Wireless Netw
DOI 10.1007/s11276-012-0473-9

Efficient reporting node selection-based MAC protocol for wireless sensor networks

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Abstract Wireless sensor networks rely on the cooperative effort of the densely deployed sensor nodes to report the detected events. As a result, sensor observations are highly correlated in the space domain. Typically, multiple sensor nodes may report the same event. Consequently, redundant information may be transmitted by the different sensor nodes, leading thus to unnecessary energy wastage. In this paper, we investigate the relationship between the spatial correlation and the number of reporting nodes by developing a new analytical model based on the theoretical framework of the CC-MAC (correlation-based collaborative medium access control) protocol (Vuran and Akyildiz in IEEE/ACM Trans Netw 14(2): 316–3292006). We show that the reporting task can be delegated to a small subset of sensor nodes without transgressing the distortion constraint. Building on this result, a simple spatial correlation medium access control protocol is then proposed to achieve further energy conservation and faster reporting latency than CC-MAC.

Keywords Wireless sensor networks · Energy conservation · MAC protocol · Performance analysis

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1 Introduction

Energy-efficiency is one of the major concerns in Wireless sensor networks (WSNs). In order to minimize the energy consumption in WSNs, several energy-efficient MAC protocols [2–4] and energy-efficient routing protocols [5, 6] have been proposed in the literature. These schemes aim to decrease 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, 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 [2–4, 7–11] suggested wake-up scheduling schemes at the MAC layer to activate sleeping nodes when it is needed. On the other hand, works in [5, 6] addressed the problem at the network layer by proposing new routing solutions that take into account the sleep state of some network nodes.

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. In this regard, the key performance metrics in WSN networks 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, increasingly research efforts are dedicated to the investigation of the tradeoffs either between energy consumption and data delivery delay [3, 12] or between energy consumption and reliability [13].

Published online: 22 June 2012

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 [1, 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, [1] proposed a MAC protocol called CC-MAC (Correlation-based Collaborative Medium Access Control) 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. By exploiting the spatial correlation among sensor nodes, authors in [1] determined, the minimum number of representative nodes N_{min} that need at least to be activated in order to achieve the required data reliability at the sink. Accordingly, each representative node needs to transmit only one report to accomplish the desired reliability. 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.

Based on the same philosophy of the CC-MAC protocol [1], we present in this paper a new MAC protocol aiming at achieving further energy conservation. To accomplish this, we first propose a new scheme to select the optimal set of nodes which will handle the reporting tasks. Indeed, we assert that the reporting task can be limited to a smaller set of nodes compared to Vuran and Akyildiz [1]. Typically, each representative node in our study is allowed to transmit as many packets as needed to fulfill the reliability requirement as opposed to Vuran and Akyildiz [1] where each representative node transmits only one report. In our study, we suppose that each reporting node will estimate the event anew before sending any new report. Our aim is to introduce additional flexibility to select among the reporting nodes, which may lead to supplementary energy conservation. In doing so, we demonstrate that, compared to Vuran and Akyildiz [1], further energy conservation and faster reporting latency can be realized.

Building on this new selection scheme, we conceive our distributed Spatial-Correlation MAC (SC-MAC) protocol that regulates medium access and prevents redundant transmissions from closely located sensors. In addition, this protocol takes into account the required information reliability at the sink node (i.e., collector node). Specifically, when the sink receives enough reports to attain the required information reliability, it asks the selected reporting nodes to stop the event reporting in order to avoid unnecessary energy wastage.

In this study, we provide a theoretical framework to calculate the average number of reports $R(N)$ needed to be received at the sink node from the N selected reporting nodes in order to achieve the required information reliability. Based on these results, we present an in-depth analysis of the impact of the number of active reporting nodes N on both the latency and the energy required to report reliably an event. Specifically, we derive, by means of simulations, the optimal number of reporting nodes N_{opt} that minimizes the energy consumption. This value is then used to regulate the actual implementation of our SC-MAC protocol over a real sensor network. It is worth noting that our SC-MAC protocol is simply a reliability-driven node selection scheme that shows how the spatial correlation can be exploited at the MAC layer to achieve further energy conservation. In this regard, the proposed scheme can be used, as an additional mechanism, with any low power MAC protocols such as [7–11].

In the next section, the field of WSNs is described, presenting the current state of the art as it relates to the focus of this article. Following this, Sect. 3 specifies the general problem statement. In Sect. 4, we develop a theoretical framework to study the spatial correlation in WSNs. Specifically, we derive the relationship between the desired information reliability and the number of active reporting nodes. Based on this framework, we propose in Sect. 5 our distributed SC-MAC protocol that regulates medium access by delegating the reporting task to a small subset of the sensor nodes rather than to all the nodes within the event area. SC-MAC performance analysis and simulation results are presented in Sect. 6. The article concludes with a summary of our contributions and directions for future research.

2 Related work

Current studies on WSNs focus mainly on the energy-latency tradeoffs. Indeed, 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 [15, 16]. Based on this concept, several energy-efficient MAC protocols [2–4, 7–11] and energy-efficient routing protocols [5, 6] have been proposed in the literature. Additional solutions to reduce energy consumption, based on congestion control, were also proposed in [17, 18]. These mechanisms aim at achieving further energy conservation by reducing the energy wastage resulting from the frequently occurring collisions in WSNs.

Although such schemes achieve significant energy savings, the WSN keeps 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 redundant information [1, 14, 19, 20]. 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) [1, 14] by regulating their access, or at the intermediate sensor nodes routing the information to the sink, by means of aggregation mechanisms [19, 20].

In the latter case, paths from different sources to the sink form an aggregation 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 [19, 20]. However, such schemes may affect the reliability of the information transmitted to the sink. The aggregation process at intermediate nodes must therefore be aware of the reliability constraints [18], which may become challenging in the presence of multiple aggregation points in the route to the sink.

Reducing the redundant information is more efficient when it is realized at the source nodes [1]. This is achieved by limiting the number of reporting nodes. Specifically, [1] shows 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, overhearing and redundant packet transmission. In the optimal case, only one node will be allowed to report the detected event. In such case, collisions, idle listening, overhearing 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.

Authors in [1] determined, 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 only one report 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, [1] proposed 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 [3, 4, 21]. This MAC protocol is an important achievement and represents an essential building block for future research dealing with access nodes' regulation.

In this paper, we propose a new scheme for selecting the set of representative nodes, which is the key distinguishing feature of our proposal compared to Vuran and Akyildiz [1]. We claim that the reporting task can be limited to a smaller set of nodes compared to Vuran and Akyildiz [1]. Typically, each representative node in our study is allowed to transmit as many packets as needed to attain the desired reliability as opposed to Vuran and Akyildiz [1] where each representative node transmits only one report. Our aim is to introduce additional flexibility to select among the reporting nodes, which may lead to supplementary energy conservation. Indeed, as a 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 [1]. Moreover, we derive by simulations, as it will be described in Sect. 6, the optimal number of reporting nodes N_{opt} that minimizes the energy consumption in our case.

As a second benefit of our method, we show that $E(N_{opt}) < E(N_{min})$,[1] which proves that our scheme does not only introduce more flexibility to attain the desired reliability but it also enables further energy conservation. Finally, as a third benefit of our scheme, we demonstrate that it enables shorter latencies to report reliably the detected events compared to Vuran and Akyildiz [1].

Based on these results, we develop a simple distributed MAC protocol that regulates medium access and prevents redundant transmissions from closely located sensors. To gauge the gain introduced by our proposal, it is compared to the CC-MAC protocol. It is worth noting that our energy-aware selection strategy can be used with any low power MAC protocols already proposed in the literature. The proposed strategy will help existing MAC protocols to achieve further energy conservation.

Furthermore, we highlight that additional signaling protocols, such as the ESRT protocol [18], could be also used to control and adjust periodically (on-line) 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 over time. In this case, signaling protocols are responsible to convey 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 activate) and $R(N)$ (i.e., the associated number of reports to achieve the desired information reliability).

[1] $E(N)$ is the average consumed energy by the network when the number of reporting node is N.

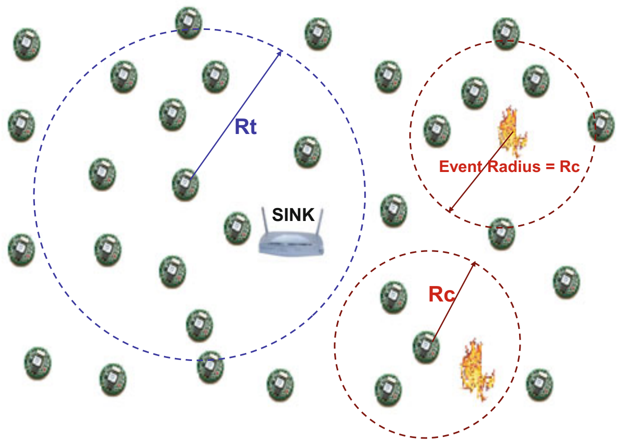

Fig. 1 Typical sensor network topology with event and sink. R_t is the transmission range of each sensor. R_c is the sensing range of each sensor. All the nodes that are within the event range R_c are able to detect the event. The sink is interested in collecting information from sensor nodes within the event radius R_c

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 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., potential 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, $N(N = 1, \ldots, N_{tot})$ 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 [18]. 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 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 average number of reports $R(N)$, the average time and the associated energy required to report reliably an event.

