Modified Greedy Algorithm for Prolonging the Lifetime of Mobile Wireless Sensor Networks

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***Abstract*— To design efficient algorithms for improving the lifetime of wireless sensor networks, one must strike a balance between minimizing the unused residual energy in the sensors nodes' batteries at the network death moment, and minimizing the energy spent to report sensory information to the sink node. A centralized greedy algorithm does this by exploring both real-time channel state and residual energy information. This paper presents a modified greedy algorithm that relax on the real-time requirements of the greedy algorithm, bringing flexibility between privileging equalized energy consumptions at the expense of reduced lifetimes, or privileging burst-like transmissions in favor of longer lifetimes. Instead of exploring current channel and residual energy information, the new algorithm uses past information on expected consumptions of the sensor nodes, thus yielding a less complex implementation. Comparisons with the greedy algorithm are made to demonstrate the potential lifetime improvements achieved with the proposed one.**

***Keywords*— Lifetime improvement, mobile wireless sensor networks, greedy algorithm.**

I. Introduction

The presence of mobile sink nodes, mobile sensor nodes or both in a wireless sensor network (WSN) characterizes a mobile wireless sensor network (MWSN) [1]. MWSNs are suitable to a myriad of applications, such as military surveillance and reconnaissance, target detection, vehicle or personnel tracking, environmental monitoring, smart homes, health monitoring, manufacturing control, smart transportation systems, security, social interaction, and other applications in telematics [1]. A potentially interesting future application is related to the WSN for military applications: a dedicated or multipurpose WSN sensor network can be the primary source for gathering information in military operations that require situation awareness of a battlefield. Due to the dynamic characteristics of the environment, the WSN should be able to adapt its sensing and transmission schemes in order to achieve the optimal result for the application [2].

Due to their dynamic topology, MWSNs impose restrictions to the system design, for instance in what concerns routing and medium access control (MAC) protocols, and quality of service (QoS) control mechanisms. Nonetheless, mobility can be explored to improve coverage, to increase the network lifetime and to handle energy control [1], particularly in military applications [3]. In this context, energy management is an important issue to be considered, since most of the sensor networks have their lifetime (or lifespan) increased if the limited energy residual of the sensor nodes can be saved somehow. This is particularly important if the sensor nodes' batteries cannot be replaced or recharged.

Lots of efforts have already been spent to prolong the lifetime of wireless sensor networks; see for example [4], [5], [6], [7], [8], [9] and references therein. Many of these attempts act on the energy spent during the task of communication among sensor nodes or between sensor nodes and sink nodes. In [10], based on solid guidelines for lifetime improvement, a greedy algorithm is proposed for controlling the communications between the sensor nodes and the sink node. In this algorithm, the balance between minimizing the unused residual energy at the network death moment in the sensors nodes' batteries, and minimizing the energy spent to report sensory information to the sink node is achieved by selecting a single sensor node at a time for communicating with the sink node, based on real-time channel state and residual energy information.

This paper presents a modified greedy algorithm that relax on the real-time requirements of the original greedy algorithm. The main attributes of the proposed algorithm are:

- Instead of exploring current channel and residual energy information, the new algorithm uses past information on expected consumptions of the sensor nodes, thus yielding a more feasible and less complex implementation when compared with the original greedy algorithm.
- It brings flexibility to the choice between (i) privileging equalized energy consumptions at the expense of reduced lifetimes, or (ii) privileging burst-like transmissions in favor of longer lifetimes. Equalized consumptions allows for more frequent communication with the sink node and make the sensor nodes die altogether. Burst-like transmissions allows less frequent communication with the sink node, but is more energy-efficient.

The remaining of the paper is organized as follows: the problem statement and system models are presented in Section II. In Section III, the original greedy algorithm presented in [10] is briefly described. Section IV is devoted to the proposed algorithm. Numerical results and discussions are given in Section V. Section VI concludes the paper.

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II. Problem Statement and System Models

It is considered an MWSN consisting of a number of sensor nodes whose communication tasks are controlled by a sink node, or other central node, in a time-frequency-division basis. The sensor nodes that can be directly controlled are those inside the sink node coverage area. Nonetheless, indirect control of all nodes or a large portion of them can be achieved by means of multi-hop communication with proper routing [11], [12], [13]. In order to decouple the performance of the proposed approach from any routing protocol that could be working in parallel, only direct communication with a mobile sink node is assumed, characterizing the SENMA (sensor network with mobile access) architecture [10]. Such a decoupling is also considered in the greedy algorithm of [10].

