Analysis of the impact of the number of reporting nodes on sensor networks lifetime

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Abstract— **Energy-efficiency is one of the major concerns in wireless sensor networks since it impacts the network lifetime. In this paper, we investigate the relationship between sensor networks performance, particularly its lifetime, and the number of reporting nodes N by using both analytical and simulation approaches. We first show that the network lifetime and the number of correctly received reports increase when N decreases. Moreover, we demonstrate that the average time required to report an event is a convex function of N. Based on these results, and as the main contribution, we prove that the optimal number of reporting nodes minimizing the energy consumption in the network does not correspond to the optimal number of reporting nodes allowing the fastest way to report an event. The tradeoff between these two requirements is therefore specific to each sensor application, depending on its particular needs. In this paper, we provide a simple methodology to achieve this tradeoff.**

I. INTRODUCTION

Energy-efficiency is a critical issue in wireless sensor networks (WSNs) due to the limited capacity of the sensor nodes' batteries. Indeed, once a WSN is in place, its lifetime must last as long as possible based on the initially provided amount of energy. In view of this, techniques minimizing energy-consumption are required to improve the network lifetime. A frequently used mechanism is to schedule sensor nodes activity so that redundant nodes enter the sleep mode as often as possible [1] [2] [3]. Another solution to reduce energy consumption, consists in realizing congestion control in order to avoid energy wastage due to frequently occurring collisions in such WSN networks [4].

The majority of previous works focused mainly on the energy minimization problem. However, minimizing the energy consumption must be achieved while respecting the specific QoS requirements of sensor applications, such as the maximum tolerable time to report an event, and the required event reliability, etc. Indeed, network lifetime and the average time required to report an event reliably are key performance metrics in WSNs. An optimal solution must therefore take into account these two metrics. Therefore, this work aims at optimizing the number of reporting nodes that achieves the energy-latency tradeoff.

Previous works addressed the energy optimization issue without considering the impact of the number of reporting nodes on the network lifetime, i.e., how the network lifetime and the reporting latency evolve with respect to the number of active reporting nodes? To the best of our knowledge, we are the first to tackle the energy optimization problem from this perspective.

In this paper, we develop a new analytical model to explore the relationship between the WSN performance (i.e., network lifetime, event reporting time) and the number of active reporting nodes. Specifically, we analyze the basic access mechanism of IEEE 802.11 DCF (distributed coordination function) with its optional request-to-send/clear-to-send (RTS/CTS) scheme. This protocol, adapted to the WSN environment, is widely used in currently deployed WSNs to arbitrate the access between competing sensor nodes to the shared medium in order to communicate with the sink node.

In our analysis we proceed as follows. We derive the expression of the collision probability as a function of the number of reporting nodes N. Based on these results, and as a first main contribution of this paper, we prove that the network lifetime increases when decreasing N. Simulation and analytical results show that the maximal network lifetime is achieved when only one reporting node is activated while the remaining nodes undergo the sleep mode. Indeed, in doing so, collisions among reporting nodes is avoided, eliminating thus unnecessary energy consumption. We then show analytically that the time required to report an event is a convex function of N, where the minimum is obtained for $N_{opt} > 1$. Consequently and as a second main contribution, we demonstrate that the fastest way to report reliably an event does not necessarily lead to the most efficient energy consumption. The tradeoff between these two requirements (i.e., energy consumption and reporting time) depends mainly on the specific QoS needs of the sensor application.

The remainder of the paper is organized as follows. Section II presents the problem statement. A brief description of the used MAC protocol is outlined in section III. In section IV, we introduce the mathematical models to evaluate the impact of the number of reporting nodes on the WSN performance. Both analytical and simulation results are discussed in section V. In section VI, we provide a simple methodology to achieve the tradeoff between energy consumption and event reporting latency. Finally, section VII concludes this paper.

II. PROBLEM STATEMENT

Let us consider a WSN as depicted in Fig. 1. In essence, a WSN ensures the supervision of a given area by the use of a sink node, which collects reports from the network. In this analysis we consider event detection driven wireless sensor applications. In other words, communications are triggered by the occurrence of a pre-specified type of events. Once an event occurs, it has to be reported to the sink by the sensor nodes. In such network, sensor nodes, within an event radius R_c, are the sources (i.e., reporting nodes) for the detected event. Recall that sensor nodes are characterized by their coverage range R_c and transmission range R_t as shown in Fig. 1.

We denote by N the number of reporting nodes for a detected event. Moreover, we denote by f the network reporting frequency. The network reporting frequency is defined as the number of packets generated per unit of time by the network to report an event. Hence, given N reporting nodes, the reporting frequency of each sensor node must be set equal to $f_s = f/N$ to get the predefined network reporting frequency. This parameter f is generally fixed by the network administrator in order to achieve a required event detection reliability, R. The desired event reliability, R, is the number of data packets required by the sink to consider the event as reliable. Once the sink node receives R reports, it instructs the sensor nodes to stop the event reporting of that event.

