation rate (packet/second) for a node N_i, f_i is the packet forwarding rate (packet/second) by a node N_i. As for the packet error probability for a node N_i, it can be expressed as follows:

$$P_{error}(N_i) = BER \cdot PKt_{size} \quad (9)$$

Where BER (Bit Error Rate) value is roughly 10^{-4} [5] and PKt_{size} is the size of the considered packet. Hence, considering the average number of failed transmissions ($\overline{Nc}$), the expression (4) of the energy spent in packet transmission in time interval [0, t] becomes:

$$Etx_i(t) = t \cdot P_{tx} \cdot \left(\left(\overline{Nc}(N_i) + 1 \right) \cdot \left(TtransPkt \cdot \left(g_i + f_i \right) \right) + \left(TtransAck \cdot f_i \right) \right) \quad (10)$$

Similarly, the expression (5) of the energy spent in packet reception in time interval [0, t] becomes:

$$Erx_i(t) = t \cdot P_{rx} \cdot \left(\left(\overline{Nc}(N_i) + 1 \right) \cdot \left(TtransPkt \cdot f_i \right) + \left(TtransAck \cdot \left(g_i + f_i \right) \right) \right) \quad (11)$$

4.4. Overheads issue

In addition to the energy spent in transmitting and receiving data packets, the sensor node consumes energy by sending and receiving control packets such as beacons and command frames.

Considering that *OverheadRate* is the average rate of control packets generation, *TtransOvPkt* is the transmission time of a control packet, P_{tx} is the power consumption in transmitting one packet and P_{rx} is the power consumption in receiving one packet, the amount of energy spent due to overheads in time interval [0, t] can be expressed as follows:

$$Eoverhead_i(t) = t \cdot \left(OverheadRate \cdot TtransOvPkt \cdot \left(P_{tx} + P_{rx} \right) \right) \quad (12)$$

4.5. Idle listening issue

The energy spent in listening to the channel is due to the waiting access channel periods.

We adapt listening to the channel equation of [4], which is intended for sensor networks based on IEEE 802.11 standard, to IEEE 802.15.4 standard. So the expression of the energy spent in listening to the channel in time interval [0, t] will be:

$$Eidle_i(t) = NumberPkt_i(t) \cdot CCA \cdot P_{idle} \cdot t_{slot} \quad (13)$$

Where P_{idle} is the power consumption in idle state, t_{slot} is the time of a slot, $NumberPkt(t)$ is the number of packets arriving before the time *t,* and *CCA* is clear channel assessment used by the station after the backoff to verify if the channel is clear or busy .

4.6. Overhearing issue

It is common that any packet transmitted by a node is received by all its neighbours even though only one of them is the intended receiver. This phenomenon is called overhearing. So the energy spent in overhearing depends on the traffic generation and forwarding rates (g_k,f_k) of neighbours ($H'(N_i)$). Thus, from (11) we have:

$$Eoverhearing(t) = t \cdot P_{rx} \cdot \sum_{k \in H'(N_i)} \left(\left(Nc(N_k) + 1 \right) \cdot \left(TtransPKt \cdot \left(g_k + f_k \right) \right) + \left(TtransAck \cdot f_k \right) \right) \quad (14)$$

where $H'(N_i)$ is the set of nodes located in the neighbourhood of the node N_i and transmitting traffic destined to other nodes, P_{rx} is the power consumption in receiving one packet, *TtransPkt* is the transmission time of a data packet, *TtransAck* is the transmission time of an acknowledgement, g_k is the packet generation rate (packet/second) for a node N_k and f_k is the packet forwarding rate (packet/second) by a node N_k.

