Toward Reliable and Efficient Reporting in Wireless Sensor Networks

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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 network performance, particularly its lifetime, and the number of active reporting nodes N by using both analytical and simulation approaches. We first demonstrate that decreasing the number of reporting nodes increases the number of reports that need to be sent to the sink in order to achieve the desired information reliability regarding a detected event. On one side, we show that reducing the number of reporting nodes reduces the probability of collision occurrence. Based on these results and as the first main contribution, we derive the optimal number of reporting nodes N_{opt_energy} that minimizes the energy consumed to report reliably the occurrence of an event. In other words, we prove that limiting the reporting tasks of a detected event to a small subset of sensor nodes (i.e., N_{opt_energy}), instead of using all the sensor nodes in the event area, enables significant energy conservation. Furthermore, with regard to the latency properties, we show that the average time required to reliably report an event is a convex function of the number of reporting nodes, where the minimum is obtained for a given $N_{opt\_latency} \neq N_{opt\_energy}$. Consequently and as the second main contribution, we demonstrate that the fastest way to reliably report an event does not correspond to the optimal way of consuming the scarce network energy. The trade-off between these two requirements is sensor application specific, depending on this one particular need in terms of quality of service. To the best of our knowledge, we are the first to tackle the energy efficiency problem from this perspective while considering the energy-reliability-latency trade-offs.

Index Terms—Wireless sensor networks, energy conservation, number of reporting nodes, information reliability, performance analysis.

1 Introduction

Energy efficiency is a critical issue in wireless sensor networks (WSNs) due to the limited capacity of the sensor nodes' batteries [1]. Once a WSN is in place, its lifetime must last as long as possible based on the initially provided amount of energy. Consequently, techniques minimizing energy consumption are required to improve the network lifetime. A widely employed mechanism is to schedule sensor nodes' activity so that redundant nodes enter the sleep mode as often as possible [2], [3]. Based on this concept, several energy-efficient MAC protocols [4], [5], [6] and energy-efficient routing protocols [7], [8] have been proposed in the literature. Additional solutions for reducing energy consumption based on congestion control are also proposed in [9] and [10]. These mechanisms aim at achieving further energy conservation by reducing the energy wastage resulting from the frequently occurring collisions in WSNs.

As such, 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 information reliability of the reported event (i.e., the accuracy of the reported information). In this regard, the key performance metrics in WSNs are both the *network lifetime* and the *average time required to report reliably an event*. The optimal solution must therefore take into account these two metrics. In view of this, increasing research efforts have been recently trying to investigate the trade-offs either between energy consumption and data delivery delay [5], [11] or between energy consumption and reliability [12]. In this paper, we rather aim at optimizing a particular system metric, which is the number of reporting nodes, to achieve the triplet energy-reliability-latency requirements all together.

Indeed, the current studies addressed the energy optimization issue without considering the impact of the number of reporting nodes on the WSN performance, i.e., how the network lifetime and the reporting latency evolve with respect to the number of active reporting nodes. Our work is motivated by the results in [13] and [14], which highlight the significant energy conservation that could be achieved when spatial and temporal correlation is exploited to reduce the number of redundant transmitted packets in the network. Specifically, [14] proposed a MAC protocol that reduces the number of transmitted packets regarding an observed event by limiting the reporting tasks to a small number of sensor nodes, hence benefiting from the spatial correlation among the densely deployed sensor nodes within the event area.

In this paper, we present an in-depth analysis of the impact of the number of active reporting nodes on the WSN performance (i.e., information reliability, event reporting time, and network lifetime). Our ultimate goal is to

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determine the optimal number of reporting nodes that both minimizes the energy required to report reliably an event and respects the latency constraints. To the best of our knowledge, we are the first to tackle the energy optimization problem from this perspective while considering the energy-reliability-latency trade-offs.

To achieve this, we develop new analytical models to explore the relationship between the WSN performance (i.e., information reliability, event reporting time, and network lifetime) and the number of active reporting nodes. Specifically, we analyze the basic access mechanism of the IEEE 802.11 distributed coordination function (DCF) with its optional request-to-send/clear-to-send (RTS/CTS) scheme [15]. This basic protocol and its associated variants, adapted to the WSN environment, are widely used in the currently deployed WSNs to arbitrate the medium access between the multiple competing sensor nodes to communicate with the sink.

In our analysis, we proceed as follows: We first derive the average number of reports $R(N)$ required to report reliably an event, given that the number of active reporting nodes is N. Then, we calculate the collision probability in such networks as a function of N and the reporting frequency f. Based on these results and as the first main contribution of this paper, we derive the optimal number of reporting nodes N_{opt_energy} that minimizes the energy needed to report reliably an event. Accordingly, the maximal network lifetime is achieved when only N_{opt_energy} reporting nodes are activated while the remaining nodes undergo the sleep mode. We then show analytically that the time required to report reliably an event is a convex function of N, where the minimum is obtained for $N_{opt\_latency} \neq N_{opt\_energy}$. Consequently and as the 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 trade-off between these two requirements (i.e., energy consumption and reporting time) depends mainly on the specific QoS needs of the sensor application.

The rest of this paper is organized as follows: Section 2 discusses the related work, and Section 3 presents the general problem statement. In Section 4, we investigate the relationship between the desired information reliability and the number of active reporting nodes. Communications among sensor nodes to select the reporting nodes and the associated MAC protocol are outlined in Section 5. In Sections 6 and 7, we introduce the mathematical models to evaluate the impact of the number of reporting nodes on the WSN performance. Analytical and simulation results are discussed in Section 8. Finally, Section 9 concludes this paper.

2 Related Work

As stated before, in order to minimize the energy consumption in WSNs, several energy-efficient MAC protocols [4], [5], [6] and energy-efficient routing protocols [7], [8] have been proposed in the literature. These schemes aim at decreasing the energy consumption by using sleep schedules. The key idea behind this concept is to turn off completely some parts of the sensor circuitry (e.g., microprocessor, memory, and radio) when it does not receive or transmit data instead of keeping the sensor node in the idle mode. This scheme simply attempts to reduce wasted energy due to idle listening, i.e., lost energy, while listening to receive possible traffic that is not sent. To do so, works in [4], [5], and [6] suggest wake-up scheduling schemes at the MAC layer to activate sleeping nodes when it is needed. On the other hand, works in [7] and [8] address the problem at the network layer by proposing new routing solutions that take into account the sleep state of some network nodes.

Although there is significant energy saving achieved by such schemes, the WSN keeps always sending redundant data. Typically, WSNs rely on the cooperative effort of the densely deployed sensor nodes to report detected events. As a result, multiple sensor nodes may report the same event. To further decrease energy consumption, several works are now focusing on the elimination of the useless redundant information [13], [14], [16], [17]. The reduction of the number of redundant packets can be achieved either at the data originator level (i.e., sensor nodes that detect the event) [13], [14] by regulating their access or at the intermediate sensor nodes routing the information to the sink by means of aggregation mechanisms [16], [17].

In the latter case, paths from different sources to the sink form an aggregate tree, where the redundant data at the branching nodes are replaced by a single message. In doing so, the number of packets traversing the network is considerably reduced, which leads to significant energy conservation [16], [17]. However, such schemes affect the reliability of the information transmitted to the sink. The aggregation process at intermediate nodes must therefore be aware of these reliability constraints [10], which may become so in case of challenging multiple aggregation points in the route to the sink.

Reducing the redundant information is more efficient when it is realized at the source nodes [14]. This is achieved by limiting the number of access reporting nodes. Specifically, Vuran and Akyildiz [14] show that using a small subset of the nodes (called representative nodes), rather than all the sensor nodes in the event area, to report the detected event reduces considerably the energy consumption. Indeed, limiting the number of reporting nodes alleviates the energy wastage caused by collisions, idle listening, and redundant packet transmission. In the optimal case, only one node will be allowed to report the detected event. In such a case, collisions, idle listening, and redundant packet transmission are totally eliminated. But, such choice may not guarantee the required reliability, since only one report is received by the sink regarding the observed event.

Vuran and Akyildiz [14] determine, using the spatial correlation among sensor nodes, the minimum number of representative nodes $N_{\min}$ that need at least to be activated in order to comply with the required data reliability at the sink. Accordingly, each node, among the $N_{\min}$ representative ones, needs to transmit one report only to fulfill the reliability requirement. In this case, the optimal energy consumption in the network is achieved when only $N_{\min}$ reporting nodes are activated while the remaining nodes undergo the sleep mode. To accomplish this, Vuran and Akyildiz [14] propose an enhancement of the IEEE 802.11 DCF MAC protocol in order to support the representative node selection feature. This simple MAC protocol was proven to be efficient as it outperforms existing energy-aware MAC protocols such as [5], [6], and [15]. This MAC protocol is an important achievement and represents an essential building block for future research dealing with access nodes' regulation.

As a key distinguishing feature compared to [14], each representative node in our study is allowed to transmit as many packets as needed to attain the desired reliability. Our aim is to introduce additional flexibility to select among the reporting nodes, which may lead to supplementary energy conservation. Indeed, as the first advantage of our method, we demonstrate that the required reliability could be maintained, even if the number of active reporting nodes N is less than the minimum boundary $N_{\min}$ obtained in [14]. However, this requires more than $N_{\min}$ reports to be transmitted to the sink by the $N < N_{\min}$ active reporting nodes, since the correlation among the transmitted data increases when the number of reporting nodes decreases. In this regard, additional energy may be required to report reliably the detected event.

On the other hand, reducing the number of reporting nodes beyond $N_{\min}$ decreases the energy wastage due to collisions and idle listening. Clearly, a trade-off exists between these opposite requirements to minimize energy consumption (i.e., the reduction of the energy wastage caused by collisions and idle listening when reducing N beyond N_{min}, at the expense of the increase in the number of reports that need to be sent to the sink to attain the desired reliability). To explore this trade-off, we develop new analytical models. Based on the elaborated models, we determine the optimal number of reporting nodes N_{opt_energy} that minimizes the energy consumption in reliable WSNs. As the second benefit of our method, we show that $N_{opt\_energy} < N_{\min}$, which proves that our scheme not only introduces more flexibility to attain the desired reliability but also enables further energy conservation.