In this study, we aim at analyzing the impact of the number of reporting nodes N on the WSN performance. The basic idea is to let some potential reporting nodes enter a sleep mode. In the extreme case, we only let one sensor node ($N = 1$) report a detected event with a reporting frequency $f_s = f$. Furthermore, we evaluate the collision probability, the average time required to report an event and the network lifetime as a function of N.

III. WSN COMMUNICATIONS

As stated before, communications in currently deployed WSNs are usually carried using the basic IEEE 802.11 DCF protocol and its optional RTS/CTS mechanism. Specifically, once an event is detected, the N active reporting nodes compete to access the common data channel to report the event to the sink. The IEEE 802.11 DCF access method is based on the CSMA/CA technique. Accordingly, a host wishing to transmit a frame senses the channel activity until an idle period equal to Distributed Inter Frame Space (DIFS) is detected. Then, the station waits for a random backoff interval before transmitting. The backoff time counter is decremented in terms of time slots as long as the

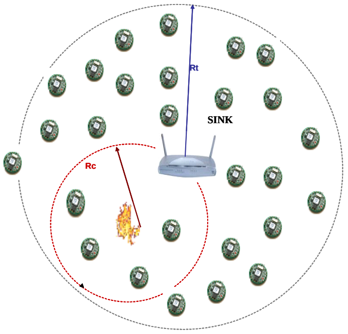

Fig. 1. Example of a sensor network.

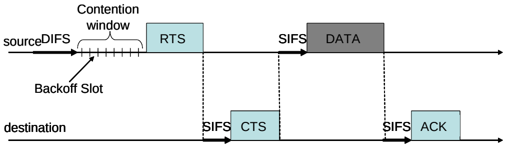

Fig. 2. Basic access mechanism of IEEE 802.11 DCF.

channel is sensed free. The counter is suspended once a transmission is detected on the channel. It resumes with the old remaining backoff interval when the channel is sensed idle again for a DIFS period. The station transmits its frame when the backoff time becomes zero. In this case, the host starts the process by sending a RTS frame.

If the frame is correctly received, the receiving host sends a CTS frame after a Short Inter Frame Space (SIFS). Once the CTS frame is received, the sending host transmits its data frame. If the sending host does not receive the CTS frame, a collision is assumed to have occurred. In this case, the sending host attempts to send the RTS frame again when the channel is free for a DIFS period augmented by the new backoff, which is calculated as follows.

For each new transmission attempt, the backoff interval is uniformly chosen from the range $[0, CW]$ in terms of time slots. At the first transmission attempt of a frame, CW equals the initial backoff window size $CW_{min} = 31$. Following to each unsuccessful transmission, CW is doubled until a maximum backoff window size value $CW_{max} = 1023$ is reached. Once the frame is successfully transmitted, the CW value is reset to CW_{min}. Figure 2 illustrates the IEEE 802.11 DCF access mechanism.

IV. WSN LIFETIME

In this section, we present a mathematical model to derive the WSN lifetime as a function of the number of reporting nodes. To achieve this, we first calculate the collision probability in such networks caused by the multiple reporting nodes. Then, we derive the expression of the average period of time required to report an event. Based on these results, we simply obtain the sensor network lifetime.

We note that in WSNs, we distinguish between two modes of functioning according to the network reporting frequency f: the saturated and unsaturated regimes. The first mode is obtained when f is high enough. In this case, each time the channel is free for transmission, each station among the N reporting ones has at least one report to transmit. In other words, for each new transmission cycle, all the reporting nodes compete to access the common channel. In contrast, in the unsaturated regime, it may happen that the channel remains free. This is the case when f is chosen to be relatively low.

Generally, the saturated mode is considered in order to ensure reliable WSNs. In this regard, we consider in this paper the saturated model.

A. Probability of collision

Assume N reporting stations contending to access the common channel. In saturation conditions, each station has always a report to transmit. In this case, a collision occurs when two or more backoff counters $B_i (i = 1, ..., N)$ of different stations expire at the same time.

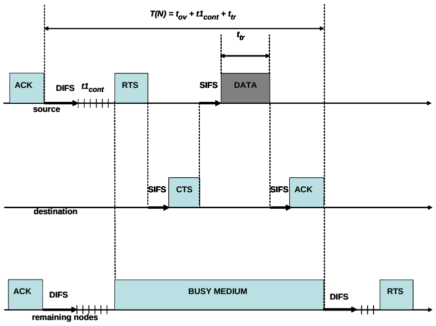

Fig. 3. The reporting transmission cycle RTC: successful transmission from the first attempt.

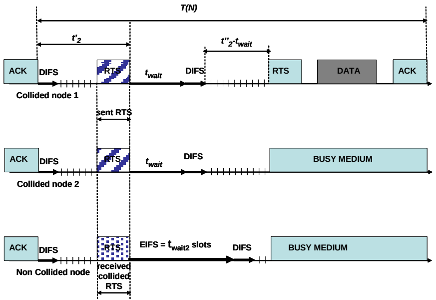

Fig. 4. The reporting transmission cycle RTC: successful transmission following to a first collision.