A. Problem Statement

It is assumed that the sensor nodes spend most of their energies during communication events with the sink node. We associate the term *activity level*, which was coined in [14], to the amount of time or time-frequency resources allocated to these events. Since the communication process is typically organized in frames (or superframes), and each frame is divided in time or time-frequency slots, then the activity levels define the fraction of slots in a frame that each sensor is allowed to use for communication purposes. Due to the node mobility, the problem is to determine dynamically the activity levels assigned to the sensor nodes so that the network lifetime is prolonged. In this context, the proposed algorithm can be applied to any wireless sensor network that employs a centralized manager to maintain network schedule, e.g. WirelessHART [15], ISA100.11a [16], [17], and IEEE 802.15.4e [18], [19].

B. Proposed System Model

Let the k-th lifetime improvement event denotes the moment in which the sensor nodes are controlled by the action of the central node, for $k = 1, 2, \ldots, K$. Each of these control events acts on groups of F frames indexed by $f = 1, 2, \ldots, F$, based on information on the energy consumption of the sensor nodes in the preceding F frames. Thus, low mobility or fixed WSNs will demand less frequent control events, i.e. large F, whilst WSNs with high mobility nodes will need more frequent control, i.e. small F or even $F = 1$. The value of KF is associated to the interval of analysis corresponding to KF frames indexed by $t = f + (k-1)F = 1, 2, \ldots, KF$, and represents the time over which the network is in operation.

The number of sensor nodes is denoted by N, and they are indexed by $n = 1, 2, \ldots, N$. A single sink node is assumed. The energies in the sensor nodes' batteries associated to the f-th frame and k-th control event are given by the residual energy N-dimensional vector $\mathbf{s}_f(k)$. The activity level vector is defined by $\mathbf{x}_f(k)$, with $\mathbf{x}_f(k) \succeq 0$ and $\mathbf{1}^{\mathrm{T}}\mathbf{x}_f(k) = 1$, where $\succeq$ represents component-wise inequality, $\mathbf{1}$ is the all-one N-dimensional vector, and the superscript T denotes transposition. If, for instance, an element $x_{n,f}(k)$ of this vector is 0.1, it means that the n-th sensor node may occupy 10% of the slots during the f-th frame pertaining to the k-th block of F frames.

During the f-th frame associated to the k-th control event, the energies that are expected to be consumed by the sensor nodes are given by $\mathbf{b}_f(k) \circ \mathbf{x}_f(k)$, where the symbol $\circ$ denotes the Hadamard product (element-wise multiplication), and $\mathbf{b}_f(k)$ is the maximum consumption vector containing the energies that the sensor nodes are expected to spend if the maximum activity level of 1 is assigned to them. The elements of $\mathbf{b}_f(k)$ depend on the positions of the sensor nodes relative to the sink node, which is assumed to be known. Notice that gathering this information is by far simpler than performing channel estimation, which is a computational costly process that contributes with increased energy consumption and system complexity. Specifically, each element of $\mathbf{b}_f(k)$ will be proportional to the transmit power necessary for a target error rate in the received data at the sink node, which in turn will depend on the physical layer specifications. Assume that this target error rate is achieved if the received signal power at the sink node is P_{target}. From the log-distance path loss model [20, pp. 199-202],

$$P_{\text{target}} = \frac{P_{\text{ref}}(d_0)}{(d/d_0)^{\eta}}, \tag{1}$$

where $P_{\text{ref}}(d_0)$ is a reference power at a close-in reference distance d_0 from the sensor node transmitter, η is the environment-dependent loss exponent, and d is the distance of analysis. Typical values of η range from 2 in the free-space propagation scenario to 4 or even more in obstructed areas. The energy consumed by a sensor node at a distance d from the sink node will be proportional to $P_{\text{ref}}(d_0) = (d/d_0)^{\eta} P_{\text{target}}$. Given that P_{target} is constant and assuming $d_0 = 1$ meter without loss of generality, then the energy consumption of a sensor node located at a distance d from the sink node will be proportional to d^{η}. Then, representing the sensor and sink node coordinates by the vectors $\mathbf{c}_{\text{s}}$ and $\mathbf{c}_{\text{sk}}$, respectively, each element of $\mathbf{b}_f(k)$ will be proportional to $\|\mathbf{c}_{\text{s}} - \mathbf{c}_{\text{sk}}\|^{\eta}$, where $\|\cdot\|$ stands for the Euclidean norm. The actual proportionality will depend on the sensor node specific hardware and battery characteristics and must be determined in a case-by-case analysis.