However, this choice may not comply with the latency constraints. Recall that in our study, we aim at deriving the optimal numbers of reporting nodes that minimize both the energy consumption and the reporting latency. In this regard, as the second stage of our optimization process, we have to make sure that the adopted number of reporting nodes ensures the maximum tolerated latency. To the best of our knowledge, this is the first effort that considers the triplet energy-reliability-latency constraints.

It is worth noting that, as it will be described later in Section 5, we will adapt the MAC proposed in [14] to meet our specific requirements. Furthermore, additional signaling protocols such as the ESRT protocol [10] could be also used to control and adjust periodically (online) the WSN setting parameters in order to maintain the desired reliability level.

Recall that the WSN topology changes over time, since some nodes may die. In this case, signaling protocols are responsible for conveying the network state modifications to the sink node in order to calculate the new optimal setting parameters N (i.e., the number of reporting nodes to be activated) and $R(N)$ (i.e., the associated number of reports to achieve the desired information reliability). We note that in [10], the reliability $R(N)$ of the event information, measured in terms of the number of received packets at the sink, was considered to be a fixed parameter, which is defined by the application, regardless of the network state. Unlike [10], we demonstrate here that the reliability $R(N)$, required to not exceed a certain information distortion, depends mainly on the number of the reporting nodes N.

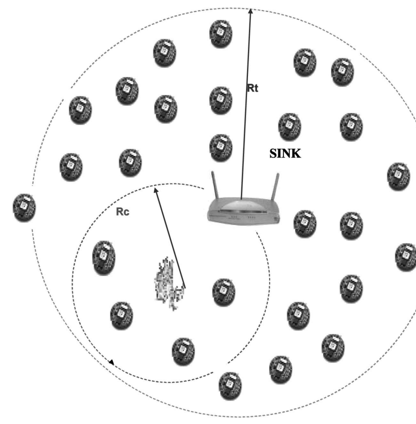


Fig. 1. Example of a sensor network.

To summarize, our study enables us to derive the optimal setting parameters (the number of reporting nodes N, the associated number of reports $R(N)$, and reporting frequency f) to be used later by protocols such as [10], [14] in order to achieve the energy-reliability-latency trade-offs.

3 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 prespecified type of events. Once an event occurs, it has to be reported to the sink by the sensor nodes. In such a 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 (i.e., sensing range) and transmission range R_t, as shown in Fig. 1.

We denote by N_{tot} the total number of sensor nodes within the event area. Then, $N (N \in \{1, \ldots, N_{tot}\})$ represents the number of active nodes allowed to report that 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 active 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 the optimal energy consumption. The N reporting nodes keep generating reports at a rate f_s until the required event detection reliability $R(N)$ is achieved. The desired event reliability $R(N)$ is the number of data packets required by the sink to consider the event as reliable [10]. An event is said to be reliably reported when the required information accuracy is achieved at the sink node. Once the sink node receives $R(N)$ reports, it instructs the sensor nodes to stop the event reporting.

In this study, we aim at analyzing the impact of the number of active reporting nodes N on the WSN performance. The basic idea is to let some potential reporting nodes enter the 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 average number of reports $R(N)$, the collision probability, the average time, and the associated energy required to report reliably an event. To perceive the pure effect of the varying number of reporting nodes N, we suppose in this work, as in [10], that all the sensor nodes are within one hop from the sink (see Fig. 1). Doing so, we avoid the slight impact of the multihop routing. Note that similar results can be easily obtained for multihop WSNs, as will be shown in Section 7.

4 Relationship between Information Reliability and the Number of Reporting Nodes

In this section, we extend the work in [14] to derive the number of reports $R(N)$ required to report reliably an event (i.e., to ensure the required information accuracy), given that the number of active reporting nodes is N. This consists of calculating the minimal number of reports $R(N)$ that need to be sent to the sink by the N active reporting nodes in order to not exceed a predefined tolerable information distortion $D_{\max}$. The event reporting operation is considered reliable only when the distortion between the event source S and its estimation at the sink becomes less than $D_{\max}$.

In [14], the authors provide an expression of the observed information distortion at the sink D when each node, among the N representative ones (out of the N_{tot} sensor nodes in the event area), transmits only one report to the sink. Accordingly, the distortion can be written as follows:

$$D(N) = \sigma_S^2 - \frac{\sigma_S^4}{N\left(\sigma_S^2 + \sigma_N^2\right)}\left(2\sum_{i=1}^{N}\rho_{(s,i)} - 1\right) + \frac{\sigma_S^6}{N^2\left(\sigma_S^2 + \sigma_N^2\right)^2}\sum_{i=1}^{N}\sum_{j\neq i}^{N}\rho_{(i,j)}, \quad (1)$$

where the following hold:

- σ_S^2 and σ_N^2 are the variance of the event information S_i and the observation noise N_i of each sensor node n_i $(i = 1, \ldots, N)$, respectively.
- $\rho_{(s,i)}$ denotes the correlation coefficient between the event source located at coordinate s and the sensor node n_i $(i = 1, \ldots, N)$.
- $\rho_{(i,j)}$ denotes the correlation coefficient between nodes n_i and n_j $(i, j = 1, \ldots, N)$.

To derive (1), the observation noise N_i of each sensor node n_i is modeled as independent and identically distributed Gaussian random variable of zero mean and variance σ_N^2. Moreover, the event information S_i sensed by the node n_i, which is an observation of the original event source S, is modeled as a joint Gaussian random variable (JGRV) as follows:

$$E\{S_i\} = 0 \quad var\{S_i\} = \sigma_S^2,\ i = 1, \ldots, N, \qquad \rho_{(i,j)} = \frac{E[S_i, S_j]}{\sigma_S^2} = e^{-\left(d_{(i,j)}/\theta_1\right)},\ \text{for } \theta_1 > 0, \quad (2)$$

where $d_{(i,j)}$ denotes the distance between nodes n_i and n_j. We note that in this case, the correlation coefficient $\rho_{(i,j)}$ between the sensor observations is estimated using the Power Experimental model [18].

Hence, D simply measures the distortion between the original event S and its estimation at the sink obtained through the N observations $X_i = S_i + N_i$. Based on the expression of D, Vuran and Akyildiz [14] derive the minimum number $N_{\min}$ of reporting nodes that need to be activated among the N_{tot} potential ones in order to not exceed the tolerable information distortion $D_{\max}$. In this case, receiving $N_{\min}$ reports at the sink, i.e., one report from each sensor node, is sufficient to attain the desired reliability.

As mentioned before, unlike the work in [14], in our study, we allow each reporting node to transmit as much packets as needed to attain the desired reliability. Doing so, the required reliability could be achieved, even if the number of active reporting nodes $N < N_{\min}$. However, this would imply probably more than $N_{\min}$ reports to be received at the sink level in order to fulfill the reliability requirements. Indeed, the correlation among the transmitted data by the WSN increases when the number of reporting nodes decreases. From this perspective, additional energy could be required to report reliably an event, since more reports need to be sent.

However, activating only $N < N_{\min}$ sensor nodes reduces the energy wastage due to collisions and idle listening. There must be an optimal value of $N = N_{opt\_energy} \in [1, \ldots, N_{\min}]$ that achieves the above-mentioned trade-off, i.e., that minimizes the energy required to report reliably an event. Henceforth, our aim is to demonstrate that $N_{opt\_energy} < N_{\min}$. In doing so, we prove, as will be shown in Section 8, that our proposal enables further energy conservation when compared to [14], as well as additional flexibility to attain the desired reliability.

To start, we have to derive a generalized expression of the distortion $D(N, r)$ that takes into account both the number of active reporting nodes N and the total number of reports r that they transmit to the sink. Recall that in [14], the expression of the distortion (see (1)) is derived for the particular case that $r = N$. Using the same model for the information collection and the same assumptions as in [14], $D(N, r)$ can be expressed as follows:

$$D(N, r) = \sigma_S^2 - \frac{\sigma_S^4}{r\left(\sigma_S^2 + \sigma_N^2\right)}\left(2\sum_{k=1}^{r}\rho_{(s,n(k))} - 1\right) + \frac{\sigma_S^6}{r^2\left(\sigma_S^2 + \sigma_N^2\right)^2}\sum_{k=1}^{r}\sum_{m\neq k}^{r}\rho_{(n(k),n(m))}, \quad (3)$$

where $n(k)$ denotes the coordinate of the sensor node that transmits the kth report. We note that in our study, we use

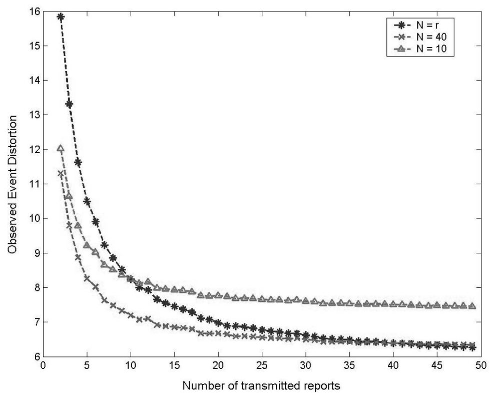


Fig. 2. Average distortion as a function of the number of transmitted reports, considering different numbers of active reporting nodes.