4 Relationship between information reliability and the number of reporting nodes

In this section, we extend the work in [1] to derive the number of reports $R(N)$ required to report reliably an event given that the number of active reporting nodes is N. This consists in 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}. We use similar notations as in our previous work [22], and present some of the equations from the model in [22] with brief explanations here for this paper to be self-contained.

In [1], the authors provided 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:

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

where

- 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 i.i.d 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:

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

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 [23].

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, the authors in [1] derived 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 [1], 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, the lower the number of reporting nodes N the lower the energy wastage due to collisions, overhearing and idle listening. There must be an optimal value of $N = N_{opt}$ that achieves the above-mentioned tradeoff, i.e., that minimizes the energy required to report reliably an event. Henceforth, our aim is to demonstrate that $E\ (N_{opt}) < E\ (N_{min})$. In doing so, we prove, as it will be shown in Sect. 6, that our proposal enables further energy conservation when compared to Vuran and Akyildiz [1], 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 [1], the expression of the distortion (see (1)) is derived for the particular case $r = N$. Using the same model for the information collection and the same assumptions as in [1], $D(N, r)$ can be expressed as follows:

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

where $n(k)$ denotes the coordinate of the sensor node that transmits the kth report. We note that in our study we use the CSMA/CA-based DCF MAC protocol with appropriate modifications. According to the CSMA/CA mechanism, all the N competing reporting nodes have equal probability to access the medium. In this regard, the node that transmits the kth report (i.e., $n(k)$) can be with equal probability 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

$$\rho_{(s,n(k))} = \frac{1}{N}\sum\nolimits_{i=1}^{N}\rho_{(s,i)}, \quad \forall k = 1, \ldots, r.$$
$$\rho_{(n(k),n(m))} = \frac{1}{N^2}\sum\nolimits_{i=1}^{N}\sum\nolimits_{j=1}^{N}\rho_{(i,j)}, \forall k, m = 1, \ldots, r. \tag{4}$$

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:

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

Figure 2 plots the distortion evolution according to both our method (i.e., using (5)) and work in [1] (i.e., using (1)). The distortion is plotted as a function of the number of transmitted reports r by the N active reporting nodes.

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., $N = 10$, $N = 20$, $N = 30$ 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 of 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 is the value of N, the greater is 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 the maximal tolerable distortion D_{max} is equal to 8. To achieve this, at least $r = 12$ reports need to be transmitted 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

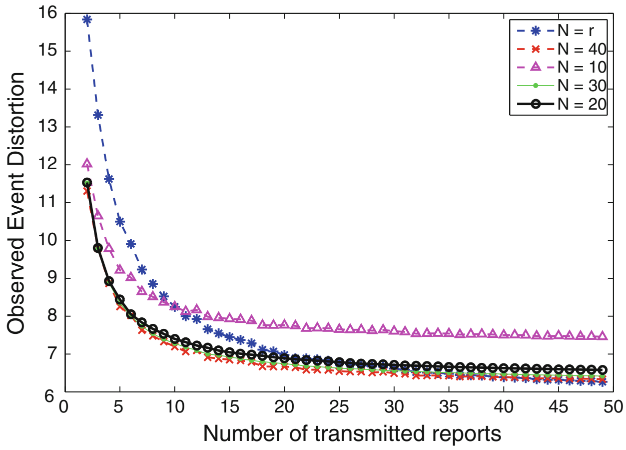

Fig. 2 Average distortion as a function of the number of transmitted reports considering different values of active reporting nodes

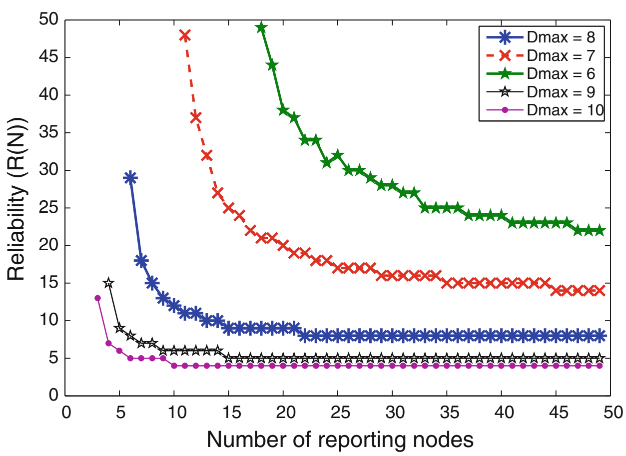

Fig. 3 Average reliability as a function of the number of reporting nodes for different distortion values

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.

Let us now consider the results regarding the method introduced in [1], 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 $N = 40$, $N = 30$, $N = 20$ and $N = 10$ when $r = 40$, $r = 30$, $r = 20$ 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 $D_{max} = 8$, implies activating at least $N_{min} = 11$ sensor nodes to fulfill the distortion requirement. According to this method, activating only N_{min} reporting nodes achieves 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 more flexibility in achieving the desired distortion at the sink. In the remainder of this paper, we will highlight the importance of such flexibility. We will seek the optimal number of reporting nodes that achieves the minimum energy consumption in reliable WSNs.

It is worth noting that although, in our analysis, we focused mainly in profiting from the natural spatial correlation among the sensor nodes' observations to reduce the energy consumption, our work takes also into account the temporal correlation that appears among the successive observations generated by each reporting sensor node. To get more insights into this aspect, let consider Fig. 3. Ensuring for example $D_{max} = 8$ while activating only $N = 11$ sensor nodes, needs transmitting $r = 11$ reports, i.e., one report per sensor node. However, activating only $N = 8$ sensor nodes instead of 11 increases the number of reports that needs to be received at the sink node. $r = 16$ reports are indeed required in this case. This increase is due to the increase of the temporal correlation among nodes' observations, since each sensor needs to transmit in average two reports to the sink node to cope with the reliability requirements. From this perspective, additional energy could be required to report reliably an event, since more reports need to be sent. However, reducing the number of reporting nodes reduces the energy wastage due to collisions, overhearing and idle listening. There must be an optimal value of N_{opt} that achieves the above-mentioned trade-off, i.e., that minimizes the energy required to report reliably an event. This is the main focus of our study.

To conclude, we highlight again that our analysis takes into account the temporal correlation among successive reports sent by each sensor node. This level of correlation depends on the time difference between reports. In this regard and more importantly, the analysis presented in this section deals with the worst case by considering null the time difference between reports generated by each sensor node. Additional gain can be indeed achieved by increasing this time difference between reports. However, this should be achieved while respecting the delay constraints. This interesting point is out of the scope of this paper and represents indeed a good perspective for our future research.

5 Access in wireless sensor networks

To make use of the results provided by the distortion function $D(N, r)$, a node selection technique is required in order to select the appropriate number of reporting nodes resulting in minimum energy expenditure. For this purpose, we propose the SC-MAC protocol, which relies on the correlation radius R_{corr} concept. Typically, we assume that nodes within internode distance smaller than the correlation radius R_{corr} contain highly correlated data. As such, they should delegate the reporting task to only one sensor node. To achieve this, each sensor node runs the distributed SC-MAC protocol as it will be explained in the following.

5.1 The IEEE 802.11 DCF MAC protocol

As stated before, access to the medium in current deployed WSN is usually regulated using contention-based MAC protocols such as the basic IEEE 802.11 DCF protocol and its optional RTS/CTS mechanism or the IEEE 802.15.4 protocol. To illustrate our results and for comparison purposes, we use the IEEE 802.11 DCF protocol as in [1]. Moreover, the transmission bit rate is set equal to 40 kbs^{-1} [24] instead of the bit rate specified in the IEEE 802.11 standard (i.e., 11, 54 or 108 Mbs^{-1}), to fit the low bit rate required in wireless sensor environment.

In classical WSNs, once an event is detected, the N_{tot} active reporting nodes compete to access the common data channel to report the event to the sink 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 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 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 $CW_{max} =$ 1,023 is reached. Once the frame is successfully transmitted, the CW value is reset to CW_{min}. Figure 4 illustrates the IEEE 802.11 DCF access mechanism.

5.2 Description of the proposed SC-MAC protocol

Due to energy consideration and the event-based traffic in WSNs, the above described DCF protocol can not 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 nodes 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 [25]. 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 [3, 4]. In view of this, we apply our reporting node selection technique to the IEEE 802.11 DCF protocol.