Hereafter, we assume that the number of transmissions that are subject to multiple successive collisions is negligible. This assumption, denoted henceforth by assumption 1, is widely used in literature to simplify the analytical models. Accordingly, following to a successful transmission, we can also assume that the backoff $B_i (i = 1, ..., N)$ of each reporting station takes a value in $[0, CW_{min}]$. This second assumption (assumption 2) holds since we omit successive collisions occurrence as explained in [5]. The accuracy of these approximations is justified, as it will be demonstrated in the next section, through the perfect match between the analytical and simulation results.

Let us now calculate the probability of collision occurrence $P_c(N)$ during the next reporting transmission cycle (RTC). The RTC is defined as the time spent between two successive acknowledgment transmissions by the sink node. Recall that the sink node sends an acknowledgment frame after the reception of each report. In other words, RTC is the time required by the WSN to report an event to the sink. Before we delve in calculations, it is important to note that our model gives simple expression and more accurate results of the collision probability than [5].

As we neglect multiple successive collisions occurrence, during an RTC cycle, a report can be either successfully transmitted from the first attempt (Fig. 3), or following to a first collision (Fig. 4). Hence, a collision can only occur at the beginning of the RTC cycle with a probability $P_c(N)$, while all the reporting nodes' backoffs $B_i (i = 1, ..., N)$ vary between $[0, CW_{min}]$.

A collision occurs when several backoff counters expire at the same time. Hence, the probability of collision $P_c(N)$ can be written as follows:

$$P_c(N) = \Pr\{\overline{U}\} = \sum_{k=0}^{CW_{min}} \Pr\{X = k, \overline{U}\} \tag{1}$$

where the random variable X denotes $(\min_{i \in <1,N>} B_i)$ and the event $\overline{U}$ is defined as follows:

$$\begin{aligned} \overline{U} &= \{\exists i, j \in <1, N>, i \neq j, B_i = B_j = X\} \\ &= \{\text{Collided transmission }\}. \end{aligned} \tag{2}$$

The event $\{X = k, \overline{U}\}$ simply implies that the backoff counter becomes zero for the first time in k slots for at least two stations, which leads to a collision occurrence. Thus, $\Pr\{X = k, \overline{U}\}$ can be derived as follows:

$$\Pr\{X = k, \overline{U}\} = \sum_{i=2}^{N} \binom{N}{i} \frac{(CW_{\min} - k)^{N-i}}{(CW_{\min} + 1)^{N}} \tag{3}$$

B. Average time to report an event

In this section, we evaluate the average time $T(N)$ of an RTC. It is the mean time required by the WSN to successfully transmit a report when the number of reporting nodes equals to N. In such network, access among the N reporting nodes is arbitrated by the IEEE 802.11 DCF protocol. Hence, the overall transmission time can be written as follows:

$$T\left(N\right) = t_{tr} + t_{ov} + t_{cont}\left(N\right) \tag{4}$$

where t_{tr} is the transmission time of the data packet and t_{ov} is a constant overhead, which can be simply deduced from Fig. 2, and thus given by:

$$t_{ov} = DIFS + t_{RTS} + 3 \cdot SIFS + t_{CTS} + t_{ACK}. \tag{5}$$

Moreover, $t_{cont}(N)$ represents the average time spent in contention procedure when N reporting nodes compete for the medium access with their associated backoffs $B_i (i = 1, ..., N)$ ranging between $[0, CW]$. In other words, it is the extra time lost due to the collision occurrence. Hereafter, we focus on $t_{cont}(N)$ calculations. As stated before, we neglect in our study the successive collisions occurrence. Doing so, we distinguish between two cases:

- Case 1: The report is transmitted successfully by one of the reporting nodes from the first attempt (i.e., following a successfully transmitted report) (See Fig. 3).
- Case 2: The report is transmitted successfully by one of the reporting hosts following to a first collision occurrence on the medium (See Fig. 4).

a) Case 1: This case happens with a probability $(1 - P_c(N))$. In this case, $t_{cont}(N) = t1_{cont}(N)$ is simply the average backoff time spent by the transmitting node, denoted by node j, before accessing to the data channel (See Fig. 3). According to assumption 2 (Refer to subsection IV-A), all the reporting nodes' backoff counters take values in $[0, CW_{min}]$ at the beginning of an RTC cycle. Moreover, as the report is successfully transmitted, the transmitting node j has certainly the minimum backoff value among the N competing access nodes (i.e., $X = B_j$). In addition $\forall i \neq j$, we have $B_i > B_j$. Let U denote that event:

$$\begin{aligned} U &= \{\exists! j \in <1, N>, B_j = X\} \\ &= \{\text{Successful transmission}\}. \end{aligned} \tag{6}$$