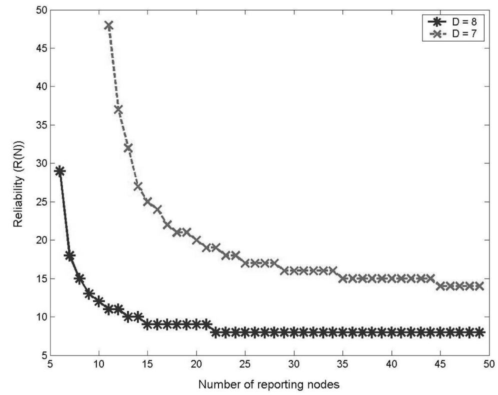


Fig. 3. Average reliability as a function of the number of reporting nodes for different distortion values.

the same CSMA/CA-based DCF MAC protocol proposed in [14]. According to the CSMA/CA mechanism, all the N competing reporting nodes have equal probability of accessing the medium. In this regard, the node that transmits the kth report (i.e., $n(k)$) can be of equal probability with one of the N reporting nodes. In other words, $\Pr\{n(k) = n_i\} = \frac{1}{N}$, $\forall i = 1, \ldots, N$. Hence, we get

$$\begin{aligned} \rho_{(s,n(k))} &= \frac{1}{N}\sum_{i=1}^{N} \rho_{(s,i)}, \qquad \forall k = 1, \ldots, r, \\ \rho_{(n(k),n(m))} &= \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} \rho_{(i,j)}, \ \forall k, m = 1, \ldots, r, \end{aligned} \tag{4}$$

where i and j $(i, j = 1, \ldots N)$ are respectively the coordinates of the sensor nodes n_i and n_j. Substituting (4) in (3), the distortion $D(N, r)$ can be therefore written as follows:

$$\begin{aligned} D(N, r) = \sigma_S^2 &- \frac{\sigma_S^4}{r(\sigma_S^2 + \sigma_N^2)}\left(2\frac{r}{N}\sum_{i=1}^{N}\rho_{(s,i)} - 1\right) \\ &+ \frac{\sigma_S^6}{r(\sigma_S^2 + \sigma_N^2)^2}\frac{r-1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\rho_{(i,j)}. \end{aligned} \tag{5}$$

Fig. 2 plots the distortion evolution according to both our method (i.e., using (5)) and the work in [14] (i.e., using (1)). The distortion is plotted as a function of the number of transmitted reports r by the N active reporting nodes. To calculate $D(N, r)$, we consider different positions of the N_{tot} sensor nodes in the event area. Moreover, for each N_{tot}'s configuration, we take into account the different possible sets of the N selected reporting nodes among N_{tot}. As an example, in this figure, $\sigma_S = 15$, $\sigma_N = 2$ and $\theta_1 = 5{,}000$.

Let us first focus on the results generated using our method. In this case, the distortion is presented for two values of N (i.e., $N = 10$ and $N = 40$). Based on the obtained curves, two main observations can be made:

- First, the figure shows that for a given N, the observed distortion at the sink decreases logically with the increase in r, since the sink receives more information from the event area. This distortion becomes relatively constant when the number of transmitted reports is large. Indeed, in this case, the transmitted data to the sink becomes highly redundant.
- Second, the same distortion level can be achieved by different values of N. But in this case, the lower the value of N, the greater the number of reports $R(N)$ required to attain the same reliability. Indeed, the correlation among the transmitted data increases when N decreases. To illustrate this, assume that the maximal tolerable distortion $D_{\max}$ is equal to 8. To achieve this, at least $r = 16$ reports need to be transmitted by the network when we activate only $N = 10$ reporting nodes among the $N_{tot} = 50$ existing sensor nodes in the event area, whereas $r = 6$ reports are sufficient when N is set equal to 40. To gain insight regarding this finding, Fig. 3 represents the minimum number of reports $R(N)$ that need to be sent to the sink to achieve a certain distortion $D_{\max}$ as a function of the number of reporting nodes. As explained previously, we can see that $R(N)$ decreases with N. Note that there are a minimum number of nodes that need at least to be activated in order to achieve the desired reliability. In other words, when N is too small, $R(N)$ becomes infinite. As such, for each distortion value, there exist a minimum number of reporting nodes to achieve the desired information reliability.

Let us now consider the results regarding the method introduced in [14], which can be seen as a particular case where $r = N$. As expected, we can observe in Fig. 2 that the obtained curve intersects those with $N = 40$ and $N = 10$ when $r = 40$ and $r = 10$, respectively. Moreover, we can see that the distortion decreases logically with the number of transmitted reports (i.e., the number of reporting nodes). As stated before, this method entails a lower bound on the number of reporting nodes that need at least to be activated in order to respect the tolerable distortion. For instance, considering again that $D_{\max} = 8$ implies activating at least $N_{\min} = 12$ sensor nodes to fulfill the distortion requirement. According to this method, activating only $N_{\min}$ reporting nodes allows the optimal energy consumption.

Note that this same level of reliability can be achieved for $N < N_{\min}$ when considering our method (see Fig. 3). Clearly, our scheme introduces further flexibility to achieve the desired distortion at the sink. In the remainder of this

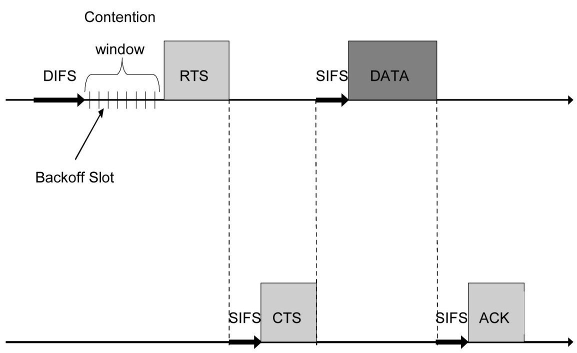


Fig. 4. Basic access mechanism of the IEEE 802.11 DCF.

paper, we will demonstrate the interest of such flexibility. We will prove that the minimum energy consumption in reliable WSNs can be achieved for $N_{opt\_energy} < N_{\min}$.

5 Access in Wireless Sensor Networks

5.1 The IEEE 802.11 Distributed Coordination Function MAC Protocol

As stated before, communications in current deployed WSN 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 first senses the channel activity until an idle period equal to a Distributed Interframe 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 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 Interframe 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 each unsuccessful transmission, CW is doubled until a maximum backoff window size value $CW_{max} = 1{,}023$ is reached. Once the frame is successfully transmitted, the CW value is reset to CW_{min}. Fig. 4 illustrates the IEEE 802.11 DCF access mechanism.

5.2 Extension of the IEEE 802.11 MAC Protocol to Support the Reporting Nodes Selection Scheme

Due to energy consideration and the event-based traffic in WSNs [19], the DCF protocol described so far cannot be directly applied. In view of this, new solutions need to be developed to meet the specific requirements of WSNs, particularly in our case, to support the reporting node selection feature.

Current energy-aware MAC design for WSNs fall into two categories: either TDMA- or contention-based protocols such as the standardized IEEE 802.11 DCF protocol are used. Although the energy conservation that could be achieved by the TDMA approach, thanks to its contention-free nature, it is not always preferred due to the associated time synchronization cost [1]. In contrast, the contention-based DCF protocol is widely used in ad hoc networks due to its simplicity and robustness. Therefore, there has been more emphasis recently on decreasing the energy consumption of the existing DCF MAC protocol rather than on conceiving new MAC mechanisms.

One attempt to achieve this is the CC-MAC protocol [14], which will be used in our study. This choice is primarily motivated by the results in [14], which demonstrate that the CC-MAC protocol outperforms the existing energy-aware MAC protocols [5], [6], [15]. Moreover, the philosophy behind the CC-MAC protocol fits our requirements best.

Recall that the key idea behind our proposal is to limit the reporting tasks of a detected event to a small subset of sensor nodes in order to save energy consumption while respecting both latency and reliability constraints. Indeed, by reducing the number of access nodes, significant energy gain can be achieved, thanks to three enabling factors:

- First, such a method alleviates the energy wastage by minimizing collisions.
- Second, we also reduce the number of redundant transmitted packets, and hence, more energy is conserved.
- Finally, additional nodes (i.e., the nonselected nodes to report the detected event) undergo the sleep state, which reduces the idle listening. We note that idle listening represents the major source of energy inefficiency, as will be shown in Section 8.

In the next section, we will show how we can derive the optimal number of reporting nodes that achieve minimal energy consumption while respecting the latency and reliability constraints. Such an algorithm runs at the sink level, and it determines dynamically, according to the current network state, the optimal setting parameters (i.e., the number of active reporting nodes N and the associated required number of reports to achieve the desired reliability $R(N)$). This information concerning the number of reporting nodes to be activated is then to be broadcast to all the sensor nodes, which must be able to make use of it in order to regulate their access. This is typically the role of the MAC protocol.

Following this philosophy, the CC-MAC protocol exploits the information about correlation, sent by the sink node, to select only a small subset of sensor nodes among all the potential ones to report the detected event. The aim in this case is to suppress the redundant information from being injected into the WSN. The selection process is achieved based on correlation radius R_{corr}, which is calculated at the sink node and indicates the average distance allowable between selected representative nodes. Note that in our study, a new set of reporting nodes is elected for each event occurrence, even if the same event occurs again in the same region. As such, the reporting node role rotates among the sensor nodes within the event area, which allows us to equalize the energy consumption throughout the network.

The operation of the CC-MAC protocol can be described as follows: At the beginning, all the sensor nodes in the event area contend for the medium access according to the basic IEEE 802.11 DCF protocol, as explained in Section 5.1. Once a sensor node accesses the medium by sending correctly a RTS frame, all the other nodes within the R_{corr} radius stop their transmission attempt and undergo the sleep mode. Then, the remaining active nodes try again to access the medium, and the selection process is executed once more until all the representative nodes are elected.

Now, to make use of the CC-MAC protocol, we only need to calculate the appropriate R_{corr} that enables us to activate exactly N sensor nodes. In other words, we need to derive the correspondence between R_{corr} and N. This is easily given by the following expression:

$$N \cdot \Pi \cdot R_{corr}(N)^2 = \Pi \cdot R_c^2.$$

This expression simply implies that the surface covered by the N correlation areas (i.e., the disk of radius $R_{corr}(N)$, where the elected reporting node at the center) associated with the N elected reporting nodes corresponds to the entire event area. We underline that the main advantage of the CC-MAC protocol is its simplicity, since it needs no modifications in the existing DCF MAC protocol. It only introduces an additional mechanism to limit the medium access to a small subset of N nodes rather than to use all the potential ones (i.e., N_{tot}). Using the CC-MAC protocol, the N_{tot} sensor nodes choose their representatives only based on the information about the value of N sent by the sink, without requiring any explicit internode communication, thus keeping the simplicity and the distributed feature of the original DCF protocol.