It is assumed that the estimated consumption during the first F frames is constant, yielding $\mathbf{b}_1(1) = \mathbf{b}_2(1) = \ldots = \mathbf{b}_F(1)$, meaning that transmissions during the first frame are done before the sensor nodes start moving. From the perspective of a system simulation, the subsequent vectors $\mathbf{b}_f(k)$ could be determined by assigning a mobility model to the nodes and computing the energy consumptions as previously described. However, this would demand the adoption of a model for the energy consumption of the nodes, which is beyond the scope of this paper. Without loss of generality, the element $b_{n,f}(k)$ of $\mathbf{b}_f(k)$ can be the correlated values of a random variable that will simulate variations in the energy consumptions as time elapses. The correlation level will determine the rate of variation in the consumptions from one frame to the next due to node mobility of any other cause. Specifically, let the auxiliary parameters $b_{\min}$ and $b_{\max}$ denote the minimum and maximum energy consumptions if the sensor node transmitter is *on* during the whole interval of a frame (which only happens if its activity level is 1), when positioned at minimum and maximum distances from the sink node, respectively. The elements of $\mathbf{b}_f(k)$ are made be uniformly distributed in $[b_{\min}, b_{\max}]$, with a correlation coefficient ρ between the energy consumptions in two consecutive frames. The method adopted for generating the correlated uniform random variates implemented in the present model is from [21], assuming a triangular correlation function to guarantee the same correlation coefficient between the consumptions during any two neighbor frames.

The lifetime of the network is defined here as the time interval during which all sensor nodes are in full operation. In other words, the instant at which the first sensor node fails with high probability (does not work properly) or fails permanently (ends its operation, or die) due to insufficient energy will determine the network lifetime. This definition has been adopted in several references, as for instance in [22], [23], [10], [11], [12], [14], and references therein. The value of t at which the residual energy of any sensor node becomes less than or equal to a given fraction of its maximum stored energy $\max\{\mathbf{s}_1(1)\}$ is defined as the *death instant*, t_{d}, and the corresponding residual energy is defined and the *death energy* s_{d} [14]. The death energy is a sensor-dependent parameter that relies on the characteristics of the battery and on the battery voltage level in which the sensor node starts to fail in accomplishing part or the totality of its functions.

III. The Greedy Algorithm Revisited

In the greedy algorithm [10], the sensor node exclusively selected by a central node for transmission at a given moment is the one with maximum energy-efficiency index

$$\gamma_n = e_n - E_r(c_n), \tag{2}$$

where e_n is the residual energy in the sensor node n at the beginning of a transmission, and $E_r(c_n)$ is the required reporting energy as a function of the channel gain c_n from the n-th sensor node to the sink node. Adapted to our notation, $E_r(c_n)$ corresponds to the element $b_{n,f}(k)$ of the maximum consumption vector $\mathbf{b}_f(k)$ at each k and f. The residual energy e_n starts with $s_{n,1}(1)$, i.e. the initial energy in the n-th sensor battery, and is updated for each k and f according to energy expenditure provided by the greedy algorithm, that is $e_n \leftarrow e_n - x_{n,f}(k) b_{n,f}(k)$, with $x_{n,f}(k)$ being the activity state which is 1 for $n = \arg\max_i \gamma_i$, and zero otherwise. From this formulation it is evident that the greedy algorithm uses *current* (real-time) channel state information c_n and residual energy information e_n. Notice that the term activity state is used here in the context of the greedy algorithm only to represent the *on* (activity state 1) and *off* (activity state 0) states of the sensor nodes' transmitters as determined by the algorithm, thus establishing consistence with the term activity level defined in [14] and adopted in this paper.