5. DELAY ANALYTICAL MODEL

In this section, we use a holistic analysis [12, 13, 14, 15] in order to determine the communication delay or the response time in one hop (noted: R_i for message m_i) of the traffics. The response time is the accumulation of the waiting time in the queue (noted: W_i) and the service time (noted C_i). Hence:

$$R_i = C_i + W_i \quad (15)$$

In a network, a message m_i waits in the queue during W_i and then will be transmitted according to medium access protocol duration (as service time) of a C_i time. This response time (noted: R_i^k) of message m_i is determined according to a node N_k . We can deduce the global response time (noted: GR_i^k) of message m_i from the node N_k to the sink by the path $path_i$ (set of nodes) :

$$GR_i^k = \sum_{N_l \in path_i} R_i^l \quad (16)$$

5.1. Basic equations for reliable networks

We assume that all messages have the same size and consequently the same time service.

According to the IEEE 802.15.4 standard [7], the MAC sub-layer needs a period of time to process data received by the physical layer. To permit this, two successive frames transmitted from a node must be separated by at least one *IFS* period. The length of the *IFS* period depends on the size of the frame that has just been transmitted. Frames having lengths of up to *aMaxSIFSFrameSize* shall be followed by a *SIFS* (*short inter-frame spacing*) period. Frames with lengths greater than *aMaxSIFSFrameSize* shall be followed by a *LIFS* (*long inter-frame spacing*) period. Also according to the standard, the backoff algorithm of the access method CSMA/CA (*Carrier Sense Multiple Access with Collision Avoidance)* has some parameters fixed by MIB (*MAC Information Base*). Each node maintains these parameters for each transmission attempt. The *CW* (*contention window length*) is the most important parameter. It defines the number of backoff periods that need to be clear of activity before the transmission can begin.

The service time is the sum of the times of backoff, the clear channel assessment (*CCA*), frame transmission and reception of acknowledgment after the inter-fame spacing IFS:

$$C = Tbackoff_0 + CCA + TtransPKt + TtransAck + IFS \qquad (17)$$

The average time of the *backoff* is the half value of the contention window *CW* to get the medium access :

$$Tbackoff_i = \frac{CW_i}{2} \cdot aUnitBackoffPeriod \qquad (18)$$

Where $CW_i = 2^{BE_i - 1}$, $BE_i = macMinBE + i$ and $BE_i \le aMaxBE$ the number of *backoff* stages in the IEEE 802.15.4 standard [7].

For $W^k(t)$ the waiting time in the queue for a message at the instant *t*, it is defined to be the cumulative workload for the previous traffics in the queue of the node. So:

$$W^k(t) = C \cdot NumberPkt_k(t) \qquad (19)$$

Where $NumberPkt(t)$ is the number of packets arriving before the time *t* and it depends on the traffic generation and forwarding rates (g_k, f_k) at the node N_k of the message m_i.

$$NumberPkt_k(t) = \lfloor t \cdot g_k \rfloor + \delta(g_k) + \sum_{i \in forwarded\_traffics_k} \left(\lfloor t \cdot f_k^i \rfloor + \delta(f_i) \right) \qquad (20)$$

Where $\delta(x)$ is equal to zero if x is equal to zero, otherwise it is equal to 1. f_k^i is the traffic forwarded by the node N_k and generated by the source node N_i. $forwarded\_traffics_k$ is the set of traffics forwarded by the node N_k.

The $W_i(t)$ is a sequence which converges when $W_i(l) = l$ [12] , so $W_i = l$. At this instant, we can conclude that the sequence converges and the cumulative workload is finished. A necessary condition of convergence is:

$$C \cdot \left(g_k + \sum_{i \in forwarded\_traffics_k} f_k^i \right) \le 1 \qquad (21)$$

5.2. Equations for non reliable networks

In non reliable networks, transmission errors can take place. So, we based our analysis on the $\overline{Nc}$ which is the average number of failed transmissions of a packet before being successfully transmitted (computed from the equation 6). Thus, the service time, the medium access protocol duration is:

$$C = TransmissionTime + RetransmissionTime \qquad (22)$$

We consider $\overline{Nc}$ failed retransmission. So, in each time, the node will spend a backoff of $\frac{CW_i}{2}$ (in average) and wait for the acknowledgement until the time limits *macAckWaitDuration* [7] before retransmission.