Note that

$$\Pr\{U\} = 1 - \Pr\{\overline{U}\}. \tag{7}$$

Doing so, $t1_{cont}(N)$ can be expressed as follows:

$$t1_{cont}(N) = E[X|U] \; Slots \tag{8}$$

where

$$E[X|U] = E[X, U] / \Pr\{U\}. \tag{9}$$

Moreover, $E[X, U]$ can be written as follows:

$$E[X, U] = \sum_{k=0}^{CW_{min}} k \Pr\{X = k, U\}. \tag{10}$$

where $\Pr\{X = k, U\}$ can be simply derived based on (3):

$$\begin{aligned} \Pr\{X = k, U\} &= \Pr\{X = k\} - \Pr\{X = k, \overline{U}\} \\ &= \binom{N}{1} \frac{(CW_{\min} - k)^{N-1}}{(CW_{\min} + 1)^{N}} \end{aligned} \tag{11}$$

b) Case 2: In this case, the report is successfully transmitted by one of the reporting nodes after a first failed attempt. Such case happens with a probability $P_c(N)$. $t_{cont}(N) = t2_{cont}\left(N\right)$ is therefore the sum of the time spent from the beginning of the RTC cycle until the end of the transmission of the collided RTS frame $(t_2'\left(N\right))$ and the average backoff time required by the new transmitting node j to access to the channel in order to transmit correctly another RTS frame $(t_2''\left(N\right))$ (See Fig. 4). Hence, we get:

$$t2_{cont}\left(N\right) = t_2'\left(N\right) + t_2''\left(N\right). \tag{12}$$

And we have:

$$t_2'\left(N\right) = DIFS + t_{RTS} + E[X|\overline{U}] \text{ Slots} \tag{13}$$

where $E[X|\overline{U}]$ is the average backoff time of the collided stations. It can be simply derived using the fact that $E[X|\overline{U}] = E[X, \overline{U}] / \Pr\{\overline{U}\}$. Doing so, we have:

$$B_c\left(N\right) = E[X, \overline{U}] = \sum_{k=0}^{CW_{min}} k \Pr\{X = k, \overline{U}\}. \tag{14}$$

where $\Pr\{X = k, \overline{U}\}$ is given by (3).

Let us now focus on the calculation of $t_2''\left(N\right)$. As we mentioned before, a collision can occur only when $N_c (N_c \geq 2)$ stations send RTS requests at the same time. The N_c collided stations perceive the collision as they do not receive the CTS frame from the sink after $t_{CTS} + SIFS = t_{wait}$ units of time. On the other side, the remaining $N - N_c$ nodes, which did not participate in the collision, detect immediately the collision occurrence as they receive a collided RTS frame and they will wait for a period of time equal to $EIFS = t_{wait2} \cdot Slots$ before attempting again to access the channel. In this case, starting from the collision occurrence backoff counters of these $N - N_c$ nodes take values in $[t_{wait2}, (t_{wait2} + CW_{min})]$.

On the other hand, the backoff windows of the N_c collided stations double. Accordingly, the backoff counters of the collided stations take values in $[0, (2 \times CW_{min})]$. However, these stations have to wait for a period of time approximately equal to 11 slots corresponding to $t_{wait} = t_{CTS} + SIFS$ before they try again to access to the data channel. Hence, starting from the collision occurrence, the backoff counters of the N_c collided stations vary between $[t_{wait}, t_{wait} + (2 \times CW_{min})]$, whereas the remaining nodes' backoff counters vary between $[t_{wait2}, (t_{wait2} + CW_{min})]$.

Let the random variable X' denote $(\min_{i \in <1,N>} B_i)$ and U' be the following event:

$$\begin{aligned} U' &= \{\exists! j \in <1, N>, B_j = X'\} \\ &= \{\text{Successful transmission}\}. \end{aligned} \tag{15}$$

We recall that we aim at calculating $t_2''\left(N\right)$, which is the average backoff time required by the WSN to successfully transmit a new report after a first failed attempt. $t_2''\left(N\right)$ can be therefore written as:

$$t_2''\left(N\right) = E[X', U'|\overline{U}] \tag{16}$$

which leads to:

$$t_2''\left(N\right) = \sum_{k=t_{wait}}^{t_{wait}+(2 \times CW_{min})-1} k \Pr\{X' = k, U'|\overline{U}\}. \tag{17}$$

In order to calculate $t_2''\left(N\right)$, we have first to derive the expression of $\Pr\{X' = k, U'|\overline{U}\}$. To achieve this, three cases are to be distinguished according to the value of X' (in terms of time slots).

i)$t_{wait} \leq X' = k < t_{wait2}$

In this case, the host j that accesses the medium is one of the N_c collided stations. Using the theorem of total probability, we get:

$$\Pr\{X' = k, U'|\overline{U}\} = \sum_{n=2}^{N} \Pr\{X' = k, U', N_c = n|\overline{U}\}. \tag{18}$$

This yield to

$$\begin{aligned} \Pr\{X' = k, U'|\overline{U}\} = \sum_{n=2}^{N} &\Pr\{X' = k, U'|N_c = n, \overline{U}\} \\ &\times \Pr\{N_c = n|\overline{U}\} \end{aligned} \tag{19}$$