IV. Proposed Modified Greedy Algorithm

The first modification with respect to the original greedy algorithm is the computation of the energy-efficiency index (2) in two different ways, as follows:

$$\begin{aligned} \gamma_n &= e_n - E_r(c_n), \quad \text{if} \quad w = 0, \\ \gamma_n &= e_n, \qquad\qquad\quad \text{if} \quad w = 1, \end{aligned} \tag{3}$$

with $w = 0$ yielding an operation similar to the original greedy algorithm, i.e. burst-like transmissions followed by silent periods, and $w = 1$ yielding energy consumptions more equalized and, thus, sensor nodes more continually transmitting and dying almost together. When $w = 0$, the node enabled for transmission by a central node is the one with maximum energy-efficiency index, that is

$$\begin{aligned} x_{n,f}(k) &= 1, \quad n = \arg\max_i \gamma_i, \\ x_{n,f}(k) &= 0, \quad \text{otherwise}. \end{aligned} \tag{4}$$

When $w = 1$, continuously variable activity levels are assigned by the central node according to

$$x_{n,f}(k) = \frac{\gamma_n - \min \boldsymbol{\gamma}}{\sum_{i=1}^{N} (\gamma_i - \min \boldsymbol{\gamma})}, \tag{5}$$

where $\boldsymbol{\gamma}$ is the vector with energy-efficiency indexes. These activity levels are simply the energy-efficiency indexes γ_n normalized in order be greater than or equal to zero, and to add-up to one.

The additional most important modification with respect to the original greedy algorithm is the use of residual and consumption information from the *past* block of F frames to compute the activity levels for the subsequent one, which can be observed from the **Algorithm 1**. It is worth emphasizing that the initial energies of the sensor nodes' batteries must be different from each other for the proper operation of the algorithm when $w = 1$. This will be naturally accomplished in practice, since it is virtually impossible that equality among the stored energies holds.

V. Numerical Results

The results presented in this section were obtained assuming that the initial energy in the sensor nodes' batteries and the energy consumptions are not actual ones, but scaled so as to anticipate the network death with respect to a real one, thus preventing the simulations of lasting prohibitively large intervals. Such a scaling has been also adopted for instance in [10], and, though it changes the absolute lifetimes, it does not affect the conclusions regarding relative lifetime improvements or comparisons. Those results associated to the non-controlled network were obtained by setting identical equivalent activity levels $x'_{n,f}(k) = 1/N$ to all sensor nodes during the whole interval of analysis. These activity levels are nothing more than the average of the activity levels of all sensor nodes, which add up to 1, up to the death instant of the network. As a consequence, the sensor nodes' residual energies in the non-controlled network vary as determined by their consumptions computed according to $\mathbf{x}'_f(k)\mathbf{b}_f(k)$, with $\mathbf{b}_f(k)$ being the same maximum consumption vector considered in the controlled network.

For the sake of a clear visualization of the results in the graphs, firstly $N = 10$ sensor nodes is considered. Larger numbers of nodes are analyzed subsequently. Whenever a

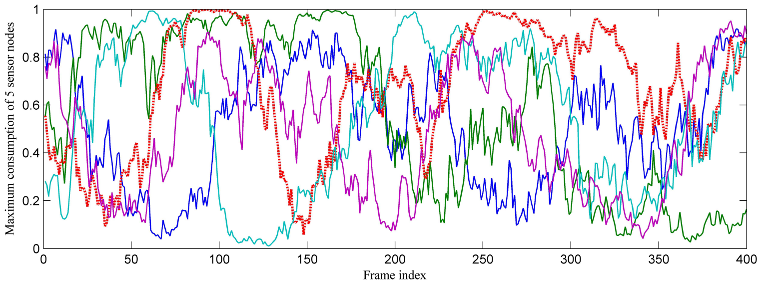

Fig. 1 - Maximum energy consumptions of five sensor nodes during 400 frames, for $\rho = 0.98$.