$$RetransmissionTime = \left(\sum_{i=0}^{\overline{Nc}} \frac{CW_i}{2} \right) \cdot UnitBackoffPeriod + \overline{Nc} \cdot macAckWaitDuration \quad (23)$$

We compute the transmission time as the service time with a *backoff* related to the $\overline{Nc}$ retransmission:

$$TransmissionTime = Tbackoff_{\overline{Nc}} + CCA + TtransPKt + TtransAck + IFS \quad (24)$$

6. PERFORMANCE EVALUATION

Our proposed model is evaluated by using NS-2.31. In our simulations, we consider a network composed of 16 sensor nodes and 1 sink (PAN coordinator). The nodes are distributed on a 70 x 70 m grid. All sensor nodes are FFDs (Full-Function Devices) except the leaf nodes are RFD (Reduced-Function Devices). The root of the tree is the PAN coordinator (sink) located in the upper left corner of the grid (Fig. 1). We also considered a direct transmission mode from leaf nodes to the sink and a CBR (Constant Bit Rate) traffic with a traffic load up to 1pps (IEEE 802.15.4 maintains a high packet delivery ratio for application traffic up to 1pps [10]). We considered that the leaf nodes don't begin their transmissions simultaneously and that they transmit packets with the same length and with the same rate.

We also considered that the values of power consumption in idle, transmit and receive state are respectively 712 µW, 31.32 mW and 35.28 mW (according to the study results of Chipcon CC2420 [3] [8]).

6.1. Network lifetime prediction

According to related works, we define four analysis classes with different assumptions. The first is the complete analysis model (noted *AM*). The second is the analysis model not considering overhearing energy waste (noted: *AMwithoutOverhear*) which is a similar approach to [2, 4] works. The third is the analysis model not considering collision due to interference energy waste (noted *AMwithoutInterf*). The last is the analysis model not considering overhearing and collision due to interference energy waste (noted *AMwithoutOverInterf*) which is a similar approach to [1, 6] works.

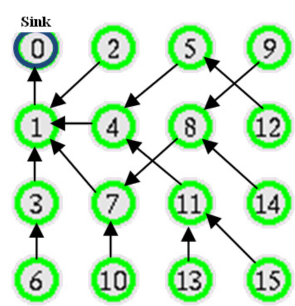


Figure 1. Simulated network tree topology.

The Figure 2 indicates that there is a slight difference between network lifetime predicted by our analytical model (*AM*) and that found by NS-2 simulator. This difference is due to the estimation of different unpredictable overheads. The impact of this phenomenon decreases as the traffic generated increases, because in the case of heavy traffic, the amount of energy spent in sending and receiving data packets becomes important relatively to overheads. Hence, more traffic is increasing more our analytical model (*AM*) is able to better predict the network lifetime; such as in the case of a packet generation rate of 1 pps.

The Figure 2 indicates also that our complete analytical model (*AM*) offers better network lifetime prediction compared with that ignoring overhearing and interference energy waste (*AMwithoutOverInterf*) which is a similar approach to [1, 6] works. In addition, our complete analytical model (*AM*) predicts network lifetime better than model not considering overhearing energy waste (*AMwithoutOverhear*) which is a similar approach to [2, 4] works.

To prove the importance of collision probability due to interference and overhearing energy consumption in our analytical model, we analyzed the variation of these parameters according to inter-node distance and packet generation rate (Fig. 3 and Fig. 4) for the greediest node in term of energy consumption (node 4).