6 Performance Analysis

In this section, we present mathematical models for deriving both the WSN lifetime and the average time required to report an event as functions of the number of reporting nodes N and the reporting frequency f. To achieve this, we first calculate the collision probability in such networks caused by the multiple reporting nodes. Then, we derive the average time required to report reliably an event (i.e., to transmit $R(N)$ reports). Based on this result, we can easily obtain the associated consumed energy. Finally, using the analytic formula given in [20], we obtain the expression of the WSN lifetime.

In this study, we distinguish between two modes of functioning according to the network reporting frequency f: the saturated and the 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, for the sake of simplicity, previous works limited their studies to the saturated mode. The unsaturated mode was considered in few papers such as in [10] by means of simulations. In this work, we develop an analytical model for each mode. To our knowledge, we are the first to study analytically the WSN performance under the unsaturated regime. Our aim is to analyze the impact of the reporting frequency f, in addition to N, on the WSN performance.

6.1 Probability of Collision in IEEE 802.11 Distributed Coordination Function-Based MAC Protocols

In this section, we derive the collision probability as a function of the number of reporting nodes N and the reporting frequency f, considering both the saturated and the unsaturated regimes. We note that collision is a key factor that impacts the total energy consumption and the time required to report an event. In fact, the more frequent the collisions are, the more that time and energy are spent to report an event.

6.1.1 *Probability of Collision in the Saturated Regime*

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 $B_i (i = 1, \dots, N)$ of different stations expire at the same time.

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 the literature to simplify the analytical models. Accordingly, following a successful transmission, we can also assume that the backoff $B_i (i = 1, \dots, N)$ 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 [21]. The accuracy of these approximations is justified, as will be demonstrated in Section 8, through the perfect match between the analytical and simulation results.

Let us now calculate the probability of collision occurrence $P_{col\_sat}(N)$ when reporting an event, that is, during a 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, the RTC is the time required by the WSN to report an event to the sink. Before we delve in the calculations, it is important to note that our model gives a simple expression and more accurate results of the collision probability than [21].

As we neglect the occurrence of multiple successive collisions, during an RTC cycle, a report can be either successfully transmitted from the first attempt (Fig. 5a) or

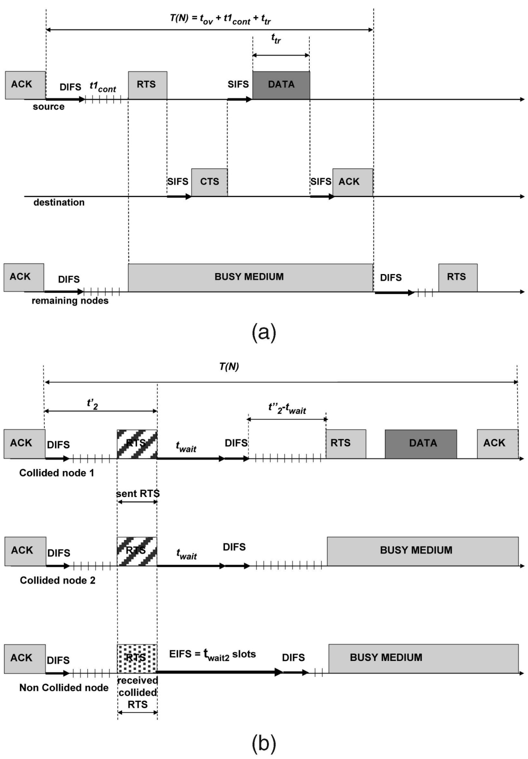


Fig. 5. The RTC. (a) Successful transmission from the first attempt. (b) Successful transmission after a first failed attempt.

following a first collision (Fig. 5b). Hence, a collision can only occur at the beginning of the RTC cycle with a probability $P_{col\_sat}(N) = P_c(N)$, where $P_c(N)$ is the probability of collision among N competing access nodes, with their associated backoffs $B_i (i = 1, \ldots, N)$ ranging 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:

$$P_c(N) = \Pr\{\overline{U}\} = \sum_{k=0}^{CW_{min}} \Pr\{X = k, \overline{U}\}, \tag{6}$$

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

$$\begin{aligned} \overline{U} &= \{\exists i, j \in < 1, N >, i \neq j, B_i = B_j = X\} \\ &= \{\text{Collided transmission}\}. \end{aligned} \tag{7}$$

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:

$$\Pr\{X = k, \overline{U}\} = \sum_{i=2}^{N} \binom{N}{i} \frac{(CW_{\min} - k)^{N-i}}{(CW_{\min} + 1)^N}. \tag{8}$$

6.1.2 Probability of Collision in the Unsaturated Regime

In the unsaturated regime, the reporting frequency of each station is relatively low. Specifically, a reporting node may have no report to transmit at the beginning of a new RTC cycle. Recall that previous works limited their study to the saturated regime, omitting the unsaturated one. In other words, the collision probability is always calculated by considering the saturated regime. So, to the best of our knowledge, we are the first to derive this parameter in the unsaturated regime.

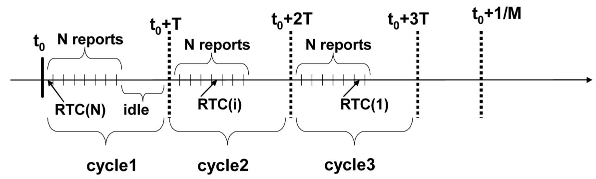


Fig. 6. Transmission cycles in the unsaturated regime.

In order to compute the probability of collision, we assume that all the reporting nodes detect an occurring event exactly at the same time. Then, they will try to send new reports each $T = 1/f_s$ units of time until the desired event reliability R is attained. In the unsaturated regime, we deal with successive cycles of T units of time. During each cycle, N reports are transmitted to the sink (see Fig. 6). Each cycle of T units of time is thus composed of N successive RTC cycles corresponding to the N reports' transmission, followed by an idle period. This idle period is interrupted, and thus, the next cycle T begins as soon as the reporting nodes generate their new reports. In this regard, T can be expressed as follows:

$$T = \sum_{i=1}^{N} RTC(i) + \text{idle\_period}, \tag{9}$$

where $RTC(i)$ corresponds to the time required by the WSN to report an event to the sink when the number of active reporting nodes (i.e., nodes that have not yet transmitted their reports) is i.

Specifically, at the beginning of a cycle T, all the N reporting nodes generate new reports to transmit to the sink. Immediately, the reporting nodes leave their idle states (see Fig. 6) and proceed according to the DCF algorithm, as described in Section 5.1, to transmit their reports.

Let us now calculate the collision probability among access nodes trying to report the detected event. It is defined as the probability of collision when there is at least one packet to be sent by the N reporting nodes. Hence, the probability of collision can be written as follows:

$$P_{col\_unsat}(N) = \Pr\{\text{Collision occurs} | Y \geq 1\},$$

where Y denotes the stationary state of the stochastic process $\{Y(t), t \geq 0\}$, which represents the number of reporting nodes still having a packet to transmit. By conditioning on the stationary state Y, we get

$$\begin{aligned} P_{col\_unsat}(N) = \sum_{i=1}^{N} &\Pr\{\text{Collision occurs} | Y = i\} \\ &\times \Pr\{Y = i | Y \geq 1\}, \end{aligned}$$

where $\Pr\{\text{Collision occurs} | Y = i\}$ can be derived by simply using (6) as follows:

$$\Pr\{\text{Collision occurs} | Y = i\} = P_c(i). \tag{10}$$

On the other side, the expression of $\Pr\{Y = i|Y \geq 1\}$ is simply given by

$$\Pr\{Y = i|Y \geq 1\} = \frac{RTC(i)}{\sum_{j=1}^{N} RTC(j)} \simeq \frac{1}{N}. \quad (11)$$

Finally, we derive the expression of the collision probability as follows:

$$P_{col\_unsat}(N) = \frac{1}{N}\sum_{i=1}^{N} P_c(i). \quad (12)$$

6.2 Average Time to Report an Event

In this section, we evaluate the average time of an RTC in both the saturated and the unsaturated regimes. It is the mean time required by the WSN to successfully transmit a report when the number of reporting nodes equals N.

6.2.1 Average Time to Report an Event in the Saturated Regime

Considering the network under the saturation conditions, the overall transmission time of a report (i.e., the RTC) can be written as follows:

$$T_{sat}(N) = t_{tr} + t_{ov} + t_{cont}(N), \quad (13)$$

where t_{tr} is the transmission time of the data packet, and t_{ov} is a constant overhead, which can be simply deduced based on Fig. 4 and is thus given by

$$t_{ov} = DIFS + t_{RTS} + 3 \cdot SIFS + t_{CTS} + t_{ACK}. \quad (14)$$

Moreover, $t_{cont}(N)$ represents the average time spent in the contention procedure when N reporting nodes compete for the medium access, with their associated backoffs $B_i (i = 1, \ldots, N)$ ranging between $[0, CW]$. In other words, it is the extra time lost due to the collision occurrence. The derivation of $t_{cont}(N)$ is provided in the Appendix. Note that in the context of our reliable WSN, the average time needed to report reliably an event in the saturated regime is $R(N) \times T_{sat}(N)$.

6.2.2 Average Time to Report an Event in the Unsaturated Regime

In the unsaturated regime, the reporting frequency of each station is low enough so that the medium remains free for a period of time after the transmission of N reports. As stated before, we deal with successive cycles of $T = \frac{1}{f}$ units of time. During each cycle, N reports are transmitted to the sink (see Fig. 6). Specifically, at the beginning of a cycle, all the N reporting nodes compete to access the channel, similar to the saturated regime. Once the first report is successfully transmitted, the remaining $(N-1)$ nodes compete again to access the data channel. Then, once the next report is transmitted successfully, the $(N-2)$ remaining nodes compete once more to access the medium, and so on, until all the reports are transmitted. Hence, we get

$$T_{unsat}(N) = \frac{1}{N}\sum_{i=1}^{N} T_{sat}(i). \quad (15)$$

The average time required to report reliably an event in the unsaturated regime can be therefore written as follows:

$$\frac{1}{f} \times \left\lfloor \frac{R(N)}{N} \right\rfloor + \left(R(N) - \left\lfloor \frac{R(N)}{N} \right\rfloor N \right) \times T_{unsat}(N).$$

6.3 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, the reporting frequency f, and the desired reliability $R(N)$. Based on [20], the average network lifetime can be expressed as follows:

$$T_{network\_lifetime}(N, f) = \frac{E_{initial} - E_w}{E_{WSN}(N, f)}, \quad (16)$$

with

$$E_{WSN}(N, f) = \lambda E_{RTC}(N, f) + E_c, \quad (17)$$

where $E_{WSN}(N, f)$ is the average amount of energy consumed per unit of time by the network, 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., $R(N) \times M$), and $E_{RTC}(N, f)$ 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 $E_{RTC}(N, f)$ and E_c.