Algorithm 1 - Modified greedy algorithm

Input:
  Number of sensor nodes, N,
  Number of frames spanned by each control event, F,
  Initial energy levels of the batteries, $\mathbf{s}_1(1)$,
  Estimated consumptions $\mathbf{b}_1(1) = \mathbf{b}_2(1) = \ldots \mathbf{b}_F(1)$,
  Priority coefficient, $w = 0$ or $w = 1$.
Set $e_n = s_{n,1}(1)$, $n = 1, 2, \ldots, N$
for $k = 1, 2, \ldots$ (up to the network death), **do**
  for $f = 1, 2, \ldots, F$, **do**
    if $w = 0$ **then**
      Compute $\gamma_n = e_n - b_{n,f}(k)$, $n = 1, 2, \ldots, N$
      Compute $x_{n,f}(k) = 1, \;\; n = \arg\max_i \gamma_i$
        $x_{n,f}(k) = 0, \;$ otherwise.
    end if
    if $w = 1$ **then**
      Compute $\gamma_n = e_n$, $n = 1, 2, \ldots, N$
      Compute $x_{n,f}(k) = \frac{\gamma_n - \min \boldsymbol{\gamma}}{\sum_{i=1}^{N}(\gamma_i - \min \boldsymbol{\gamma})}$
    end if
    Update residual energies according to
    $e_n \leftarrow e_n - x_{n,f}(k) b_{n,f}(k)$, $n = 1, 2, \ldots, N$.
  end for
  Compute vectors $\mathbf{b}_f(k+1)$, $f = 1, 2, \ldots, F$, based on information on past sensor nodes' locations.
  Assign time or time-frequency slots to the sensor nodes according to the activity levels in $\mathbf{x}_f(k)$, $f = 1, 2, \ldots, F$.
end for

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normalized energy value is called, it means that its value was normalized with respect to the maximum initial stored energy in the sensor node's batteries. When it is stated that a single realization of random consumptions was adopted, it means that the maximum energy consumptions of the sensor nodes were generated for the whole interval of analysis according to the correlation coefficient $\rho = 0.98$, $b_{\min} = 0.001$ and $b_{\max} = 1$, and stored to be reused. The death energy was set to 5% of $S_{\max}$. It is important to notice that the apparently high correlation $\rho = 0.98$ represents in fact high mobility nodes. This can be verified from Fig. 1, where the maximum consumption of 5 sensor nodes are shown for the interval of 400 frames, assuming $\rho = 0.98$: observe that the consumptions indicated by the tick dashed line changes from the maximum (the corresponding sensor node is farthest away from the sink node) to the minimum (the sensor node is close to the sink node) in less than 30 frames, which is a quite fast change from a practical standpoint.

Fig. 2 shows the residual energies attained with the proposed algorithm for $w = 0$, $N = 10$, $K = 400$, $F = 1$, $\rho = 0.98$, $b_{\min} = 0.001$, $b_{\max} = 1$, and approximately identical initial energies $\mathbf{s}_1(1) \approx \mathbf{10}$. The residual energies in the non-controlled network is also shown for reference. From this figure it can be noticed the lifetime improvement of approximately 244% achieved by the controlled network with respect to the non-controlled one (the death instants are identified by the big dots). Moreover, it can be observed the burst-like nature of the transmissions, which in this figure is associated to the steep residual energy changes followed by silent periods during which the residual energies are kept unchanged. The burst-like transmissions can be more clearly observed in Fig. 3, where the stems indicate the activity levels (states *on* or *off* in this case) of the sensor nodes' transmitters; only the interval of the first 100 frames is shown in this figure.

Figs. 4 and 5 show the residual energies and activity levels attained with the proposed algorithm, now for $w = 1$. The remaining parameters are the same as those adopted for plotting Figs. 2 and 3, that is $N = 10$, $K = 400$, $F = 1$, $\rho = 0.98$, $b_{\min} = 0.001$, $b_{\max} = 1$, and $\mathbf{s}_1(1) \approx \mathbf{10}$. The residual energies in the non-controlled network is also shown for reference in Fig. 4, from where it can be noticed the lifetime improvement of approximately 190% achieved by the controlled network with respect to the non-controlled one (again, the death instants are identified by the big dots). In this scenario, it can be observed that the burst-like nature of the transmissions is not occurring, which can be concluded from Fig. 4 by observing that no steep changes or stable periods appear in the residual energy record. In other words, when $w = 1$ the proposed algorithm prioritizes equalized consumptions, at the cost of a reduced lifetime improvement with respect to the situation when $w = 0$. From Fig. 5 one can observe that the activity levels are not anymore zeros or ones, but vary continually as time elapses, maintaining a more frequent communication between the sensor nodes and the sink node. This can be particularly useful to avoid the waste of communication resources characteristic of the burst-like transmission when a given sensor node is enabled without having enough data to be reported to the sink node. Furthermore, a more frequent communication also avoids the need of storing sensory data up to the moment when the node is allowed to transmit them.