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 method alleviates the energy wastage by minimizing collisions.
- Second, we also reduce the number of redundant transmitted packets and hence more energy is conserved.

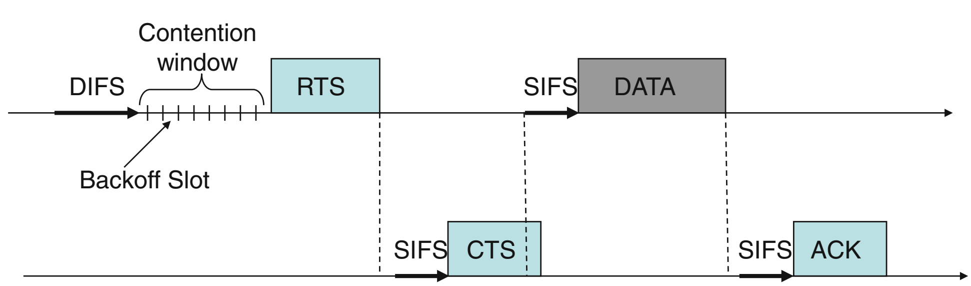

Fig. 4 Basic access mechanism of IEEE 802.11 DCF

- Finally, additional nodes (i.e., the non selected nodes to report the detected event) undergo the sleep state, which reduces the idle listening as well as overhearing. We note that the idle listening and overhearing represent the major sources of energy inefficiency [4, 9]. In fact, with a conventional WSNs, nodes keep listening to the radio channel whenever they do not transmit to be able to receive traffic that have not been, possibly, sent. As the power consumption of a transceiver in receive mode is far from being negligible, idle listening becomes clearly the main source of energy wastage in scenarios where the channel is idle most of the time as in wireless sensor environment. Low power MAC protocols must use sleep techniques to mitigate idle listening. Overhearing must also not be underestimated. If the idle listening problem is efficiently addressed by a MAC protocol, the following important source of energy wastage becomes overhearing, especially in dense sensor networks. Indeed, the unnecessary energy consumed by a sensor node while receiving inappropriate data or signaling messages, which are not intended to it must be alleviated.

In the next section, we will show how to derive the optimal number of reporting nodes that achieves minimal energy consumption while respecting the latency and reliability constraints. Such algorithm runs at the sink level and dynamically determines, 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 is used to derive the corresponding R_{corr} using the algorithm shown in Fig. 6. The tuple (N, $R(N)$, R_{corr}) is then to be broadcasted, during the network setup, to all the sensor nodes, which must be able to make use of it in order to regulate their access.

Based on this information, the proposed MAC protocol selects only a small subset of sensor nodes (i.e., N) 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 indicates the average distance allowable between selected reporting nodes. The sensor nodes within the event radius use this information about R_{corr} and collaborate in order to form correlation regions in a distributed manner and choose accordingly the reporting nodes. The goal of the proposed SC-MAC protocol is to select the reporting nodes without any explicit internode communication.

The operation of the proposed 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 Sect. 1. Once a sensor node accesses the medium by sending correctly a RTS frame, all the other nodes within R_{corr} radius stop their transmission attempt and undergo the sleep mode. Following the report transmission, the remaining active nodes try again to access the medium and the selection process is executed once more until all the reporting nodes are elected as shown in Fig. 5.

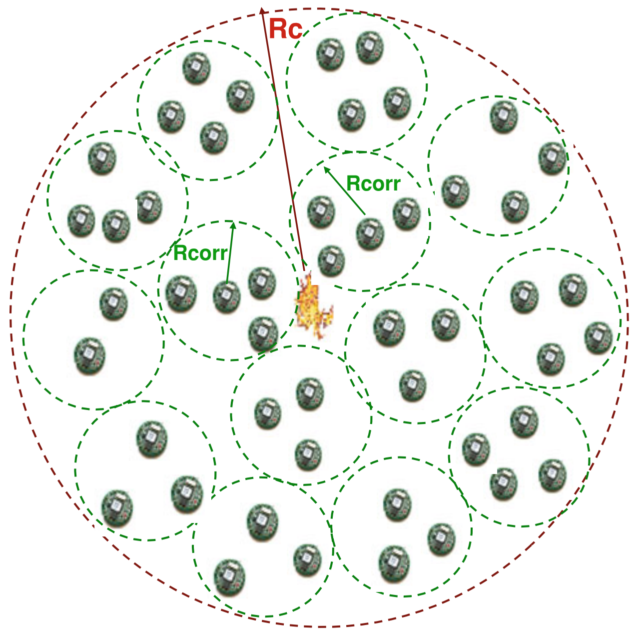

Fig. 5 Reporting node selection

Now, to make use of our protocol, we only need to derive 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 the tuple (N, $R(N)$). This is done at the sink level, which calculates R_{corr} using the algorithm depicted in Fig. 6.

This pseudo-code simply calculates the average number of remaining active nodes after sending R reports giving a fixed radius R_{corr}. The associated results are reported in Fig. 7. Thus, knowing the tuple (N, $R(N)$), we can easily determine R_{corr} as shown in Fig. 7.

It is worth noting that the calculated R_{corr} is an average value that is calculated considering different possible positions of the sensor nodes (see the algorithm in Fig. 6). In other words, for each tuple (N, $R(N)$) corresponds only a unique value of R_{corr}, regardless of the current exact positions of the N reporting nodes. The effectiveness of this algorithm will be studied in the next section.

From this perspective, the calculation of $R_{corr}(N)$ is another key distinguishing feature of our proposal compared to CC-MAC [1]. In fact, in CC-MAC protocol, $R_{corr}(N)$ is determined according to the Iterative Node Selection algorithm (INS) running at the sink and which assumes node's location known to the sink; which is not

```
RemainingNodeRcorrReport = [ ]; // Matrix(Rc,MaxReport)
FOR Rcorr = 1:Rc
  NbrRemainingNodes = zeros(1,MaxReport);
  FOR iSimul = 1:NSimul
     choose_Node_position(Ntot);
     RemainingNodes = [1:Ntot];
     NbrSentReport = 0;
     WHILE(Correlated_Nodes(RemainingNodes, Rcorr )==true)
        SelectedNode = Select_Node(RemainingNodes);
        NbrSentReport = NumberSentReport +1;
        FOR Node = 1:length(RemainingNodes)
           IF distance(SelectedNode, Node)<= Rcorr
                      Remove(Node,RemainingNodes);
           END
        END
        NbrRemainingNodes(NbrSentReport) += length(RemaningNodes);

     END
  END
  NbrRemainingNodes = NbrRemainingNodes/NSimul;
  RemainingNodeRcorrReport(Rcorr)= NbrRemainingNodes;
END
```

Fig. 6 R_{corr} calculation procedure

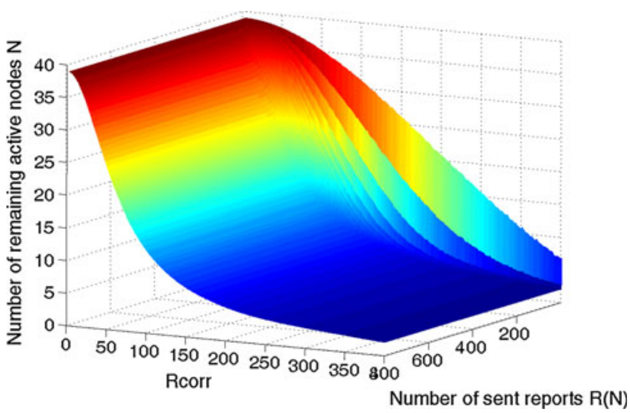

Fig. 7 How to determine R_{corr} knowing N and $R(N)$

straightforward given its underlying complexity [26], particularly if the sensors are mobile. Moreover, the high computing complexity of the INS protocol may also limit the application of the CC-MAC protocol since the INS algorithm should be re-executed after each topology or node's position change. This induces additional signaling messages in the network, since the new correlation radius R_{corr}, computed at the sink level, needs to be disseminated to all the sensor nodes. This operation is high consuming in terms of signaling messages and energy. In turn, using our method, the correlation radius remains the same regardless of the position of the N reporting nodes as long as they stay in the event area.

Indeed, using the proposed SC-MAC protocol, the N_{tot} sensor nodes choose the reporting nodes only based on the information about the values of N, $R(N)$ and R_{corr} sent by the sink, without requiring any explicit internode communication, thus keeping the simplicity and the distributed feature of the original DCF protocol. We underline that the main advantage of the proposed SC-MAC protocol is its simplicity, since it needs slight modifications in the existing DCF MAC protocol. It mainly 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}). That is why, it can be used in combination with any low power MAC protocol.