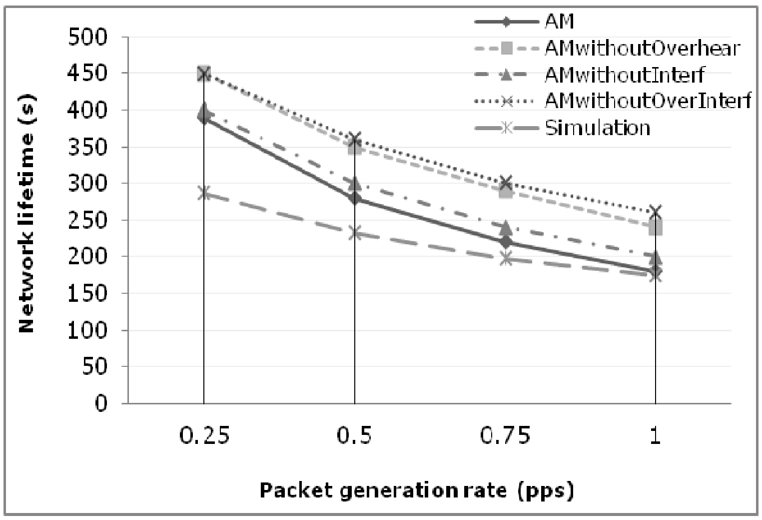
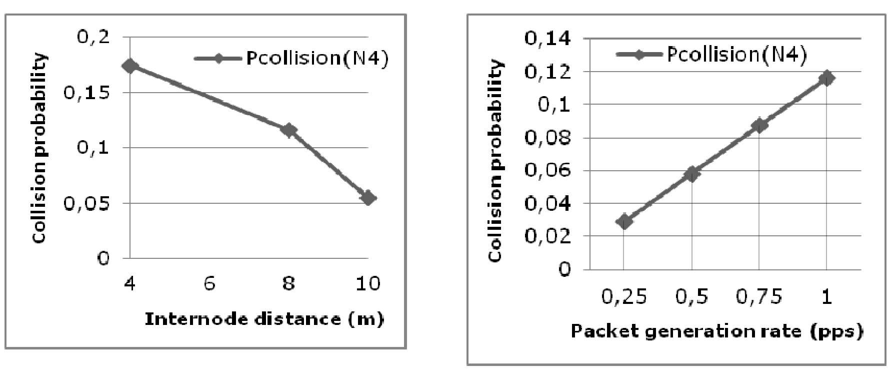


Figure 2. Variation of network lifetime according to packet generation rate.

Fig. 3 (a) shows that the collision probability is important when inter-node distance is reduced. Indeed, when we reduce inter-node distance, the number of node's neighbours becomes important and consequently collision probability rises due to interference between these neighbours. Fig. 3 (b) shows that collision probability increases relatively to traffic load.



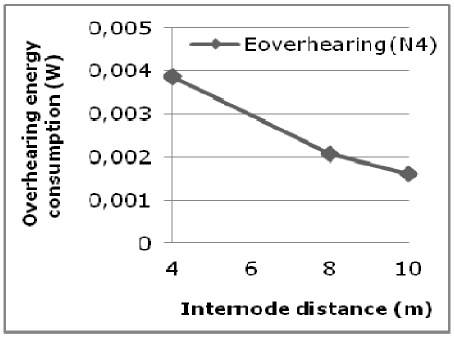
(a)

(b)

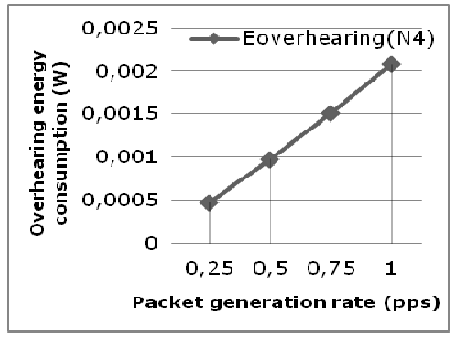
Figure 3. Variation of collision probability for the node 4 according to inter-node distance (a) and packet generation rate (b).