6.3.1 Sensor Network Lifetime in the Saturated Regime

Hereafter, we first evaluate the average energy $E_{RTC\_sat}(N)$ required by the WSN to successfully transmit a report under the saturated regime (i.e., during an RTC cycle) when the number of active reporting nodes equals N. To achieve this, we take into account transmitting, listening, idling, and sleeping energies. We denote by E_{sleep}, E_{idle}, E_{tr}, and E_{rx} the consumed energy per unit of time during the sleep, idle, transmitting, and listening states, respectively. As shown in Fig. 1, in our model, each sensor node can listen to all the other sensors and can reach the sink in one hop. In view of this, $E_{RTC\_sat}(N)$ can be simply written as follows:

$$E_{RTC\_sat}(N) = E_{tr}(N) + E_{ov}(N) + E_{cont\_sat}(N) + E_{sleep\_sat}(N), \quad (18)$$

where

- $E_{tr}(N)$ is the amount of energy consumed during the transmission of a data packet (i.e., during t_{tr}) by the N active reporting nodes,
- $E_{ov}(N)$ is the amount of energy consumed during the constant overhead period of time t_{ov} by the N active reporting nodes,

- $E_{cont\_sat}(N)$ is the amount of energy spent in the contention procedure under the saturated regime by the N active reporting nodes, and
- $E_{sleep\_sat}(N)$ is the energy consumed by the $(N_{tot} - N)$ inactive nodes (i.e., nodes under the sleep mode that do not participate in the reporting operation) during the total RTC period.

These quantities are expressed as shown in (19), where $t1_{cont}(N)$, $t''_2(N)$, and $B_c(N)$ are already defined in the Appendix for the calculation of the average time to report an event:

$$\begin{cases} E_{tr}(N) = t_r(E_{tr} + (N-1)E_{rx}), \\ E_{ov}(N) = E_{idle} \cdot N(DIFS + 3 \cdot SIFS) \\ \qquad + E_{rx} \cdot ((N-1)t_{RTS} + N \cdot t_{CTS} + N \cdot t_{ACK}) \\ \qquad + E_{tx} \cdot t_{RTS}, \\ E_{cont\_sat}(N) = (1 - P_c(N)) \times [N \cdot E_{idle} t1_{cont}(N)] + P_c(N) \\ \qquad \times \Big[E_{idle} \cdot N\big(t''_2(N) + DIFS + B_c(N) \text{ Slots}\big) \\ \qquad + \sum_{n=2}^{N} \Pr\{N_c = n|\overline{U}\} \\ \qquad \times (nE_{tx}t_{RTS} + (N-n)E_{rx}t_{RTS}) \Big], \\ E_{sleep\_sat}(N) = (N_{tot} - N) \cdot T_{sat}(N) \cdot E_{sleep}. \end{cases} \tag{19}$$

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

$$E_c = (1 - R(N) \cdot M \cdot T_{sat}(N)) \times \big(N \cdot E_{idle} + (N_{tot} - N) \cdot E_{sleep}\big). \tag{20}$$

The network lifetime in the saturated regime can be therefore expressed as follows:

$$T_{network\_lifetime}(N) = \frac{E_{initial}}{M \cdot R(N) \cdot E_{RTC\_sat}(N) + E_c}. \tag{21}$$

Recall that the denominator $(M \cdot R(N) \cdot E_{RTC\_sat}(N) + E_c) = E_{WSN}(N, f)$ simply represents the average energy consumed by the WSN per unit of time under the saturated regime when the number of active reporting nodes is set equal to N.

6.3.2 Sensor Network Lifetime in the Unsaturated Regime

In the unsaturated regime, we deal with successive cycles of $T = 1/f$ units of time. During each cycle, N reports are transmitted (see Fig. 6). Specifically, each time the $i\text{th}(i = 0, \ldots, N)$ report is successfully transmitted, the remaining $(N - i)$ nodes, which have not yet transmitted their packets, compete again to access the data channel. Hence, like in (18), the average energy required to report an event under the unsaturated regime with N reporting nodes is given by

$$E_{RTC\_unsat}(N) = E_{tr}(N) + E_{ov}(N) + E_{cont\_unsat}(N) + E_{sleep\_unsat}(N), \tag{22}$$

where $E_{tr}(N)$ and $E_{ov}(N)$ are already given in (19), and $E_{cont\_unsat}(N)$ and $E_{sleep\_unsat}(N)$ can be expressed as follows:

$$\begin{cases} E_{cont\_unsat}(N) \\ \quad = \frac{1}{N}\sum_{i=1}^{N} \Big[(1 - P_c(i)) \times [N \cdot E_{idle} t1_{cont}(i)] \\ \qquad + P_c(i) \times \Big[E_{idle} \cdot N\big(t''_2(i) + DIFS + B_c(i) \text{ Slots}\big) \\ \qquad + \sum_{n=2}^{i} \Pr\{N_c = n|\overline{U}\} \\ \qquad \times (nE_{tx}t_{RTS} + (N-n)E_{rx}t_{RTS}) \Big]\Big], \\ E_{sleep\_unsat}(N) = (N_{tot} - N) \cdot T_{unsat}(N) \cdot E_{sleep}. \end{cases} \tag{23}$$

Let us now derive the continuous energy consumption E_c under the unsaturated regime. To do so, we assume that $\frac{1}{M} > \Big(T \times \lfloor \frac{R(N)}{N} \rfloor + \Big(R(N) - \lfloor \frac{R(N)}{N} \rfloor N\Big) \times T_{unsat}(N)\Big)$, that is, the mean time between two successive events occurrence $(\frac{1}{M})$ is higher than the mean time required to report reliably an event $\Big(T \times \lfloor \frac{R(N)}{N} \rfloor + \Big(R(N) - \lfloor \frac{R(N)}{N} \rfloor N\Big)\Big)$. So, we have

$$E_c = (1 - R(N) \cdot M \cdot T_{unsat}(N)) \times \big(N \cdot E_{idle} + (N_{tot} - N) \cdot E_{sleep}\big). \tag{24}$$

Using (16), the network lifetime in the unsaturated regime can be therefore expressed as follows:

$$T_{network\_lifetime}(N) = \frac{E_{initial}}{M \cdot R(N) \cdot E_{RTC\_unsat}(N) + E_c}. \tag{25}$$

7 Extension to Multihop Networks

Due to the limited transmission range, sensor nodes deliver generally their data to the sink through multihop communications, i.e., using intermediate nodes as relays. So far, we have supposed that all the sensor nodes are within one hop from the sink in order to perceive the pure effect of our proposed method.

In this section, we extend the analytical model by considering the general case of multihop networks. Due to the lack of space, we derive here only the expressions of latency required to report an event to the sink through multihop WSNs. Similar results can be easily obtained for the energy.

As described in [5], a packet experiences the following delays at each intermediate node:

- carrier sense delay, which is determined by the contention window size,
- transmission delay of the fixed data packet (i.e., t_{tr}), and
- contention delay, which occurs when the carrier sense fails either due to the medium occupation or collision occurrence.

Note that this latter parameter (i.e., contention delay) is negligible, since the traffic load is very light in WSNs: typically, only one packet is forwarded through the network at the same time [5]. Consequently, there is no

TABLE 1
Simulation Parameters

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
Sleep power	0.035 W
Initial network energy	100 J

queuing delay at intermediate nodes. Moreover, the propagation and processing delays can be neglected.

Suppose there are H hops from the reporting nodes to the sink. In this case, the delay to reach the sink can be written as follows, according to whether the saturated or unsaturated regime is adopted:

$$T_{MH\_sat}(N,H) = T_{sat}(N) + H \cdot T_{sat}(1), \qquad (26)$$

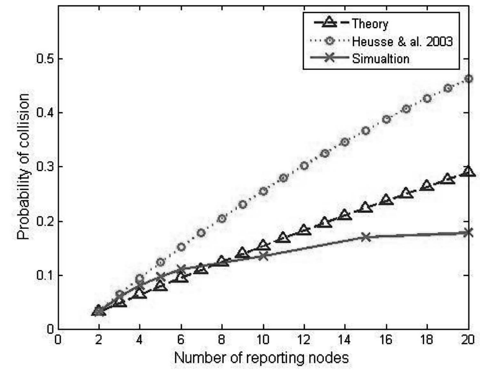
$$T_{MH\_unsat}(N,H) = T_{unsat}(N) + H \cdot T_{unsat}(1). \qquad (27)$$

8 Performance Evaluation

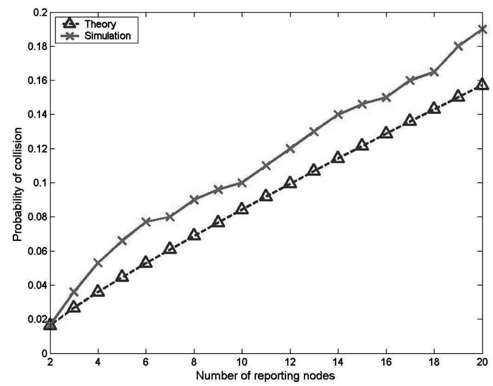
In this section, we evaluate the impact of the reporting nodes on the WSN performance by using both analytical and simulation approaches. The simulations are run on ns-2 [22].