Hereafter, we list the basic operations of our proposed SC-MAC. Each time a specific source node, n_i $(i = 1, \ldots, N_{tot})$, transmits its event record to the sink, all of its correlated neighbors (within a radius R_{corr}) enter a sleep mode. The proposed SC-MAC protocol aims at building correlation regions in an iterative way. In each correlation region, a single sensor node is responsible for the event reporting. It keeps transmitting reports until receiving a final acknowledgement frame (ACK_FIN) from the sink node. To describe the SC-MAC algorithm, we distinguish between two phases: the startup and steady phases.

- Startup phase: When an event occurs, all sensor nodes within the event radius contend for the medium by sending RTS frames. Once a node n_i captures the channel after the first contention phase, it becomes the reporting node of its correlation area. Specifically, each node n_j, within the event radius, that receives the RTS frame from node n_i, determines the distance $d(i, j)$ that separates from node n_i based on the power of the received signal. It is worth noting that, in our study we neglect errors in distance estimation since we consider a free space environment. Recall that errors in distance estimation (based on received signal strength) mainly depends on obstacles presence. That is why, assuming a free space environment highly alleviate the impact of errors in distance estimation. Based on the distance $d(i, j)$, node n_j identifies if it belongs or not to the correlation area managed by n_i. Especially, if $d(i, j) \leq R_{corr}(N)$, the node n_j dump its queue and enters immediately into the sleep mode for a period of time equal to

$$T_{sleep} = T_{remain} + T_{sm} \tag{6}$$

During this period of time only the active node will monitor the network activity. Note that, T_{sm} is an optional time which will be discussed later. Moreover, T_{remain} is an estimation of the remaining time needed by the network to report reliably the detected event. In other words, T_{remain} assess the time spent by the remaining reports $(R(N) - R_{current})$ to cross a multihop network in order to accomplish the reliable reporting operation of the detected event. Hence T_{remain} can be written as follows:

$$T_{remain} = (R(N) - R_{current}) \cdot T_{estimated\_RTC} \cdot H_{estimated} \tag{7}$$

where $H_{estimated}$ is an estimate of the hops number between n_j and the sink node. To simplify the design of our protocol, we suggest that $H_{estimated}$ reads

$$H_{estimated} = \lceil \frac{d(j, Sink)}{R_t} \rceil \quad (8)$$

Note that, in our proposal, we suppose that each node knows its location as well as the sink one so that it can determine the distance separating it from the sink and consequently the corresponding $H_{estimated}$. In addition, $T_{estimated\_RTC}$ can be expressed as follows:

$$T_{estimated\_RTC} = DIFS + Bc_{estimated} + 3 \cdot SIFS + t_{CTS} + t_{DATA} + t_{ACK} \quad (9)$$

where $Bc_{estimated}$ is the backoff counter of the last sent report.

On the other hand, if n_j does not belong to the n_i's correlation area, it will increment its local counter $R_{current}$ that indicates the current number of sent reports to the sink regarding the detected event. Then, n_j stores the identity of n_i in its reporting node list. This list contains the identities of the distinct nodes that already reported the detected event. Specifically, if the size of this list attains the desired number of active reporting nodes $N_{desired}$, the node n_j undergoes immediately the sleep mode for a period equal to T_{sleep} and the startup phase finishes. Otherwise, node n_j contends again for the medium access to report the detected event. Note that the startup phase stops either when the number of the distinct reporting nodes attains the desired $N_{desired}$ or when all the correlation regions are identified (i.e., no more sensor nodes in the event area can go to the sleep mode). It is worth noting that in our study, we suppose that the WSN is dense enough so that each reporting node can find a path to the sink despite of the fact that several nodes are in the sleep state. In fact, each time a correlated neighbor goes to the sleep mode, variations in the overall topology follow, since all the links with the correlated neighbor will be pruned from the graph as shown in Fig. 8.

- Steady phase: As mentioned before, at the end of the first startup phase, only N reporting nodes keep generating reports until they receive an ACK_FIN frame from the sink. The sink node broadcasts an ACK_FIN frame instead of the classic ACK frame when the desired event reliability, corresponding to a predefined tolerable information distortion D_{max}, is reached. We note that the ACK_FIN frame is only broadcasted by the SINK (and not by the intermediate relay nodes) when the event reliability requirement is achieved. In other words, in contrast to the standard RTS, CTS and ACK frames which are sent in hop by hop fashion, the ACK_FIN frame is only transmitted by the sink node when it receives enough reports to consider event as reliable. In this regard, applying our SC-MAC protocol implies a slight modification at the existing DFC MAC protocol of the sink node. In addition to the standard ACK frame, the sink node should broadcast an ACK_FIN frame when the desired event reliability is reached. Once an ACK_FIN frame is received, every reporting node dumps its queue and stops generating new reports. Approximately, at the same time the correlated sleeping neighbors are waken up anew if the variable T_{sm} is set equal to null. Indeed, $T_{sm} \neq 0$ means that only the previously elected reporting nodes will continue supervising the area while the other nodes in the event area remain in the sleep mode. As such, if during the T_{sm} period a new event occurs, the elected reporting nodes will directly ensure the event reporting avoiding thus unnecessary energy consumption during a new startup phase. However, due to the limited capacity of the sensor nodes' batteries the reporting load must be balanced among all the sensor nodes. Hence, the period T_{sm} must be limited. In the next section, we will see the impact of the T_{sm} duration on the network performance.

  We note that the second phase (i.e., steady phase) terminates when T_{sm} expires. At this time, all the sensor nodes are waken up again and if a new event occurs the network goes through a new startup phase. As such, a new group of reporting nodes is elected. It is worth noting that an event may not be completely reported (i.e., reliably reported $R_{current} \leq R(N)$) due to battery drain of the selected reporting nodes. In this case, the sink does not send a final acknowledgement (ACK_FIN) and can thus announce the death of the network. Recall that in our study, the network lifetime is defined as the time spent from the deployment until the network becomes unable to report events due to the lack of energy.

We also highlight that in our protocol, we consider the overhearing avoidance mechanism [3, 15]. The rationale behind this is to allow further energy consumption. Indeed, the overhearing avoidance mechanism consists in letting nodes that overhear the RTS request sent by the current reporting node to undergo the sleep mode during the transmission of the report. To achieve this, we distinguish between two cases. In the first case, the sensor node that overhears the RTS frame is not within the event area. The sensor node will therefore undergo the sleep mode during a period equal to CTS+DATA+ACK. In the second case, the node that overhears the RTS frame is within the event radius. This node will undergo the sleep mode during only the CTS+DATA period. It has to wake up before the acknowledgment transmission by the sink in order to be able to receive the potential ACK_FIN frame.

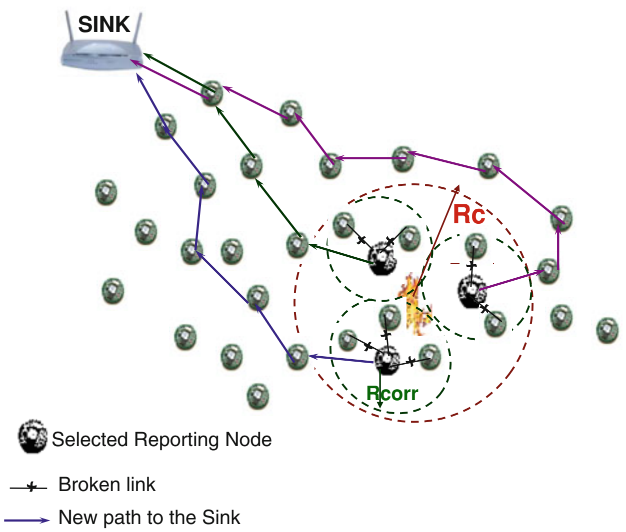

Fig. 8 New paths formation. The reporting nodes transmit their reports through new paths since all correlation neighbors undergo the sleep mode

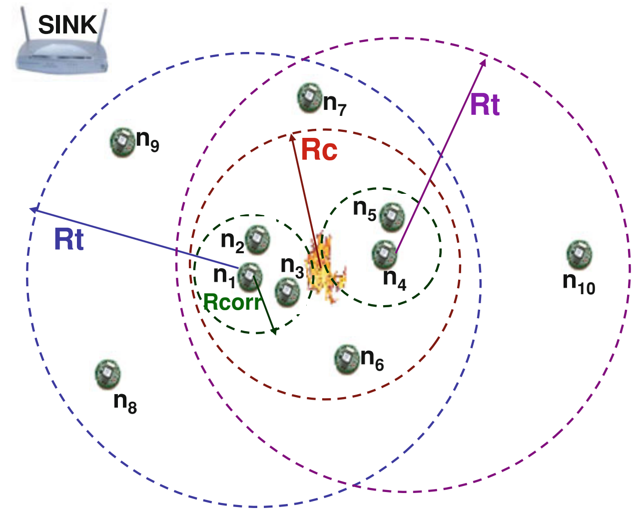

Fig. 9 Simple network example: case study

5.3 Illustrative example

To illustrate the SC-MAC scheme, we consider the simple network example shown in Fig. 9. Accordingly, 6 nodes, labelled $n_1, \ldots, n_6$, sense the occurred event. We assume that the optimal number of active reporting nodes that minimizes the energy consumption is $N_{opt} = 2$. The associated number of reports to achieve the desired information reliability is $R(N_{opt}) = 10$.