The figure 4 (a) shows that the overhearing energy waste is important when inter-node distance is reduced. In fact, when nodes are closer to each other, the neighbours' number of the node 4 increases and consequently the amount of energy spent by the node 4 in receiving packets destined to other nodes grows.

The figure 4 (b) indicates that the overhearing energy waste increases according to the packet generation rate. Indeed, when the neighbours of the node 4 generate more packets, this node consumes more energy in receiving these undesirable packets.



(a)



(b)

Figure 4. Variation of overhearing energy consumption for the node 4 according to inter-node distance (a) and packet generation rate (b).

6.2. Communication delay prediction

In this section, we maintained the same simulation parameters mentioned above and we varied the packet generation rate.
In Table 1, we present the difference between the simulation and the analytical results of average communication delay according to various packet generation rates and bit error rates (BER). Table 1 shows that our analytical model results are close to simulation results. We can also observe that the difference between the simulation and the analytical results of average delay tends to zero when the BER decreases. This is due essentially to the reduced iner-node distance used in simulation ensuring a low BER. Table 1 indicates also that our analytical model results are close to simulation results if the packet generation rate increases. This interpretation proves that our analytical model considers well the time in the queue which will be correctly estimated for heavy traffic.

Table 1. |AnalyticalDelay-SimulationDelay| according to packet generation rate and BER.

Packet generation rate (pps) / BER	1/10	1/9	1/8
0	0,019363 s	0,017394 s	0,009457 s
0,0001	0,0529 s	0,051 s	0,024 s
0,0007	0,87 s	0,8681 s	0,841258 s
0,0008	1,111 s	1,109 s	1,082518 s

7. CONCLUSION

Wireless sensor networks should maintain a balance between the network lifetime and the real-time requirements. In this paper, we proposed a complete analytical model to predict the lifetime and the communication delay for IEEE 802.15.4 wireless sensor networks. In fact, our model considers the most important sources of energy waste and communication latency, namely packet retransmissions, overhearing, collisions due to interference, idle listening and overheads. We computed the average number of failed transmissions according to collision and packet error probabilities. The overhearing was estimated relatively to the sum of neighbours' traffics. The idle listening was computed to be the energy spent in backoff and inter-frame spacing waiting periods. The overheads are globally estimated according to the average rate generation of control packets. All these parameters contribute to a realistic prediction of the network lifetime and the delay.

Based on NS-2 simulations, performance evaluation shows that our energy analytical model predicts the network lifetime better than other approaches ignoring the energy waste caused by overhearing and collisions due to interference. Our analysis proves also the importance of these two parameters especially in the case of small inter-node distance and heavy traffic cases. In communication delay concern, performance evaluation proves that our delay analytical model gives a reliable prediction of the average delay especially in the case of an increasing packet generation rate and a low bit error rate.

REFERENCES

[1] Sofiane Ouni, Salsabil Gherairi, Farouk Kamoun, "Real-time quality of service with delay guarantee in sensor networks", International Journal of Sensor Networks, Volume 9 Issue 1, 2011.

[2] F. Bouabdallah, N. Bouabdallah, "The Tradeoff Between Maximizing the Sensor Network Lifetime and the Fastest Way to Report Reliably an Event Using Reporting Nodes' Selection", Computer Communications Journal (Elsevier), Vol. 31, Issue 9, pp. 1763 – 1776, June 2008.

[3] B. Gao, C. He, "An Individual Beacon Order Adaptation Algorithm for IEEE 802.15.4 Networks", in Proceedings of IEEE International Conference on Communications Systems, November 2008.

[4] F. Othman, N. Bouabdallah, R. Boutaba, "Load-Balanced Routing Scheme for Energy-Efficient Wireless Sensor Networks", IEEE GLOBECOM 2008, New Orleans, LA, USA, December 2008.

[5] K. Shuaib, M. Alnuaimi, M. Boulmalf, I. Jawhar, F. Sallabi, A. Lakas, "Performance Evaluation of IEEE 802.15.4: Experimental and Simulation Results," Journal of Communications, V2, No.4, pp. 29-37, June 2007.