In our simulations, the sensor nodes are randomly deployed in the sensor field with a density d. The average number of nodes that senses an occurring event is $N_{tot} = d \cdot \Pi \cdot R_c^2$, where N_{tot} is set equal to 50. Hence, the number of active reporting nodes N varies between 1 and $N_{tot} = 50$. The event source is represented by a mobile node that generates events with a rate M. 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, we note that the sensor nodes may die due to energy depletion, leading to variation in the overall topology. Moreover, each sensor node can reach the sink in one hop in order to communicate its sensing data. We use the same IEEE-802.11-DCF-based MAC protocol proposed in [14] to arbitrate the access between reporting nodes. The parameters setting in our experiments are listed in Table 1.

Let us first focus on the impact of N on the collision probability in the network, as shown in Fig. 7. We can see that collisions increase in the saturated and the unsaturated regimes with the increase in 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 (i.e., the RTC). To alleviate these shortcomings, we have to reduce the number of reporting nodes. We note that Fig. 7 shows a good match between analytical and simulation results, which confirms the accuracy of our models. This also holds for the remaining simulations described in this section. Moreover, we can observe that our analytical results match better the simulation results than those given in [21], as shown in Fig. 7a.



(a)



(b)

Fig. 7. Probability of collision. (a) Saturated-regime case: $P_{\mathrm{col}\_sat}(N)$. (b) Unsaturated-regime case: $P_{\mathrm{col}\_unsat}(N)$.

Fig. 8 plots the average backoff time (i.e., $t1_{cont}(N, CW_{\min}) = \min_{i=<1,N>} B_i$, where B_i denotes the backoff of reporting node i) required by a host to access the medium in order to report successfully an event to the sink node in the saturated regime (see Fig. 5a). We can observe that this waiting time decreases when the number of reporting nodes N increases, since $\min_{i=<1,N>} B_i$ decreases with N. Doing so, the overall time required to report an event (i.e., an RTC cycle) may be reduced.

According to Figs. 7a and 8, we can see that we have two opposite requirements to minimize the time required to

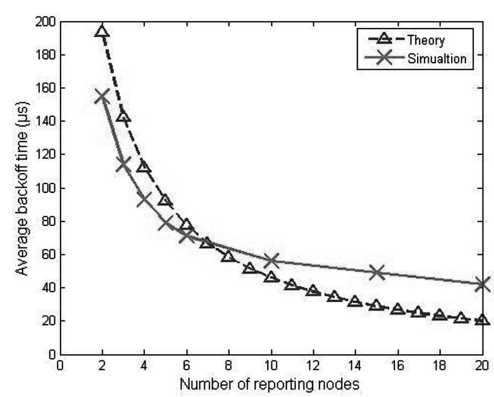


Fig. 8. Average backoff time for a successful transmission in the saturated regime (i.e., $t1_{cont}$).

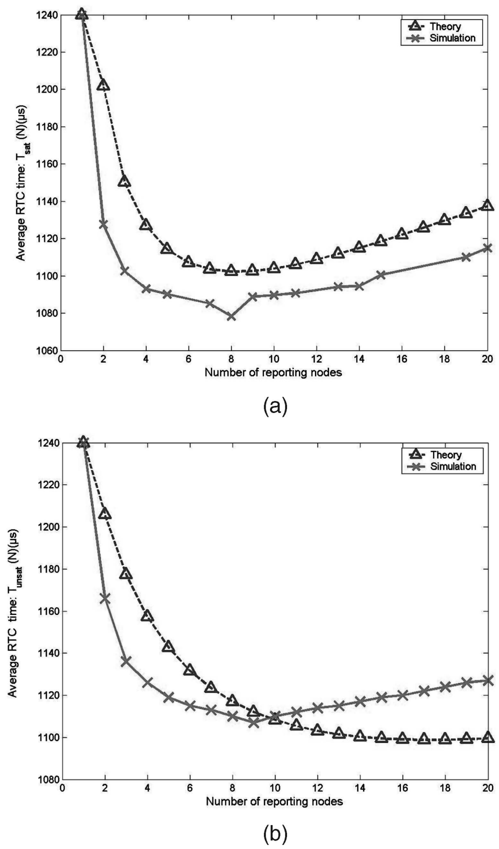


Fig. 9. Average time to report an event (i.e., the RTC). (a) Saturated regime-case: $T_{sat}(N)$. (b) Unsaturated-regime case: $T_{unsat}(N)$.

report an event in the saturated regime. 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, raising the number of reporting nodes N increases the probability of collision, which amplifies the time lost in the contention procedure during each RTC cycle. Hence, the optimal RTC is a trade-off between these two opposite requirements. Reconciling these requirements, the minimum RTC time is obtained for $N_{opt\_RTC} = 8$, as shown in Fig. 9a. This figure shows that the RTC cycle in the saturated regime is a convex function of N, where the minimum is obtained for $N_{opt\_RTC} = 8$. Similar behavior is also observed in the unsaturated regime (see Fig. 9b), where the minimum RTC time is obtained in this case for $N_{opt\_RTC} = 9$.

In the previous paragraph, we investigated the time needed to transmit a report to the sink when the number of active reporting nodes is N. Let us now focus rather on the overall time required to report reliably an event (i.e., to transmit $R(N)$ reports). To do so, we assume that the maximal tolerable distortion is $D_{\max} = 8$. Recall that the number of reports $R(N)$ that need to be transmitted to the sink node in order to achieve the desired distortion is shown in Fig. 3. Accordingly, the average time required to report reliably an event in the saturated and the unsaturated regimes are presented in Fig. 10. In both cases, the minimal latency is obtained for $N_{opt\_latency} = 15$. In other words, the fastest way to report reliably an event is to let only $N_{opt\_latency}$ nodes, among the N_{tot} potential ones, to report a detected event. In this case, the remaining $(N_{tot} - N_{opt\_latency})$ reporting nodes undergo the sleep mode.

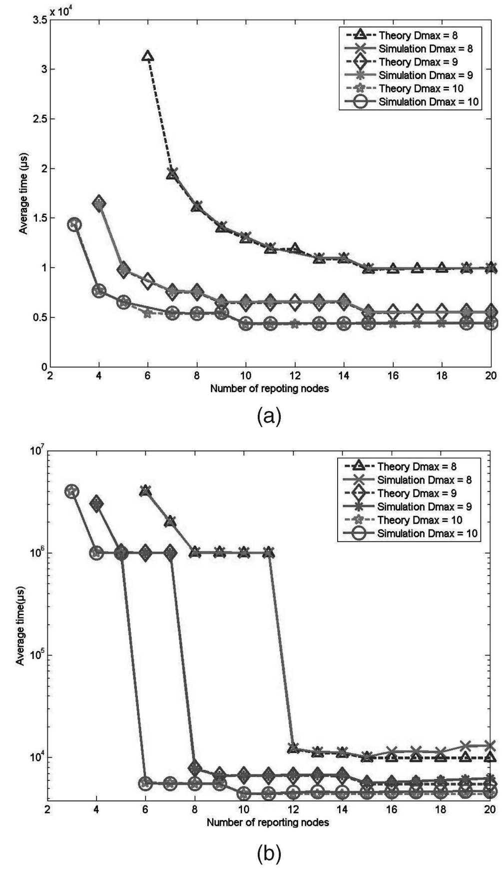


Fig. 10. Average time to report reliably an event. (a) Saturated-regime case. (b) Unsaturated-regime case.

So far, we have presented the impact of N on the reporting latency. In what follows, we are interested rather in understanding the impact of the reporting frequency f on the average time required to report reliably an event. Fig. 11 reports latency as a function of f for varying the setting of N. In this case, when f exceeds approximately 900 reports/s, we deal with the saturated regime; otherwise, we get the unsaturated regime. Fig. 11 shows that the average time required to report reliably an event decreases significantly in the case of the saturated regime. Indeed, the saturated regime enables a faster access to the medium in order to report an event (i.e., $\min_{i=<1,N>} B_i$) compared to the

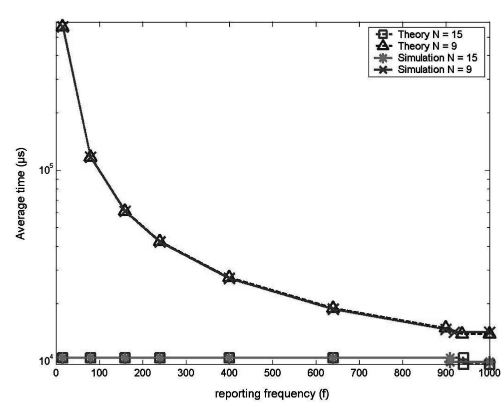


Fig. 11. Average time to report reliably an event.

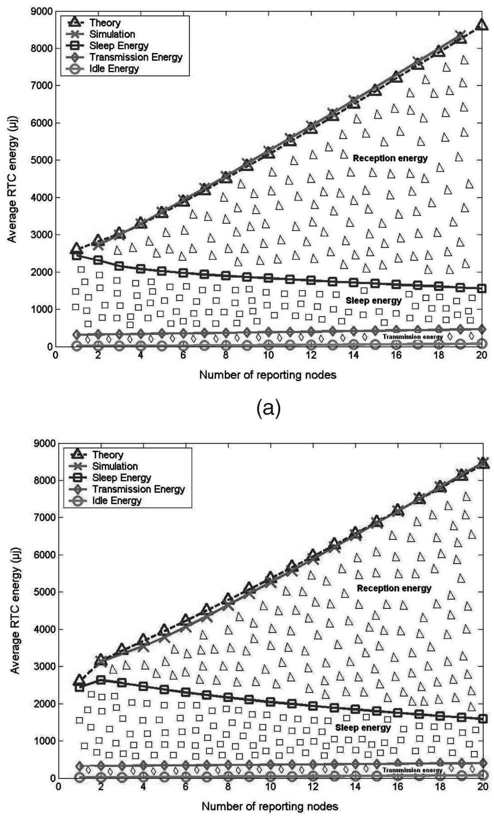


Fig. 12. The average amount of energy consumed by the network to transmit a report. (a) Saturated-regime case. (b) Unsaturated-regime case.