The SC-MAC operation begins with the startup phase. All the sensor nodes within the event radius (i.e., $n_1, \ldots, n_6$) contend for the medium access by sending RTS frames. Suppose that n_1 is the first node that captures the channel by sending correctly a RTS frame through the following route [n_1, n_7, *sink node*]. Immediately, the following three actions follow:

1. nodes n_2 and n_3 undergo the sleep mode during a T_{sleep} period since they are inside the correlation region of n_1.
2. n_1 and the remaining sensor nodes outside of the correlation region of n_1 (i.e., n_4, n_5, and n_6) store the identity of n_1 in their own reporting node lists. Moreover, each sensor node increments its local counter $R_{current}$, which becomes equal to 1. Recall that $R_{current}$ indicates the current number of sent reports to the sink. Since $R_{current} < R(N_{opt})$ and the size of the reporting list $< N_{opt}$, the SC-MAC procedure, particularly the startup phase, continue.
3. Overhearing avoidance procedure: We distinguish here between two set of nodes. The first set comprises $\{n_4, n_5, n_6\}$, i.e., the nodes that overhear the RTS frame and are in the event area. These nodes undergo the sleep mode during the $T_{OA1} = CTS + DATA$ period. The second set of nodes $\{n_8, n_9\}$ is composed of the remaining nodes that overhear the RTS frame, except n_7 that belongs to the path towards the sink. The nodes in this second set undergoes the sleep mode during a longer period equal to $T_{OA2} = CTS + DATA + ACK$.

As the desired N_{opt} is not yet attained nor $R(N_{opt})$, the startup phase continues. The remaining active nodes $\{n_1, n_4, n_5, n_6\}$ contend again for the medium access. Suppose that n_4 captures the channel by sending correctly a RTS frame through the route [n_4, n_7, *sink node*]. As before, the following three actions ensue:

1. n_5 undergoes the sleep mode during T_{sleep} since it is inside the correlation region of n_4.
2. n_1, n_4 and n_6 update their report counters $R_{current}$ and their reporting lists. This latter contains two elements $\{n_1, n_4\}$, which is equal to the desired N_{opt}. Hence, immediately:
   (a) The remaining active reporting nodes that do not belong to the reporting list (i.e., n_6 in our case) enter the sleep mode during T_{sleep}.
   (b) The startup phase terminates.
3. Overhearing avoidance procedure: n_1 undergoes the sleep mode during T_{OA1} period, while n_{10} undergoes the sleep mode during T_{OA2} period.

As the desired N_{opt} is attained, the startup phase terminates. The steady phase begins since $R_{current} = 2 < R(N_{opt}) = 10$. Suppose now that n_1 captures again the channel. Then, the following action follows:

1. Overhearing avoidance procedure: n_4 undergoes the sleep mode during T_{OA1} period, while n_8 and n_9 undergoes the sleep mode during T_{OA2}.

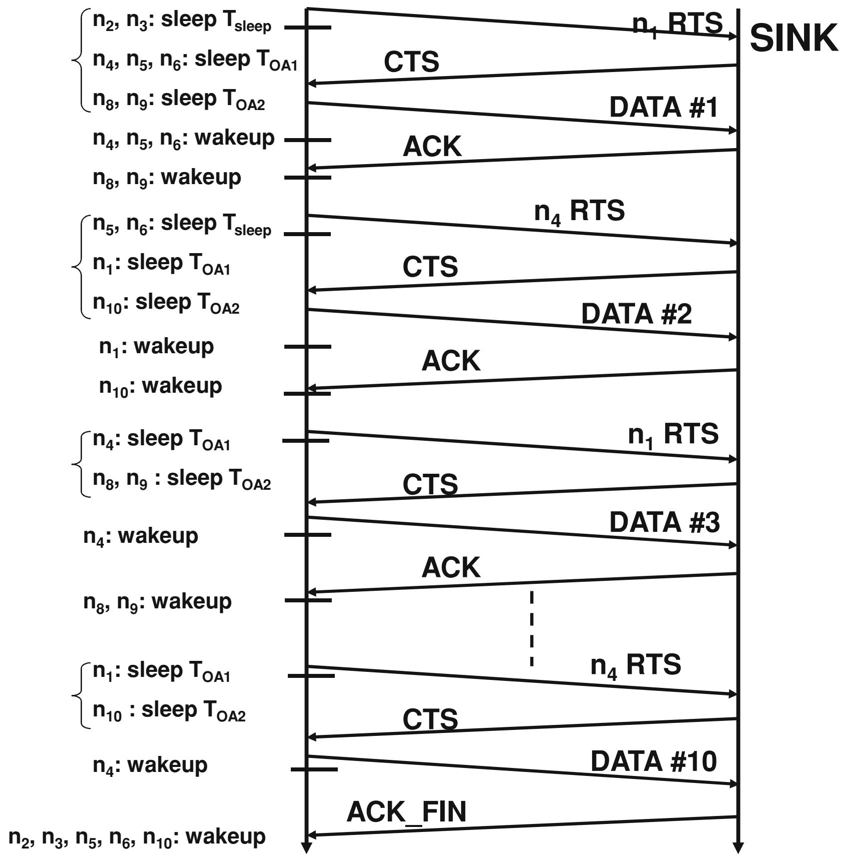

Fig. 10 SC-MAC procedure over the simple network example of Fig. 9

The steady phase continues until the reception of an ACK_FIN by the reporting nodes from the sink. The ACK_FIN indicates that $R(N_{opt})$ reports are already received by the sink node. In Fig. 10, the messages exchanged during this example are shown.

6 Performance evaluation

In this section, we evaluate the performance of the proposed SC-MAC protocol. A simulation model has been developed using ns-2 [27]. We first analyze our SC-MAC protocol. Specifically, we study the energy consumption during both the startup and steady phases. Then, we conduct a comparison study between our protocol and CC-MAC. In our model, we consider 40 mobile sensor nodes randomly deployed in a 500 × 500 m^2 sensor field. The event source is represented by a mobile node that generates events periodically. The parameters setting in our experiments are listed in Table 1. We note that our simulations are run until a very narrow 97.5 % confidence interval is achieved. Once this objective is accomplished, the simulations stop automatically.

6.1 SC-MAC performance evaluation

As mentioned before, we will first focus on the analysis of our proposed SC-MAC protocol. We study the behavior of the network during both the startup and steady phases. To do so, we first set the variable $T_{sm} = 0$. Recall that T_{sm} is a variable introduced to avoid repetitive startup phases. In other words, the elected reporting nodes during the first startup phase continue monitoring the network activity during the total period of T_{sm}.

Let us focus on the impact of the number of reporting nodes (N) on the average amount of energy consumed by the network to send one report as shown in Fig. 11. This figure shows that the amount of energy consumed by the network to send one report 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 leading to an important increase in the number of overhearers. As a result, the total amount of energy consumed by the network in the reception of the signaling messages (i.e., RTS and ACK messages) increases considerably. Recall that our SC-MAC protocol makes also use of the overhearing

Table 1 Simulation parameters

Communication range	100 m
Sensing range	50 m
Packet length	30 bytes
IFQ length	65 packets
Transmit power	24.75 mW
Receive power	13.5 mW
Idle power	13.5 mW
Sleep power	15 µW
Initial network energy	100 J
Transmission bit rate	40 kbs^{-1}
Event occurrence frequency	10 s

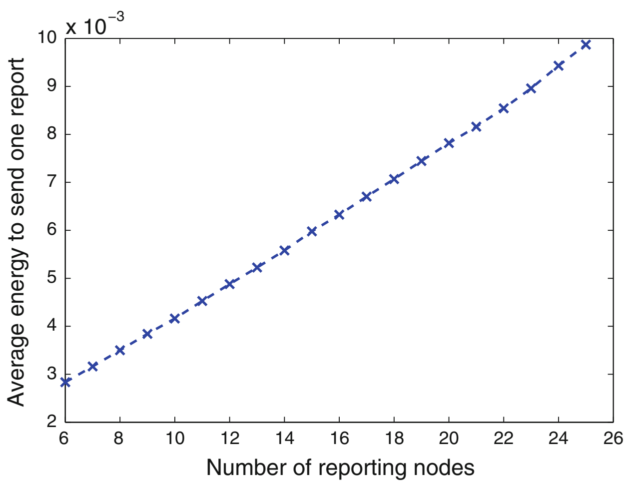

Fig. 11 The amount of enregy required by the wsn to send one report

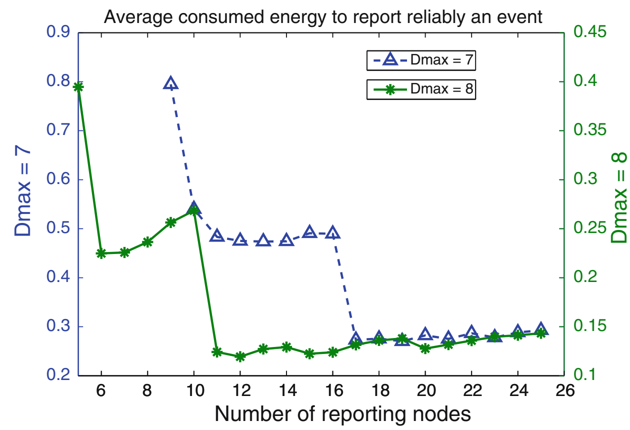

Fig. 12 Average energy required by the WSN to report reliably an event

avoidance mechanism, which prevents overhearers among the active reporting nodes from receiving the CTS and DATA messages.