As a closing set of results, Fig. 6 shows the average lifetimes

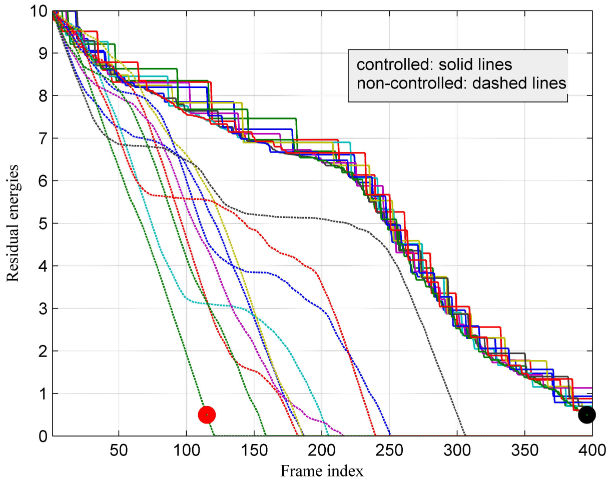

Fig. 2 - Residual energies attained in the controlled and non-controlled networks for $w = 0$, $N = 10$, $K = 400$, $F = 1$, $\rho = 0.98$, $b_{\min} = 0.001$, $b_{\max} = 1$, $\mathbf{s}_1(1) \approx \mathbf{10}$.

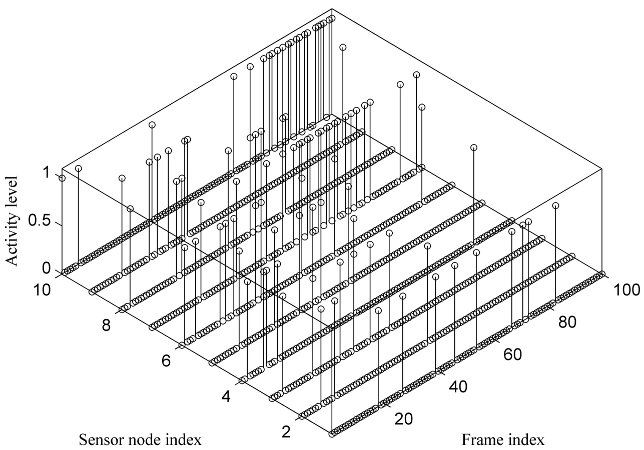

Fig. 3 - Mutually exclusive sensor nodes' activity states during each frame in the controlled network during 100 frames. These states are associated to the residual energies in Fig. 2.

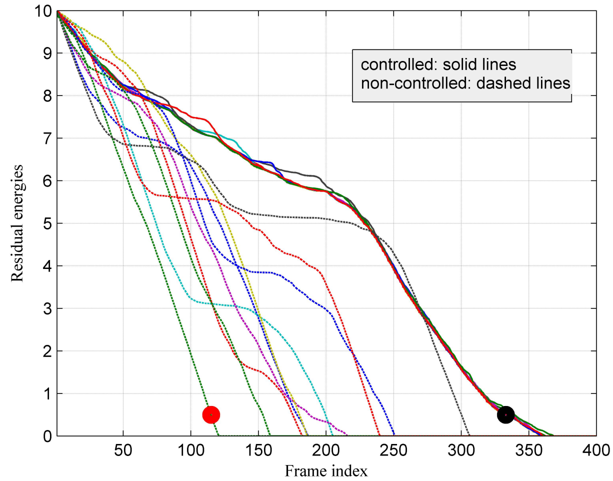

Fig. 4 - Residual energies attained in the controlled and non-controlled networks for $w = 1$, $N = 10$, $K = 400$, $F = 1$, $\rho = 0.98$, $b_{\min} = 0.001$, $b_{\max} = 1$, $\mathbf{s}_1(1) \approx \mathbf{10}$.