Since the transmitting node j participate in the previous collision, we have:

$$\Pr\{X' = k, U' | N_c = n, \overline{U}\} = \binom{n}{1} \frac{(2 \times CW_{min} + t_{wait} - k)^{N-n-1}}{(2 \times CW_{min} + 1)^{N-n}} \tag{20}$$

Moreover, we have:

$$\Pr\{N_c = n | \overline{U}\} = \frac{\Pr\{N_c = n, \overline{U}\}}{\Pr\{\overline{U}\}} = \frac{\Pr\{N_c = n\}}{\Pr\{\overline{U}\}} \tag{21}$$

where

$$\Pr\{N_c = n\} = \sum_{k=0}^{CW_{min}} \binom{N}{n} \frac{(CW_{min} - k)^{N-n}}{(CW_{min} + 1)^{N}} \tag{22}$$

ii) $t_{wait2} \leq X' = k \leq t_{wait2} + CW_{\min}$

In this case the host j that accesses the channel may be either one of the N_c stations, which already participated in the first collision, or belongs to the $N - N_c$ remaining ones. Accordingly, we distinguish between two sub-cases:

Sub-case b.1): The transmitting host j already participated in the first collision. Such event is denoted by C. In this case, we have:

$$\Pr\{X' = k, U', C | \overline{U}\} = \sum_{n=2}^{N} \Pr\{X' = k, U', C | N_c = n, \overline{U}\} \times \Pr\{N_c = n | \overline{U}\} \tag{23}$$

where

$$\Pr\{X' = k, U', C | N_c = n, \overline{U}\} = \binom{n}{1} \frac{(CW_{min} + t_{wait2} - k)^{N-n} (2 \times CW_{min} + t_{wait} - k)^{n-1}}{(CW_{min} + 1)^{N-n} (2 \times CW_{min} + 1)^{n}} \tag{24}$$

And $\Pr\{N_c = n | \overline{U}\}$ is already given by (21).

Sub-case b.2): The transmitting host j did not participate in the first collision. Such event is denoted by $\overline{C}$. In this case, we have:

$$\Pr\{X' = k, U', \overline{C} | \overline{U}\} = \sum_{n=2}^{N} \Pr\{X' = k, U', \overline{C} | N_c = n, \overline{U}\} \times \Pr\{N_c = n | \overline{U}\} \tag{25}$$

where

$$\Pr\{X' = k, U', \overline{C} | N_c = n, \overline{U}\} = \binom{N-n}{1} \frac{(CW_{min} + t_{wait2} - k)^{N-n-1} (2 \times CW_{min} + t_{wait} - k)^{n}}{(CW_{min} + 1)^{N-n} (2 \times CW_{min} + 1)^{n}} \tag{26}$$

Putting both sub-cases together, we get the expression of $\Pr\{X' = k, U' | \overline{U}\}$ when $(t_{wait} \leq X' = k \leq CW_{\min})$ as follows:

$$\Pr\{X' = k, U' | \overline{U}\} = \Pr\{X' = k, U', C | \overline{U}\} + \Pr\{X' = k, U', \overline{C} | \overline{U}\}. \tag{27}$$

iii) $CW_{min} + t_{wait2} < X' = k < t_{wait} + 2 \times CW_{min}$

This case happens only when all the N reporting nodes participated in the first collision (i.e., $N_c = N$). Thus, we have:

$$\Pr\{X' = k, U' | \overline{U}\} = \Pr\{X' = k, U', N_c = N | \overline{U}\}. \tag{28}$$

This leads to

$$\Pr\{X' = k, U' | \overline{U}\} = \Pr\{X' = k, U' | N_c = N, \overline{U}\} \times \Pr\{N_c = N | \overline{U}\} \tag{29}$$

where

$$\Pr\{X' = k, U' | N_c = N, \overline{U}\} = \binom{N}{1} \frac{(2 \times CW_{min} + t_{wait} - k)^{N-1}}{(2 \times CW_{min} + 1)^{N}} \tag{30}$$

And $\Pr\{N_c = N | \overline{U}\}$ is already given by (21).

Moreover, using (17), (18), (27) and (29), we simply derive $t''_2(N)$ and thus we get the expression of $t2_{cont}(N)$ by means of (12). Doing so, we finally derive the expression of $t_{cont}(N)$, which is given by:

$$t_{cont}(N) = \Big(1 - P_c(N)\Big) t1_{cont}(N) + P_c(N)\, t2_{cont}(N). \tag{31}$$

By substituting (31) in (4), we obtain the average time required to report an event when the number of reporting nodes is N. Hence, the average time needed to report reliably an event is: $R \times T(N)$.