Figure 12 represents the average amount of energy consumed by the network to report reliably an event as a function of the number of reporting nodes N for two representative values of the maximal tolerable distortion $D_{max} = 7$ and $D_{max} = 8$. This figure shows that the average amount of energy consumed by the network to report reliably an event is minimal for $N_{opt} = 17$ when $D_{max} = 7$ and for $N_{opt} = 12$ when $D_{max} = 8$. In fact, according to Figs. 3 and 11, we can see that we have two opposite requirements to minimize the amount of energy required to report reliably an event. On one hand, increasing N raises the average amount of energy consumed by the network to send one report (see Fig. 11). On the other hand, raising the number of reporting nodes N, decreases 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 tradeoff between the above mentioned opposite requirements as shown in Fig. 12. Specifically, assuming that the maximal tolerable distortion at the sink is $D_{max} = 8$, the minimal energy consumption is obtained when only $N_{opt} = 12$ reporting nodes out of the N_{tot} ones are activated whereas the remaining ones undergo the sleep mode. Based on this result, we can state that using a small subset of the nodes rather than all sensor nodes in the event area to report reliably an event reduces considerably the energy consumption. To get more insight into this result, we study hereafter the energy consumption in startup and steady phases separately.

Figure 13 plots the number of successfully transmitted reports during the startup phase. It represents the number of transmitted reports needed during the startup phase in order to keep only N active nodes among the N_{tot} potential reporting ones. We can observe that the needed number of reports is a convex function of the desired N. Indeed, for high values of N, the number of reporting nodes $N_{tot} - N$ to put into sleep is small. Hence, we need a small number of reports to keep only N active reporting nodes. On the other hand, for small values of N, we need also a small number of reports to accomplish the startup phase. Recall that according to our mechanism, when the number of distinct reporting nodes that have succeeded to send at least one report reach the desired N, all the remaining active nodes undergo automatically the sleep mode and thus the startup phase terminates. In view of this, when the desired N gets moderate values, the number of the transmitted reports during the startup phase increases compared to the cases where N is small or high. Specifically, the maximum is obtained for $N = 16$ and $N = 10$ when the maximal tolerable distortion is $D_{max} = 7$ and $D_{max} = 8$, respectively. Following the same reasoning, it is easy to see that the total energy consumed during the startup phase is a convex function (see Fig. 14) where the maximum is

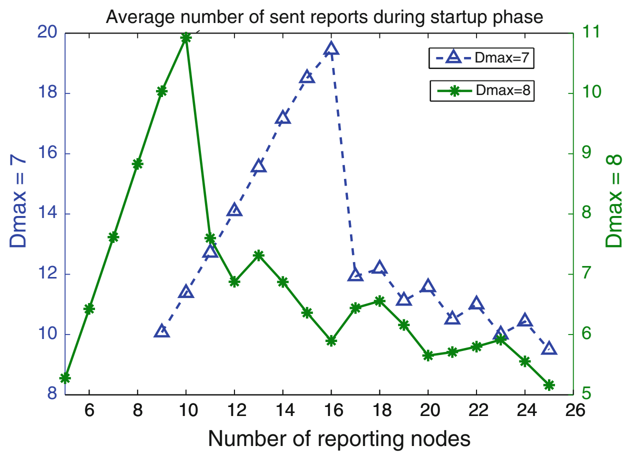

Fig. 13 Average number of sent reports during startup phase

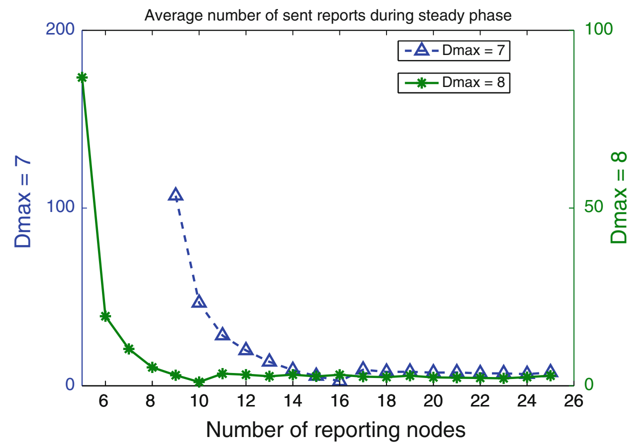

Fig. 15 Average number of sent reports during steady phase

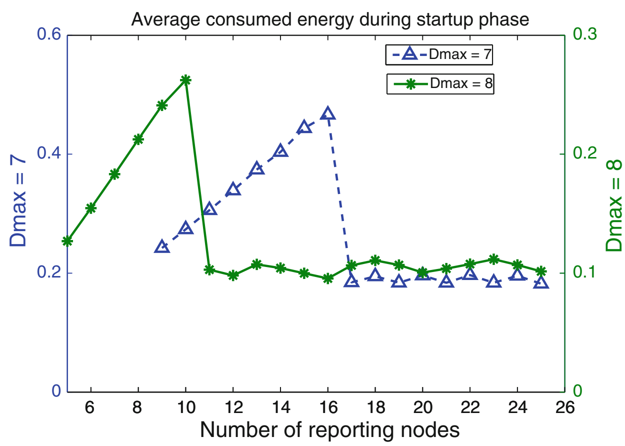

Fig. 14 Average consumed energy during startup phase

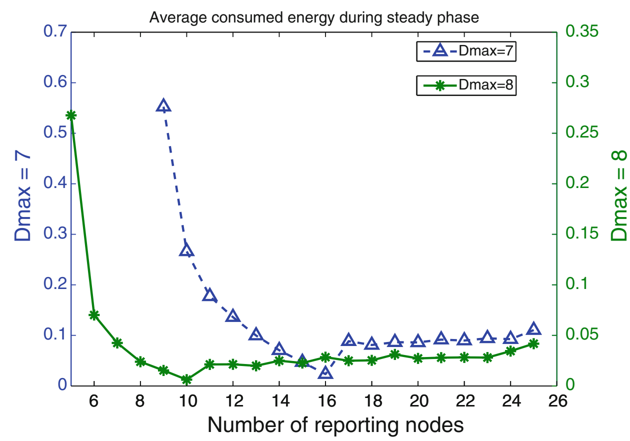

Fig. 16 Average energy consumed during steady phase

obtained again for $N = 16$ and $N = 10$ when the desired distortion is $D_{max} = 7$ and $D_{max} = 8$, respectively.

Figure 15 represents the average number of remaining reports to sent during the steady phase in order to accomplish the reliable reporting operation of the detected event; and Fig. 16 shows the associated required energy. In both figures the curves are convex where the minimum is obtained for $N = 16$ and $N = 10$ when $D_{max} = 7$ and $D_{max} = 8$, respectively. Indeed, in contrast to the startup phase where the maximum energy consumption is obtained for example for $N = 16$ when $D_{max} = 7$, putting $N = 16$ allows the minimal energy consumption during the steady phase. It is easy to see that we have two opposite requirements regarding the energy consumption during the startup and the steady phases. The tradeoff between this two requirements leads to the minimum energy consumption for instance for $N = 17$ when $D_{max} = 7$ as shown in Fig. 12.

To get more insight into the energy consumption in the network, let us consider Figs. 17 and 18 that report the average amount of energy consumed per report during both the startup and steady phases for the same two representative values of the maximal tolerable distortion $D_{max} = 7$ and $D_{max} = 8$, respectively. Building on these results, two main findings can be identified. First, the amount of energy consumed per report in the startup phase is greater than the one consumed in the steady phase. In this regard, further energy conservation can be realized by avoiding the startup phase occurrence at each event detection. One way to achieve this is by introducing the T_{sm} variable as it will be discussed below. The second finding revealed in Fig. 17 is that the optimal energy consumption per report in the startup phase is obtained for example by setting $N = 17$ when $D_{max} = 7$. This same value of N also leads to the optimal energy consumption to report reliably an event. This demonstrates again that the startup phase has a significant impact on the total energy consumption.