[6] S. C. Ergen, P. Varaiya, "Energy Efficient Routing with Delay Guarantee for Sensor Networks", ACM Wireless Networks Journal, 13(5):679-690, October 2007.

[7] IEEE-TG15.4 (2006), "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for low-rate Wireless Personal Area Networks (LR-WPANs)", IEEE standard for information technology, 2006.

[8] B. Bougard, F. Catthoor, D. C. Daly, A. Chandrakasan, and W. Dehaene, "Energy Efficiency of the IEEE 802.15.4 Standard in Dense Wireless Microsensor Networks: Modeling and Improvement Perspectives", in Proc. Design, Autom., and Test in Euro. Conf. and Exhib. (DATE'05), pp.196-201, March 2005.

[9] H. Karl, A. Willig, "Protocols and architectures for Wireless Sensor Networks", Wiley, 2005.

[10] J. Zheng, M.J. Lee, "A Comprehensive Performance Study of IEEE 802.15.4", In: Sensor Network Operations, pp. 218-237. IEEE Press, Los Alamitos 2004.

[11] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, ISO/IEC IEEE 802.11 Standard, 1999.

[12] J.A. Stankovic, M. Spuri, K. Ramamritham, G.C. Buttazzo, Deadline Scheduling for Real-Time Systems, Kluwer Academic Publisher, 1998.

[13] K. Tindell, J. Clark, "Holistic Schedulability Analysis for Distributed Hard Real-Time Systems", Microprocessing & Microprogramming, Vol. 50, Nos. 2-3, 1994.

[14] N. Audsley, A. Burns, et. al., “Fixed Priority Preemptive Scheduling: An Historical Perspective”, Real-Time Systems, 8(2/3), 1995.

[15] N. Audsley, K. Tindell, A. et. al., “The End of Line for Static Cyclic Scheduling?”, 5th Euromicro Works. on Real-Time Systems, 1993.

[16] Benoît Latré, Pieter De Mil, Ingrid Moerman, Bart Dhoedt and Piet Demeester , “Throughput and Delay Analysis of Unslotted IEEE 802.15.4”, JOURNAL OF NETWORKS, VOL. 1, NO. 1, MAY 2006.

[17] Yu-Kai Huang, Chin-Fu Kuo, Ai-Chun Pang, and Weihua Zhuang,“Stochastic Delay Guarantees in ZigBee Cluster-Tree Networks”, IEEE International Conference on Communications (ICC) 2012.

[18] Anis Koubaa, Mário Alves, Eduardo Tovar, André Cunha: An implicit GTS allocation mechanism in IEEE 802.15.4 for time-sensitive wireless sensor networks: theory and practice. Real-Time Systems 39(1-3): 169-204 (2008).

Authors

Sofiane Ouni received his Engineer, Master degree and PhD in Computer Science from Ecole Nationale des Sciences de l'Informatique (ENSI) of Tunisia in 2004. He is currently Associate Professor at the Department of Computer Science and Mathematics, at INSAT, Tunisia.
The current research interest of Dr. Sofiane Ouni includes Wireless, Ad Hoc and sensor Networks with Hard Real time guarantee. He has several published refereed articles in international journals and proceedings of international conferences. He is reviewer and organizer of International conferences on computer networks and embedded systems.

Zayneb Trabelsi Ayoub is a PhD student at University of Manouba, working on real-time communication over IEEE 802.15.4/ZigBee Wireless Sensor Networks. She received her Engineering degree in Computer Networks and Telecommunications (2009) from INSAT Tunisia and her MSc degree in Electronic Systems and Communication Networks (2010) from EPT Tunisia. She is an IEEE member.
She is currently Assistant Professor at the Department of Computer Science at Higher Institute of Computer Sciences (ISI Tunisia).