C. Sensor network lifetime

In this paper, the network lifetime $T_{network\_lifetime}(N)$, when considering N reporting nodes are active, is defined as the time spent from the deployment until the network becomes unable to report events due to the lack of energy. Typically, $T_{network\_lifetime}(N)$ depends on the total initially provided amount of energy $E_{initial}$, the rate of event occurrence M and the desired reliability R. Based on [6], the average network lifetime can be expressed as follows:

$$T_{network\_lifetime}(N) = \frac{E_{initial} - E_w}{\lambda E_{RTC}(N) + E_c} \tag{32}$$

where E_c is the constant continuous energy consumption per unit of time needed to sustain the network during its lifetime without data collection, E_w is the expected wasted energy (i.e., the total unused energy in the network when it dies), λ is the average sensor reporting rate defined as the number of transmitted reports by the WSN per unit of time (i.e., $R \times M$) and $E_{RTC}(N)$ is the expected reporting energy consumed by all the sensors to report an event. In the remainder of this paper, we ignore E_w. Indeed, E_w is negligible when we achieve balanced energy consumption across the network. Hence, to derive the network lifetime, we only need to calculate $E_{RTC}(N)$ and E_c.

We start by evaluating $E_{RTC}(N)$. To achieve this, we take into account transmitting, listening and idling energy. In contrast, we neglect sensing energy, which is relatively low. We denote by E_{idle}, E_{tr} and E_{rx} the consumed energy per unit of time during idle, transmitting and listening states, respectively. As shown in Fig. 1, in our study, each sensor node can listen to all the other sensors. In view of this, $E_{RTC}(N)$ can be simply written as follows:

$$E_{RTC}(N) = E_{tr}(N) + E_{ov}(N) + E_{cont}(N) \tag{33}$$

where $E_{tr}(N)$ is the amount of energy consumed during the transmission of a data packet (i.e., during t_{tr}), $E_{ov}(N)$ is the amount of energy consumed during the constant overhead period of time t_{ov}, and $E_{cont}(N)$ is the amount of energy spent in contention procedure. These quantities are derived as follows:

$$\begin{cases} E_{tr}(N) & = t_{tr}\,(E_{tr} + (N-1)E_{rx}) \\ E_{ov}(N) & = E_{idle} \cdot N\,(DIFS + 3 \cdot SIFS) \\ & \quad + E_{rx} \cdot ((N-1)t_{RTS} + N \cdot t_{CTS} + N \cdot t_{ACK}) \\ & \quad + E_{tx} \cdot t_{RTS} \\ E_{cont}(N) & = (1 - P_c(N))\,(N \cdot E_{idle} t1_{cont}(N)) \\ & \quad + P_c(N)\,\big(E_{idle} \cdot N\,\big(t''_2(N) + DIFS + E[X|\overline{U}] \text{ Slots}\big)\big) \\ & \quad + (E_{rx} \cdot t_{RTS}(N-1)) \\ & \quad + (E_{tx} \cdot t_{RTS}) \end{cases} \tag{34}$$

Let us now calculate the continuous energy consumption E_c considering the desired event reliability R and the mean number of events occurring by unit of time M. We assume $\frac{1}{M} \geq R \times T(N)$, that is the mean time between two successive events $\Big(\text{i.e., } \frac{1}{M}\Big)$ is higher than the mean time required to report reliably an event$\Big(\text{i.e., } R \cdot T(N)\Big)$. Hence, we get:

$$E_c = N\Big(1 - R \cdot M \cdot T(N)\Big)E_{idle} \tag{35}$$

Communication range	40 m
Sensing range	30 m
Packet length	30 bytes
IFQ length	65 packets
Transmit power	0.660 W
Receive power	0.395 W
Idle power	0.035 W
Initial energy	100 J

TABLE I
SIMULATION PARAMETERS

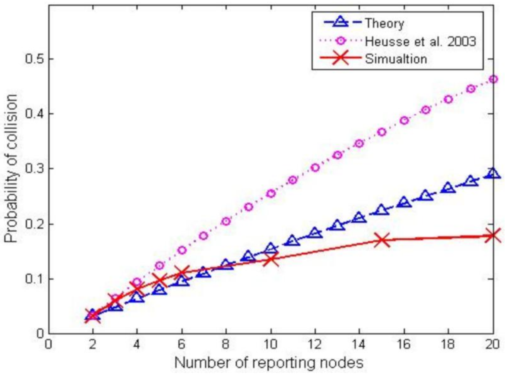

Fig. 5. Probability of collision.

The network lifetime can be therefore expressed as follows:

$$T_{network\_lifetime}(N) = \frac{E_{initial}}{M \cdot R \cdot E_{RTC}(N) + E_c} \quad (36)$$

V. PERFORMANCE EVALUATION

In this section, we evaluate the impact of the number of reporting nodes on the WSN performance using both analytical and simulation approaches. The simulations are run on *ns-2* simulator. In our simulations, we have not assumed the mobility of the sensor nodes. Therefore, the topology does not continuously vary with time during simulations. However, note that the sensor nodes may die due to energy depletion leading to variation in overall topology. Parameters' settings in our experiments are listed in table I.

Let us first focus on the impact of N on the collision probability in the network as shown in Fig. 5. We can see that this probability increases with the increase of N. Indeed, collisions become more frequent when the number of competing access nodes increases, which leads to increasingly extra energy expenditure and increases the average time to report an event (RTC). To alleviate these shortcomings, we have to reduce the number of reporting nodes. Figure 5 also shows that our analytical results match better the simulation results than those given in [5]. Indeed, our analytical results practically coincide with simulation ones, which confirms the accuracy of our models. This also holds for the remaining simulations described in this section.