Typically, the amount of energy consumed during the startup phase represents a significant part of the total energy required to report reliably an event (up to 50 %, see

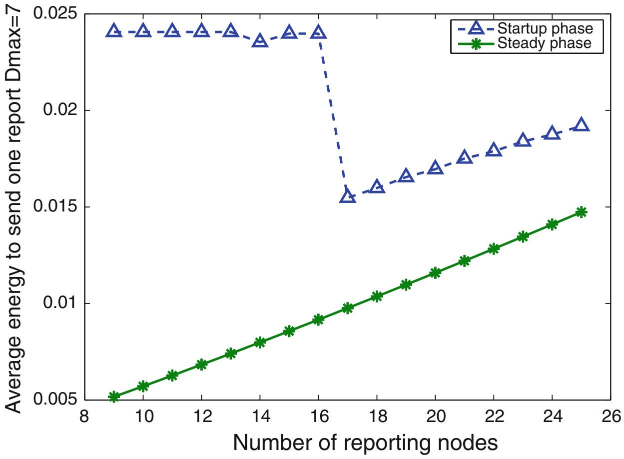

Fig. 17 Average energy to send one report during both phases: startup and steady: case $D_{max} = 7$

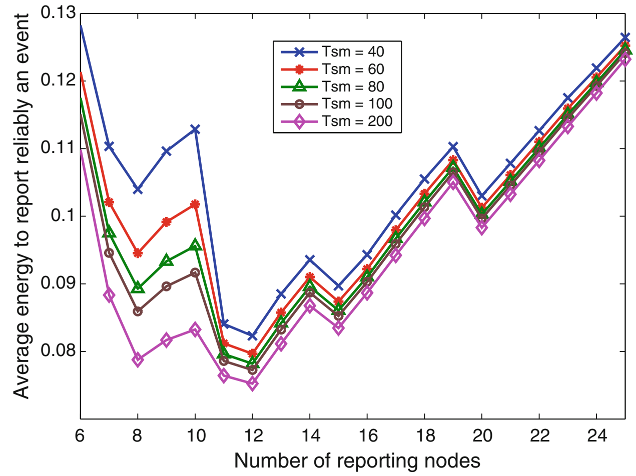

Fig. 19 T_{sm} impact on the energy consumption: case $D_{max} = 8$

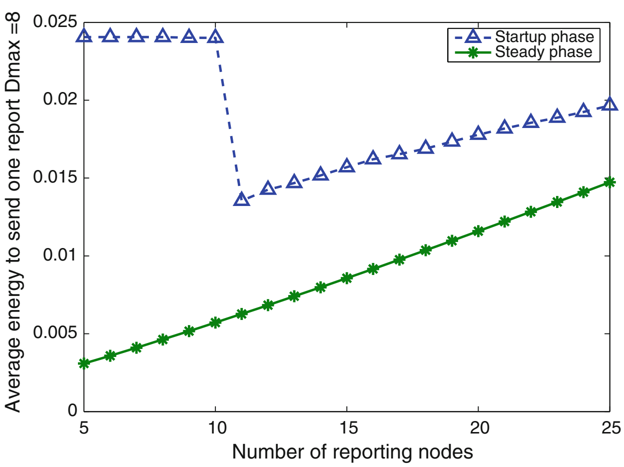

Fig. 18 Average energy to send one report during both phases: startup and steady: case $D_{max} = 8$

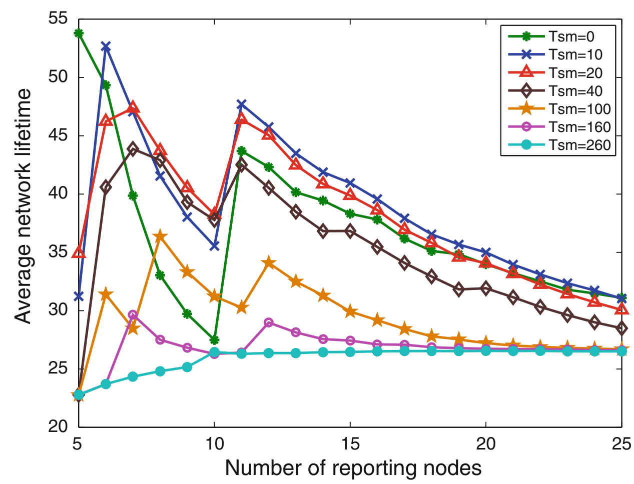

Fig. 20 Average lifetime for various T_{sm} duration: case $D_{max} = 8$

Figs. 12 and 14). In this regard, it is highly recommended to avoid the startup phase during the event reporting. To achieve this, we introduced the T_{sm} variable, which avoids electing reporting nodes for each new event occurrence. However, the period of T_{sm} must be limited in order to balance the load among all the sensor nodes as it will be shown later.

Let us now focus on the impact of T_{sm} on the network performance. The T_{sm} duration specifies how long an elected node will remain a reporting node. Specifically, if during the T_{sm} period a new event occurs, the already elected reporting nodes will immediately perform the event reporting avoiding this way to go through a new startup phase. To gain better understanding of the T_{sm} duration, we study its impact on both the energy consumption and the network lifetime as shown in Figs. 19 and 20 respectively.

Figure 19 shows the variation of the energy consumption for various values of T_{sm}. T_{sm} ranges from 40 to 200 s. We can observe that the average energy required to report reliably an event decreases with the increase of T_{sm}. Specifically, a gain of 8 % is achieved when T_{sm} increases from 40 to 200 s. Indeed, as the T_{sm} duration increases, the selection of reporting nodes (i.e., startup phase) is performed less frequently. Hence, the reporting operation requires less energy.

Following this reasoning, the greater the T_{sm} duration the lower the energy consumption. However, doing so, the capacity of the elected reporting nodes' batteries will expire quickly as the nodes have to cope with the entire network load. Once this happens, the network will be unable to report events until the expiration of the T_{sm} duration. In view of this, the choice of the T_{sm} duration must take into account the limited initial capacity of the sensor nodes' batteries and accordingly the reporting load must be balanced among all the sensor nodes.

Figure 20 shows the network lifetime for various values of T_{sm}. The network lifetime is defined as the time spent from the deployment until the network becomes unable to report events due to the lack of energy. As explained before, we can see that high values of T_{sm} lead to a deterioration of the network lifetime due to the lack of load balancing. Note that, according to Fig. 20, the maximal network lifetime is achieved for $N = 6$ when $T_{sm} = 10$ s.

Above, we have investigated the average energy needed to report reliably an event. Let us now focus rather on the average time required to report reliably an event (i.e., to transmit $R(N)$ reports). This is the time spent between the event occurrence and the reception of the final acknowledgement by all the reporting nodes. Recall that the number of reports $R(N)$ that need to be transmitted to the sink node in order to achieve the desired event reliability is shown in Fig. 3. As expected, the latency curve (see Fig. 21) follows the same pace of the curve shown in Fig. 3. In fact, as the number of reporting nodes increases the number of required reports to achieve the desired reliability decreases and hence the overall latency to report reliably an event decreases.

6.2 Comparative study

In this subsection, we conduct a comparison study between our SC-MAC protocol, the CC-MAC protocol [1] and a basic protocol without any node selection mechanism. To achieve this, we will proceed as follows. We will first compare the energy consumption generated by each of the three protocols. Then, we will focus on latency, packet drop rate and reliability metrics. We use the same simulation scenario used in the previous subsection. Moreover T_{sm} is set equal to 100 s as in [1].