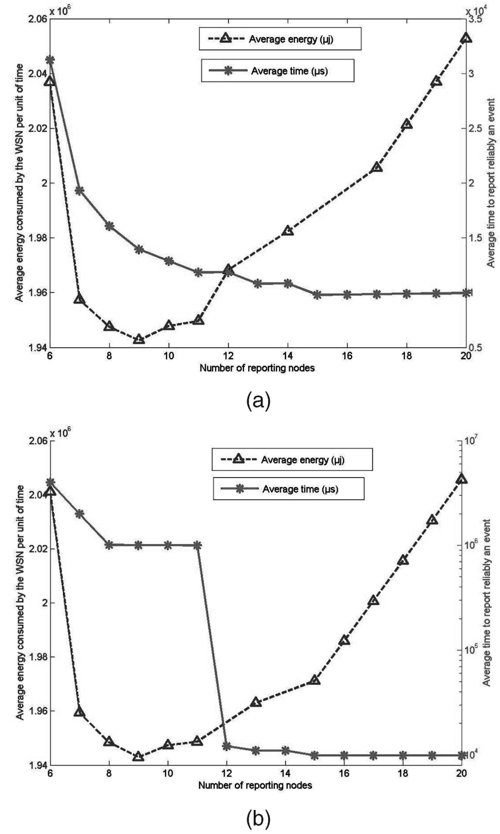


Fig. 13. The average amount of energy consumed by the WSN per unit of time, along with the average time required to report reliably an event. (a) Saturated-regime case. (b) Unsaturated-regime case.

unsaturated regime. Combining, the results in Figs. 10 and 11, we can conclude that the fastest way to report reliably an event (i.e., transmit $R(N)$ reports to the sink) is to plan a network where the number of active reporting nodes is set equal to $N_{opt\_latency} = 15$ and to adopt the saturated reporting mode.

Let us now focus on the impact of N on the energy consumption. Fig. 12 shows the average amount of energy consumed by the network during each RTC cycle (i.e., to send a report) for a varying number of reporting nodes N. Unlike the RTC curves (see Fig. 9), the figure shows that the amounts of energy $E_{RTC\_sat}(N)$ and $E_{RTC\_unsat}(N)$ are 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 (i.e., RTS and ACK) increases considerably (see the gray triangles in Fig. 12). Note that the gray squares and triangles represent the fraction of energy consumed by the overall network in the reception and sleep states, respectively.

According to these results, we can see that the optimal number of active reporting nodes that enables the minimal energy consumption when sending a report is $N = 1$ for both saturated and unsaturated regimes. In this case, the wasted energy due to both collisions and idle listening are avoided.

However, a smaller energy to send a report does not mean necessarily that the energy required to report reliably an event is reduced. Indeed, reducing the number of reporting nodes N increases the number of reports $R(N)$ that need to be transmitted to the sink in order to achieve the desired reliability (see Fig. 3). Hence, the optimal energy consumption in such reliable WSNs is a trade-off between the above-mentioned requirements, as shown in Fig. 13.

Fig. 13 represents the average amount of energy consumed per unit of time by the WSN (i.e., $E_{WSN}(N)$) for a varying number of reporting nodes N. For clarity of presentation, we report also in Fig. 13 the results regarding the latency already shown in Fig. 10. This allows us to see the trade-off between energy consumption and latency. In our simulations, we assume that the rate of event occurrence is $M = 5$ (i.e., five events occur per unit of time). We assume again that the maximal tolerable distortion at the sink is $D_{\max} = 8$. We can see that for both the saturated and the unsaturated regimes, the minimal energy consumption is obtained when only $N_{opt\_energy} = 9$ reporting nodes are activated, whereas the remaining ones undergo the sleep mode. Based on this result, we can conclude the following:

- Using a small subset of the nodes, rather than all the sensor nodes in the event area, to report reliably an event reduces considerably the energy consumption. In our case, the optimal energy consumption is achieved when only $N = 9$ out of the $N_{tot} = 50$ sensor nodes are activated.

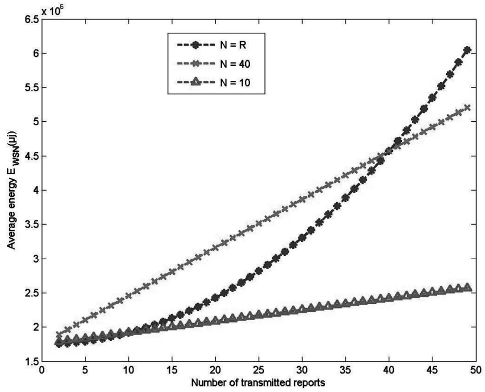


Fig. 14. The average amount of energy consumed by the WSN per unit of time as a function of the number of transmitted reports, considering different numbers of active reporting nodes.

- The fastest way to report reliably an event does not correspond to the optimal manner of consuming the network energy. Specifically, $N_{opt\_energy} = 9 \neq N_{opt\_latency} = 15$. In this regard, the choice of the number of active reporting nodes depends mainly on the specific QoS requirements of the WSN application.
- The third interesting finding is that $N_{opt\_energy} = 9 < N_{\min} = 12$. Recall that [14] stipulates that at least $N_{\min} = 12$ sensor nodes should be activated in order to comply with the reliability requirement. Our scheme relaxes this constraint, but at the expense of increasing the number of reports' transmission. Yet, our scheme reduces the energy consumption as $E_{WSN}(N = 9) < E_{WSN}(N = 12)$. Consequently, we can state that our scheme not only introduces more flexibility to attain the desired reliability but also enables further energy conservation.

In Fig. 14, we plot the average amount of energy consumed per unit of time by the WSN when varying the number of transmitted reports. In contrast to Fig. 2, where increasing the number of transmitted reports improves the observed information distortion, this leads to an increase in the energy consumption.

So far, we have showed the impact of N on the energy consumption. Hereafter, we want to understand the impact of the reporting frequency f on the energy consumption. Fig. 15 plots the average amount of energy consumed per unit of time by our reliable WSN as a function f. We can observe that the energy increases slightly when we reach the saturated regime. In fact, collisions are more frequent in the saturated regime (see Fig. 7). In this regard, more energy is wasted due to collisions. Thus, combining the results in Figs. 13 and 15, we can conclude that the optimal way of consuming energy is to activate only $N_{opt\_energy} = 9$ reporting nodes operating in the unsaturated regime. Finally, we outline that the unsaturated regime is more efficient from the energy consumption perspective, whereas the saturated regime is more interesting from the latency viewpoint (see Fig. 11).

Finally, Figs. 16a and 16b plot the network lifetime evolution in both the saturated and the unsaturated regimes, respectively, as a function of N. Similar to E_{WSN},

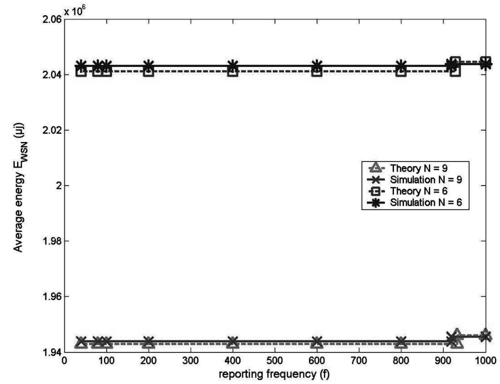


Fig. 15. Average energy consumed by the WSN per unit of time.

the maximum network lifetime is obtained when only $N_{opt\_energy} = 9$ reporting nodes are activated. This result highlights again that limiting the reporting tasks to a small subset of sensor nodes, instead of using all the potential ones in the event area, enables great energy saving. The maximal gain is obtained for $N_{opt\_energy} = 9$. In this regard, our proposal improves the network lifetime when compared to [14], where the maximal network lifetime was obtained for $N_{\min} = 12$. Note that for the sake of simplicity, we have presented the results for the case $D_{\max} = 8$ only. Similar results are, however, obtained for other values of $D_{\max}$, as shown in Table 2. For instance, when $D_{\max} = 7$, we have again $N_{opt\_energy} < N_{\min}$, where $N_{opt\_energy} = 15$, and $N_{\min} = 20$.

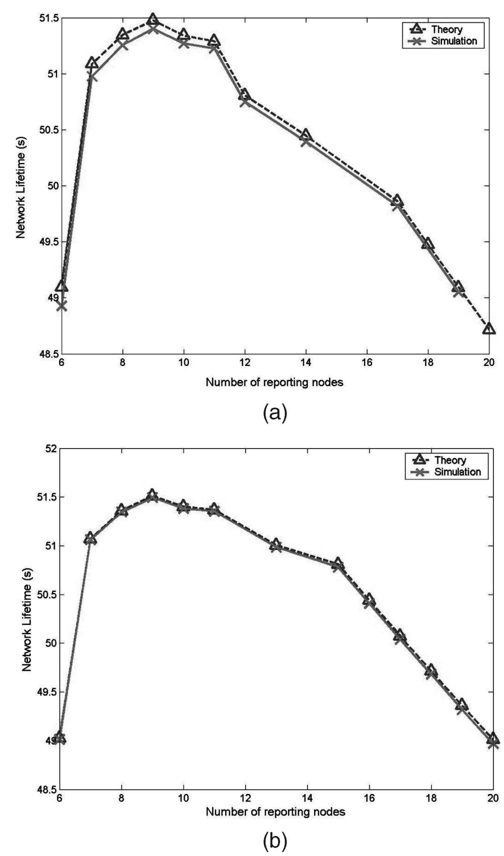


Fig. 16. Sensor network lifetime. (a) Saturated-regime case. (b) Unsaturated-regime case.