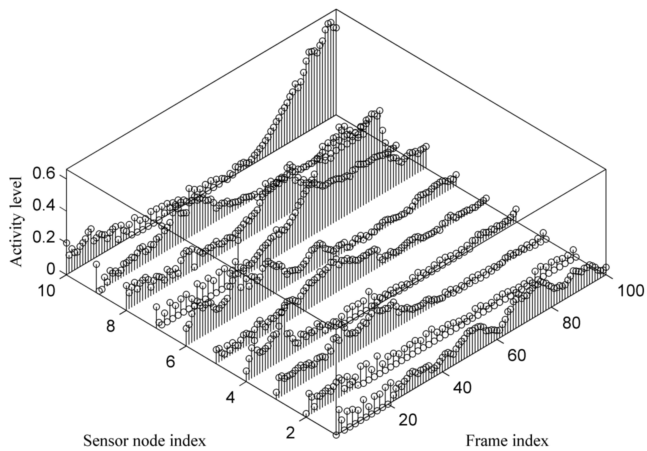

Fig. 5 - Non-mutually exclusive sensor nodes' activity levels during each frame in the controlled network during 100 frames. These levels are associated to the residual energies in Fig. 4.

achieved with the proposed algorithm and with the greedy algorithm of [10]. These results were obtained from 200 Monte Carlo events for each number of sensor nodes, ranging from $N = 10$ to $N = 100$ in steps of 10. The greedy algorithm was simulated by configuring the **Algorithm 1** with $w = 0$ and by using the *current* information on the maximum consumptions of the sensor nodes from the very beginning, instead of past information spanning back to F frames. In this case, the value of F does not matter, since the control of the sensor nodes is made in a frame-by-frame basis and using real-time information on the channel state and residual energy. The minimum energy consumption $b_{\min} = 0.01$ and the initial energies in the sensor nodes $\mathbf{s}_1(1) \approx \mathbf{5}$ were set according to the values adopted in [10], for the sake of consistency. The value of $b_{\max} = 5$ was empirically adjusted so that the lifetimes at the end points of the curve associated to the greedy algorithm approached the lifetimes reported in [10, Fig. 1]. The correlation coefficient between the energy consumptions in neighbor frames was set to $\rho = 0.98$, with $F = 1$ and $F = 10$ as the number of frames spanned by each control event. From Fig. 6 it can be firstly observed that the network lifetime is proportional to the number of sensor nodes, which is due to the fact that each sensor node has a reduced average throughput as N is increased without increasing the communication resources, thus reducing the energy expenditures on average. It can also be noticed that the greedy algorithm attains the best performance, as expected, since it uses real-time information to control the communication states of the sensor nodes. Nonetheless, the performance gap between the greedy algorithm and the proposed one is small when $F = 1$ and $w = 0$, which is consistent with the burst-like transmission in both cases, and with the high correlated past information spanning only one frame with respect to the current one. The performance gap becomes larger as N increases, when $w = 1$, which is characteristic of the lifetime penalty produced by the proposed algorithm if the equalized energy consumptions are prioritized by the choice of $w = 1$. As expected, the performance gap also becomes larger as F is increased, no matter the value of w. This is due to increased uncorrelatedness between the past and the current information spanning a block of F frames regarding the energy consumptions. Then, if F is larger than 10, or ρ is smaller than 0.98, or both, the advantage of the original greedy algorithm relative to the proposed algorithm would be more pronounced. Finally, one can conclude from Fig. 6 that, if the number of nodes is small, more flexibility is grated to the choice of w and F.

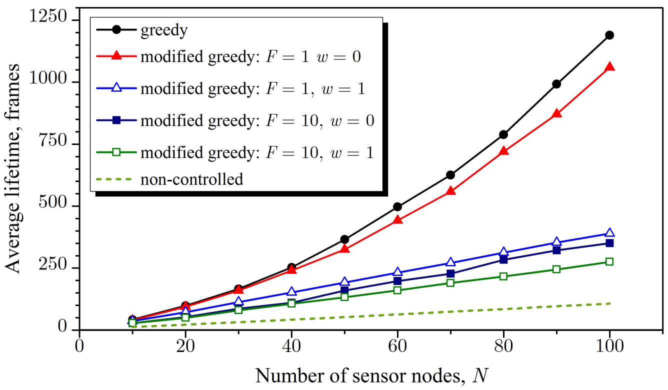

Fig. 6 - Average lifetimes achieved with the proposed algorithm and with the greedy algorithm of [10] as a function of the number of sensor nodes N, for $\rho = 0.98$, $b_{\min} = 0.01$, $b_{\max} = 5$, $\mathbf{s}_1(1) \approx \mathbf{5}$, considering $w = 0$, $w = 1$, $F = 1$ and $F = 10$.