Figure 6 plots the average backoff time $\left(\text{i.e., } t1_{cont}(N)\right)$ required by a host to access the medium in order to successfully report an event to the sink node. We can observe that this waiting time decreases when the number of reporting nodes N increases. Doing so, the overall time required to report an event $\left(\text{i.e., RTC cycle}\right)$ may be reduced.

According to Fig. 5 and Fig. 6, we can see that we have two opposite requirements to minimize the time required to report an event. On one hand, increasing N enables a faster access to the medium during each RTC cycle, and hence the average RTC time decreases. On the other hand, rising N, increases the probability of collision which amplifies the time lost in contention procedure during each RTC cycle. Hence, the optimal RTC is a tradeoff between these two opposite requirements. Reconciling these requirements, the minimum RTC time is obtained for $N_{opt\_latency} = 8$ as shown in Fig. 7. This figure shows that the RTC cycle is a convex function of N where the minimum is obtained for $N_{opt\_latency} = 8$. Accordingly, the fastest way to report reliably an event is to devise a network where the number of active reporting nodes is set equal to $N_{opt\_latency}$.

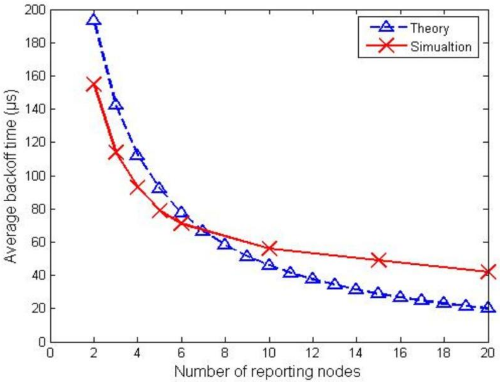

Fig. 6. Average backoff time for a successful transmission $t1_{cont}(N)$

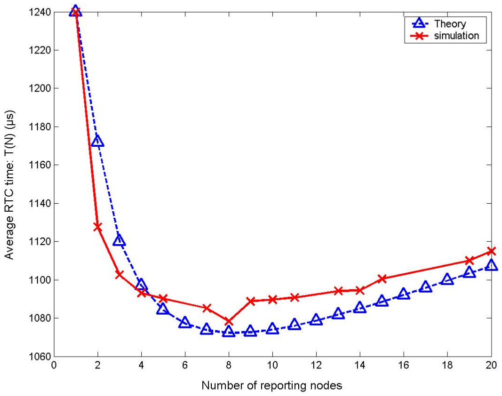

Fig. 7. Average RTC time: $T(N)$

So far, we have presented the impact of N on the reporting latency. Let us now focus on the impact of N on the energy consumption. Figure 8 shows the average amount of energy consumed by the network during each RTC cycle (i.e., to report an event) for a varying number of reporting nodes N. Unlike the RTC curves (i.e., Fig. 7), this figure shows that the amount of energy $E_{RTC}(N)$ is monotonically rising with N. This monotonous increase is mainly due to two factors. First, increasing N amplifies the wasted energy due to collisions. Moreover, increasing N means waking up more sensor nodes within the event radius R_c. Doing so, the total amount of energy consumed by the network in the reception of the signaling messages (RTS, ACK) increases considerably (see the hatched zones of Fig. 8). According to these results, we can see the optimal number of active reporting nodes that enables the minimal energy consumption when sending a report is $N_{opt\_energy} = 1$. Hence, we can conclude that the fastest way to report an event does not correspond to the optimal manner to consume the network energy. In this regard, the choice of the number of active reporting nodes depends mainly on the specific QoS needs of the WSN application.

Figure 9 plots the network lifetime evolution as a function of N for a varying values of the desired event reliability R. In our simulations, we consider the rate of event occurrence $M = 5$. In other words, it occurs in average 5 events per unit of time. Figure. 9 shows again that the smaller N is, the longer the network lifetime becomes regardless of the value of R. Thus, the maximal network lifetime is reached when N is equal to 1. Indeed, when N increases the probability of collision rises causing important energy depletion. In contrast, when N is set equal to 1, the probability of collision is null, avoiding thus extra energy expenditure due to collisions.

VI. TRADEOFF BETWEEN ENERGY AND LATENCY

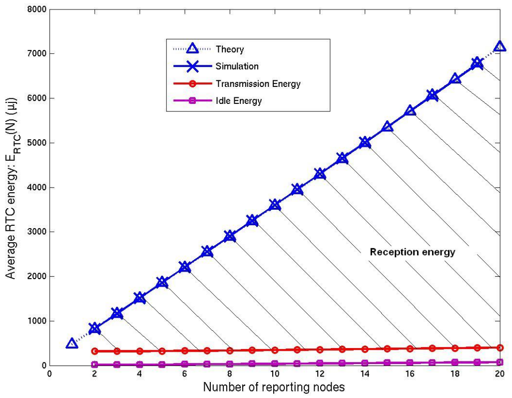

Fig. 8. The average amount of energy consumed by the network to transmit a report.