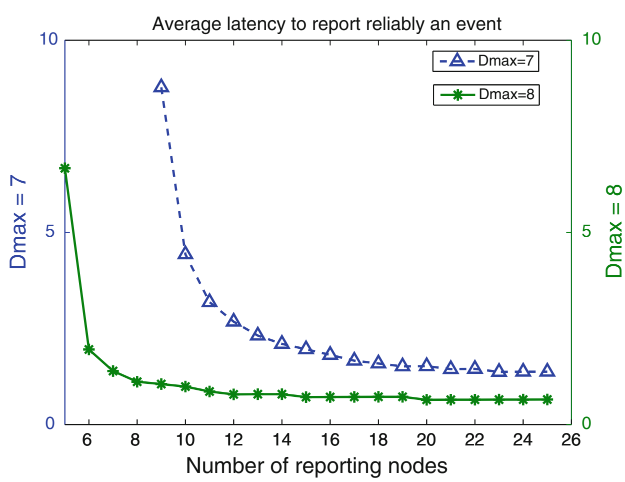

Fig. 21 Average time required to report reliably an event

Table 2 Results for different distortion values

D_{max}	7	8	9	10	11
N_{min}	19	11	8	6	5
N_{opt}	17	12	9	7	6
R_{opt}	22	10	7	5	4
$E(N_{min})(J)$	0.223	0.0812	0.0542	0.0349	0.0268
$E(N_{opt})(J)$	0.2207	0.0772	0.0428	0.0257	0.0187

The first finding, as reported in Table 2, is that $E(N_{opt}) < E(N_{min})$. For instance when $D_{max} = 7$, $E(N_{opt} = 17) < E(N_{min} = 19)$. Recall that [1] stipulated that at least $N_{min} = 19$ 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. However our scheme reduces the energy consumption as $E(N = 17) < E(N = 19)$. Consequently, we can state that our scheme does not only introduce more flexibility to attain the desired reliability, but it also enables further energy conservation. This result can also be observed in Fig. 22, which shows the minimal energy consumption according to the optimal setup of the number of reporting nodes for SC-MAC and CC-MAC protocols (i.e., N_{opt} for SC-MAC and N_{min} for CC-MAC) and also for the basic case without any node selection mechanism (i.e., $N = N_{tot}$). The figure shows the average amount of energy consumed to report reliably an event as a function of the distortion D_{max}. We can see that the node selection schemes in the CC-MAC protocol and in the SC-MAC protocol achieve high energy saving which justify their usefulness. It is worth noting that our protocol always outperforms the CC-MAC.

From the latency point of view and as shown in Fig. 23, SC-MAC outperforms also CC-MAC by achieving lower delays. Indeed, the SC-MAC scheme requires less reports to be transmitted compared to the CC-MAC to attain the desired information reliability (i.e., distortion) (see Table 2). For the same reason, the basic protocol without node selection achieves the best latencies. In fact, when the number of reporting nodes $N = N_{tot}$ the corresponding reliability level is too small compared with those of SC-MAC and CC-MAC protocols (see Fig. 3).

In order to get more insights into the potential performance improvement gained by applying our proposal instead of CC-MAC, let us consider Table 3 which quantifies the gains in terms of energy and latency for representative values of distortion. Table 3 summarizes the results of Figs. 22 and 23.

Based on these results and as a main contribution of work, we can see that significant energy conservation up to

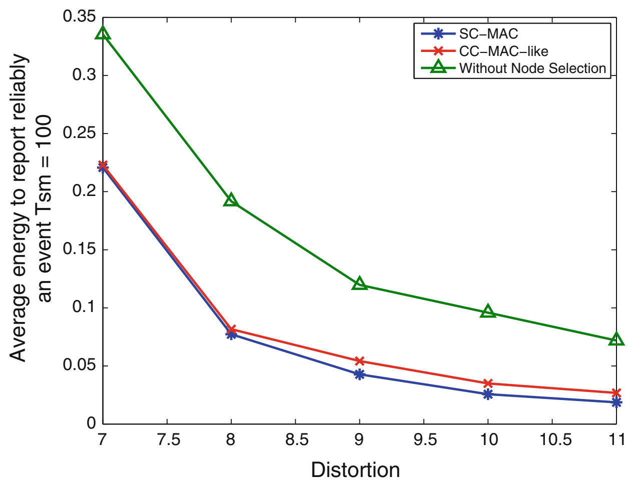

Fig. 22 Comparaison of the energy consumption among SC-MAC, CC-MAC and without node selection protocols

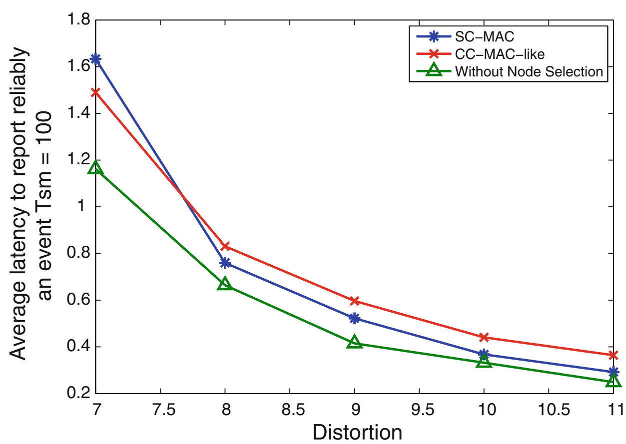

Fig. 23 Average delay to report reliably an event for the three MAC protocols

Table 3 Performance Improvement of SC-MAC compared to CC-MAC

Distortion	Energy (%)	Latency (%)
9	21,13	12,44
10	26,52	24,65
11	30,15	19,87

30 % can be achieved by applying our SC-MAC scheme. Moreover, a latency improvement up to 24 % can be also achieved, which is very important for delay sensitive applications.

Figure 24 shows the packet drop rate when using the three above mentioned protocols. The packet drop rate is defined as the proportion of packets dropped due to collisions. As expected when the number of reporting nodes $N = N_{tot}$ (i.e., the basic protocol without node selection) the packet drop rate is too high since the probability of collisions is very high. Besides, we can see that CC-MAC outperforms slightly SC-MAC. This is because the CC-MAC allows less number of reporting nodes to perform the reporting task compared to SC-MAC (see Table 2). Hence, the probability of collisions decreases which reduces the packet drop rate.

Finally, we studied the perceived information distortion as shown in Fig. 25. The goal is to validate the efficiency of our proposed algorithm to select nodes. We can see that the SC-MAC curve coincides practically with the desired distortion curve, which validates the efficiency of the algorithm used to calculate R_{corr}(see Fig. 6). This result validates also the effectiveness of the scheme used to construct the correlation regions in order to elect the reporting nodes.

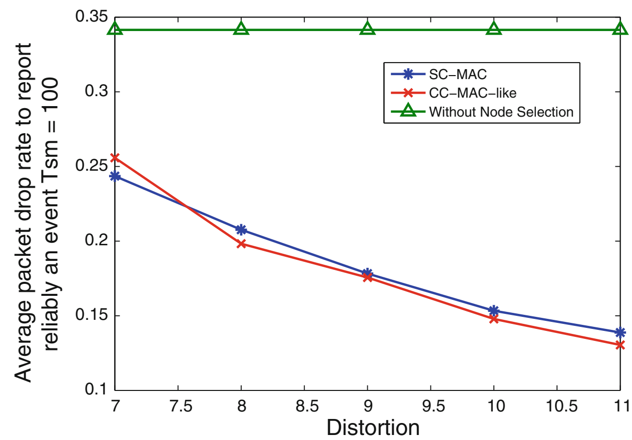

Fig. 24 Percentage of dropped packets for the three MAC protocols

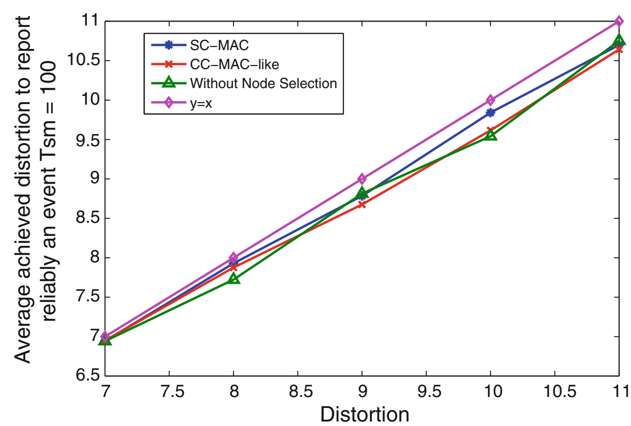

Fig. 25 Achieved distortion for the three MAC protocols

7 Conclusion

Reducing the number of event reporting nodes for an observed event by exploiting the spatial correlation enables significant energy conservation in WSNs. This can be achieved by suppressing the redundant information transmitted by closely located sensors. By allowing only a subset of nodes to report the detected event, our proposed MAC protocol reduces the energy consumption and minimizes unnecessary channel access contention, which reduces the event reporting latency.

In this paper, we have studied the relationship between the wireless sensor network performance and the number of reporting nodes based on spatial correlation constraint introduced in [1]. We first analyzed the impact of the number of reporting nodes on the number of required reports to comply with a desired reliability. As a main first contribution and compared with CC-MAC protocol [1], we have demonstrated that our proposed SC-MAC protocol minimizes the energy consumption by delegating the reporting task to only N_{opt} reporting nodes without transgressing neither the desired event reliability nor the packet drop rate. Activating more or less than N_{opt} sensor nodes increases the energy expenditure. As a second main contribution, we have proved that the average time to report reliably an event is also reduced compared to CC-MAC. These findings demonstrate that the energy-reliability-latency tradeoff is better achieved by SC-MAC protocol.

Few issues have not been considered in this paper. For instance, the scenario where multiple events occur concurrently in the network. Although not frequent, this scenario represents a challenging case study for future research.

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