TABLE 2
Results for Different Distortion Values

D_{max}	7	8	9	10
$N_{\min}$	20	12	8	6
N_{opt_energy}	15	9	5	4
$E_{WSN}\,(N_{\min})\,(10^3\mu j)$	2422.7	1968.2	1842.2	1799.5
$E_{WSN}\,(N_{opt\_energy})\,(10^3\mu j)$	2373.6	1942.6	1824.5	1796.6

9 Conclusion

In this paper, we have studied the relationship between the WSN performance and the number of reporting nodes. We first analyzed the impact of the number of reporting nodes on the number of required reports to comply with a desired reliability. Based on this analysis, we derived both the average energy and time needed to report reliably an event. As the main first contribution, we have demonstrated that the optimal way of consuming energy is to activate only N_{opt_energy} reporting nodes that operate in the unsaturated regime. Activating more or less than N_{opt_energy} sensor nodes increases the energy expenditure. As the second main contribution, we have proven that the average time to report reliably an event is a convex function of the number of reporting nodes, where the minimum is obtained for a value $N_{opt\_latency} \neq N_{opt\_energy}$. We showed in this context, that the fastest way to report reliably an event is to plan a network with $N_{opt\_latency}$ active reporting nodes operating in the saturated regime. In view of this, we have observed that the unsaturated regime is more efficient from the energy consumption perspective, whereas the saturated regime is more interesting from the latency viewpoint. Our findings lead us to conclude that the adjustment of the N parameter and the choice of the appropriate regime in order to achieve energy-reliability-latency trade-offs depends on the specific QoS requirement of the WSN application, i.e., whether more priority is given to latency or energy constraints.

There are some issues that remain to be studied. For instance, in this paper, we have not addressed the scenario where multiple events occur concurrently in the network. Although not frequent, this scenario represents a challenging case study for future research. Also, in this paper, we have not considered the mobility of the same event over time (e.g., mobile target detection applications). In such a case, we expect that the reporting nodes of the same event will change over time. It is an important extension of this work to analyze sensor network reliability, taking into account the mobility of event sources.

Appendix

Hereafter, we focus on $t_{cont}(N)$ calculations. Recall that $t_{cont}(N)$ represents the average time spent in the contention procedure when N reporting nodes compete for the medium access, with their associated backoffs $B_i(i = 1, \ldots, N)$ ranging between $[0, CW]$. As stated before, we neglect in our study the occurrence of successive collisions. In 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. 5a).
- *Case 2.* The report is transmitted successfully by one of the reporting hosts following to a first collision occurrence on the medium (see Fig. 5b).

Case 1. This case happens with a probability $1 - P_{col\_sat}(N)$. 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. 5a). According to assumption 2 (refer to Section 6.1.1), 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

$$\begin{aligned} U &= \{\exists! j \in <1, N>, B_j = X\} \\ &= \{\text{successful transmission}\}. \end{aligned} \tag{28}$$

Note that

$$\Pr\{U\} = 1 - \Pr\{\overline{U}\}. \tag{29}$$

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

$$t1_{cont}(N) = E[X|U]\ slots, \tag{30}$$

where

$$E[X|U] = E[X, U]/\Pr\{U\}. \tag{31}$$

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

$$E[X, U] = \sum_{k=0}^{CW_{min}} k \Pr\{X = k, U\}, \tag{32}$$

where $\Pr\{X = k, U\}$ can be simply derived based on (8):

$$\begin{aligned} \Pr\{X = k, U\} &= \Pr\{X = k\} - \Pr\{X = k, \overline{U}\} \\ &= \binom{N}{1} \frac{(CW_{\min} - k)^{N-1}}{(CW_{\min} + 1)^N}. \end{aligned} \tag{33}$$

Case 2. In this case, the report is successfully transmitted by one of the reporting nodes after the first failed attempt. Such a case happens with a probability $P_{col\_sat}(N)$. $t_{cont}(N) = t2_{cont}(N)$ 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 ($t_2'(N)$) 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 $t_2''(N)$ (see Fig. 5b). Hence, we get

$$t2_{cont}(N) = t_2'(N) + t_2''(N), \tag{34}$$

and we have

$$t_2'(N) = DIFS + t_{RTS} + E\left[X|\overline{U}\right] \text{ Slots}, \tag{35}$$

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

$$B_c(N) = E[X, \overline{U}] = \sum_{k=0}^{CW_{min}} k \Pr\{X = k, \overline{U}\}, \tag{36}$$

where $\Pr\{X = k, \overline{U}\}$ is given by (8).

Let us now focus on the calculation of $t''_2(N)$. As we have 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, the 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 let U' be the following event:

$$\begin{aligned} U' &= \{\exists! j \in <1, N>, B_j = X'\} \\ &= \{\text{successful transmission}\}. \end{aligned} \tag{37}$$

We recall that we aim at calculating $t''_2(N)$, which is the average backoff time required by the WSN to successfully transmit a new report after the first failed attempt. $t''_2(N)$ can be therefore written as

$$t''_2(N) = E\left[X', U'|\overline{U}\right], \tag{38}$$

which leads to

$$t''_2(N) = \sum_{k=t_{wait}}^{t_{wait}+(2\times CW_{min})-1} k \Pr\left\{X' = k, U'|\overline{U}\right\}. \tag{39}$$

In order to calculate $t''_2(N)$, 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).

Case 1: $t_{wait} \leq X' = k < t_{wait2}$. 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

$$\Pr\left\{X' = k, U'|\overline{U}\right\} = \sum_{n=2}^{N} \Pr\left\{X' = k, U', N_c = n|\overline{U}\right\}. \tag{40}$$

This yield to

$$\begin{aligned} \Pr\left\{X' = k, U'|\overline{U}\right\} = \sum_{n=2}^{N} &\Pr\left\{X' = k, U'|N_c = n, \overline{U}\right\} \\ &\times \Pr\left\{N_c = n|\overline{U}\right\}. \end{aligned} \tag{41}$$

Since the transmitting node j participates in the previous collision, we have

$$\begin{aligned} &\Pr\{X' = k, U'|N_c = n, \overline{U}\} \\ &\quad = \binom{n}{1} \frac{(2 \times CW_{min} + t_{wait} - k)^{N-n-1}}{(2 \times CW_{min} + 1)^{N-n}}. \end{aligned} \tag{42}$$

Moreover, we have

$$\Pr\left\{N_c = n|\overline{U}\right\} = \frac{\Pr\{N_c = n, \overline{U}\}}{\Pr\{\overline{U}\}} = \frac{\Pr\{N_c = n\}}{\Pr\{\overline{U}\}}, \tag{43}$$

where

$$\Pr\{N_c = n\} = \sum_{k=0}^{CW_{min}} \binom{N}{n} \frac{(CW_{min} - k)^{N-n}}{(CW_{min} + 1)^{N}}. \tag{44}$$

Case 2: $t_{wait2} \leq X' = k \leq t_{wait2} + CW_{\min}$. In this case, the host j that accesses the channel may either be one of the N_c stations, which already participated in the first collision or belong to the $N - N_c$ remaining ones. Accordingly, we distinguish between two subcases:

Subcase 1. The transmitting host j already participated in the first collision. Such an event is denoted by C. In this case, we have

$$\begin{aligned} \Pr\left\{X' = k, U', C|\overline{U}\right\} = \sum_{n=2}^{N} &\Pr\left\{X' = k, U', C|N_c = n, \overline{U}\right\} \\ &\times \Pr\left\{N_c = n|\overline{U}\right\}, \end{aligned} \tag{45}$$

where

$$\begin{aligned} &\Pr\left\{X'=k, U', C|N_c=n, \overline{U}\right\} \\ &\quad = \binom{n}{1} \frac{(CW_{min}+t_{wait2}-k)^{N-n}(2\times CW_{min}+t_{wait}-k)^{n-1}}{(CW_{min}+1)^{N-n}(2\times CW_{min}+1)^{n}}, \end{aligned} \tag{46}$$

and $\Pr\{N_c = n|\overline{U}\}$ is already given by (43).

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

$$\begin{aligned} \Pr\left\{X' = k, U', \overline{C}|\overline{U}\right\} = \sum_{n=2}^{N} &\Pr\left\{X' = k, U', \overline{C}|N_c = n, \overline{U}\right\} \\ &\times \Pr\left\{N_c = n|\overline{U}\right\}, \end{aligned} \tag{47}$$

where

$$\begin{aligned} &\Pr\left\{X'=k, U', \overline{C}|N_c=n, \overline{U}\right\} \\ &\quad = \binom{N-n}{1} \frac{(CW_{min}+t_{wait2}-k)^{N-n-1}(2\times CW_{min}+t_{wait}-k)^{n}}{(CW_{min}+1)^{N-n}(2\times CW_{min}+1)^{n}}. \end{aligned} \tag{48}$$

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

$$\begin{aligned} \Pr\left\{X' = k, U'|\overline{U}\right\} = &\Pr\left\{X' = k, U', C|\overline{U}\right\} \\ &+ \Pr\left\{X' = k, U', \overline{C}|\overline{U}\right\}. \end{aligned} \tag{49}$$

Case 3: $CW_{min} + t_{wait2} < X' = k < t_{wait} + 2 \times CW_{min}$. This case happens only when all the N reporting nodes participated in the first collision (i.e., $N_c = N$). Thus, we have

$$\Pr\{X' = k, U'|\overline{U}\} = \Pr\{X' = k, U', N_c = N|\overline{U}\}. \tag{50}$$

This leads to

$$\Pr\{X' = k, U'|\overline{U}\} = \Pr\{X' = k, U'|N_c = N, \overline{U}\} \times \Pr\{N_c = N|\overline{U}\}, \tag{51}$$

where

$$\Pr\{X' = k, U'|N_c = N, \overline{U}\} = \binom{N}{1} \frac{(2 \times CW_{min} + t_{wait} - k)^{N-1}}{(2 \times CW_{min} + 1)^N}, \tag{52}$$

and $\Pr\{N_c = N|\overline{U}\}$ is already given by (43).

Moreover, using (39), (40), (49), and (51), we simply derive $t''_2(N)$, and thus, we get the expression of $t2_{cont}(N)$ by means of (34). Doing so, we finally derive the expression of $t_{cont}(N)$, which is given by

$$t_{cont}(N) = (1 - P_c(N))t1_{cont}(N) + P_c(N)t2_{cont}(N). \tag{53}$$

By substituting (53) in (13), we obtain the average time required to report an event in the saturated regime when the number of reporting nodes is N.

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