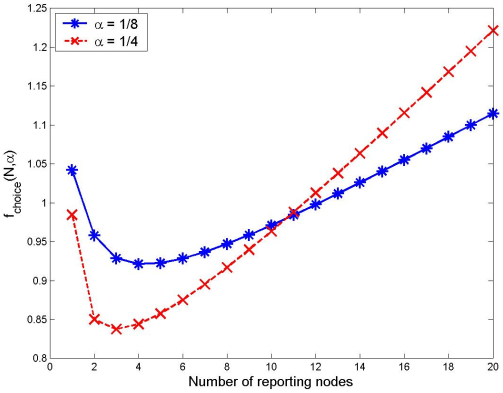

Fig. 10. Tradeoff between energy conservation and latency minimization.

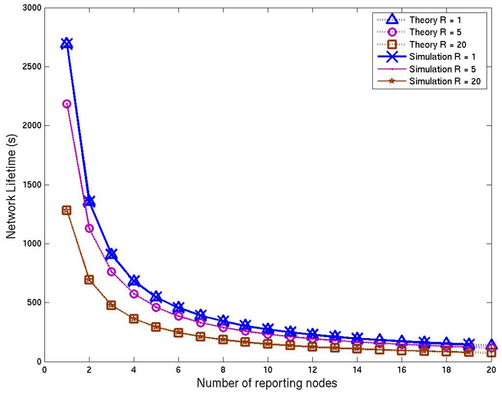

Fig. 9. Sensor network lifetime.

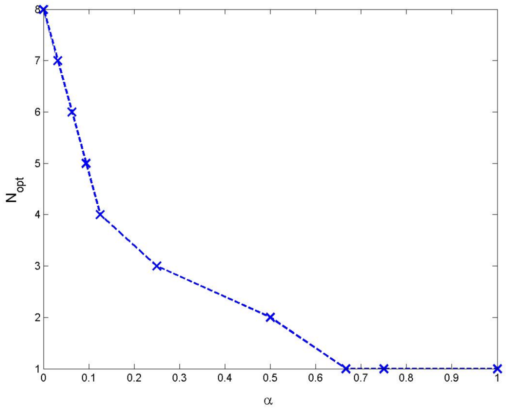

Fig. 11. The optimal number of reporting nodes for a varying value of the weight α.

As stated before, energy-efficiency is a critical issue in wireless sensor networks. However, minimizing the energy consumption in such networks must be achieved while respecting the maximum tolerable time to report an event. The optimal solution must therefore take into account both latency and energy constraints.

In this section, we propose a simple function f_{choice} to determine the optimal number of reporting nodes N_{opt} that achieves the above-mentioned tradeoff. f_{choice} can be expressed as follows:

$$f_{choice}\left(N,\alpha\right)=\alpha\cdot\frac{E_{RTC}\left(N\right)}{E_{average}}+\left(1-\alpha\right)\cdot\frac{T\left(N\right)}{T_{average}} \tag{37}$$

where α is a weight that ranges between $[0,1]$. It is fixed by the network administrator depending on the particular needs of the sensor application (i.e., whether more emphasis is given to energy conservation or to reporting latency minimization), $E_{average}$ and $T_{average}$ are respectively the mean value of $E_{RTC}\left(N\right)$ and $T\left(N\right)$ for the different number of reporting nodes N.

Figure 10 plots the evolution of f_{choice} as a function of the number of reporting nodes N. We consider two values of the weight $\alpha=1/8$ and $\alpha=1/4$. Two main observations can be identified through Fig. 10. First, f_{choice} is a convex function of N where the minimum is obtained for a certain N_{opt}. As such, N_{opt} minimizes the weighted function f_{choice} and achieves therefore the desired tradeoff between the energy conservation and reporting latency minimization. Moreover, we can observe through Fig. 10 that the value of N_{opt} depends on the weight α. Specifically, if more emphasis is given to the energy conservation aspect (i.e., α is set close to 1), the value of N_{opt} will be close to N_{opt_energy} (i.e., $N_{opt}=1$). In contrast, if more priority is given to the latency minimization aspect (i.e., α is set close to 0), the value of N_{opt} will be close to $N_{opt\_latency}$ (i.e., $N_{opt}=8$). This result is shown in Fig. 11, where N_{opt} decreases with α from $N_{opt\_latency}$ to N_{opt_energy}. It is worth noting that for the extreme cases where $\alpha=0$ and $\alpha=1$ we get respectively the same curves as in Figs. 7 and 8.

VII. CONCLUSION

In this paper, we explored the relationship between the wireless sensor network performance and the number of reporting nodes. To the best of our knowledge, we are the first to investigate the energy optimization problem from this perspective. Accordingly, we demonstrated that the optimal number of reporting nodes that minimizes the energy expenditure in the sensor network does not correspond to the fastest way to report an event. Based on this result, we proposed a simple methodology to achieve this tradeoff, which depends on the specific requirements of each WSN application.

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