VI. Conclusion

This paper presented a flexible and simple method for increasing the lifetime of fixed or mobile wireless sensor networks. The method dynamically controls the so-called communication activity levels of the sensor nodes in a way that the fractions of time or time-frequency slots in a frame are intelligently assigned to the sensor nodes to communicate with the sink node, at the same time saving energy. The proposed method is a modification of a greedy algorithm of [10], aiming at a balance between the reduction of wasted energy, the maintenance of throughput and the reduction of the energy spent for reporting sensory information to the sink node. The most significant practical appeal of the proposed method is that it only uses past information on the energy consumptions reported by the sensor nodes, thus not demanding any real-time information. Comparisons with the original greedy algorithm, which uses real-time channel state and residual energy information, unveiled that the proposed algorithm is capable of achieving attractive performances. Specifically, when the number of sensor nodes is small, more flexibility is granted to the determination of how frequently the sensor nodes are controlled, and to the choice between (i) privileging equalized consumptions of the sensor nodes and more frequent communication with the sink node, or (ii) privileging burst-like transmissions for larger lifetime improvements. As the number of sensor nodes increases, it is better to adopt burst-like transmissions and to control the sensor nodes more frequently, a situation in which the proposed algorithm performs closely to the greedy algorithm of [10], but without using current channel and residual energy information.

Referências

[1] MUNIR, S. et al. Mobile wireless sensor network: Architecture and enabling technologies for ubiquitous computing. In: *Advanced Information Networking and Applications Workshops, 2007, AINAW '07. 21st International Conference on*. [S.l.: s.n.], 2007. v. 2, p. 113–120.

[2] PAWGASAME, W. A survey in adaptive hybrid wireless sensor network for military operations. In: *2016 Second Asian Conference on Defence Technology (ACDT)*. [S.l.: s.n.], 2016. p. 78–83.

[3] ORTEGA, C. et al. Improving wsn application qos and network lifetime management using soa strategies. In: *2011 - MILCOM 2011 Military Communications Conference*. [S.l.: s.n.], 2011. p. 1580–1585. ISSN 2155-7578.

[4] PINTO, A. R. et al. Power optimization for wireless sensor networks. In: ______. *Wireless Sensor Networks - Technology and Applications*. InTech, 2012. cap. 2, p. 23–50. Disponível em: <http://cdn.intechopen.com/pdfs-wm/37846.pdf>.

[5] ANASTASI, G. et al. Energy conservation in wireless sensor networks: A survey. *Ad Hoc Networks*, v. 7, p. 537–568, 2009.

[6] ZHANG, Z. et al. Power control and localization of wireless body area networks using semidefinite programming. In: *Future Information and Communication Technologies for Ubiquitous HealthCare (Ubi-HealthTech), 2015 2nd Int. Symposium on*. [S.l.: s.n.], 2015. p. 1–5.

[7] LUO, F. et al. Node energy consumption analysis in wireless sensor networks. In: *Vehicular Technology Conference (VTC Fall), 2014 IEEE 80th*. [S.l.: s.n.], 2014. p. 1–5.

[8] ROUT, R.; GHOSH, S. Enhancement of lifetime using duty cycle and network coding in wireless sensor networks. *IEEE Trans. Wireless Commun.*, v. 12, n. 2, p. 656–667, February 2013.

[9] TASHTARIAN, F. et al. On maximizing the lifetime of wireless sensor networks in event-driven applications with mobile sinks. *IEEE Trans. Veh. Technol.*, v. 64, n. 7, p. 3177–3189, July 2015.

[10] CHEN, Y.; ZHAO, Q. On the lifetime of wireless sensor networks. *IEEE Commun. Lett.*, v. 9, n. 11, p. 976–978, November 2005. ISSN 1089-7798.

[11] CHANG, J.-H.; TASSIULAS, L. Maximum lifetime routing in wireless sensor networks. *Networking, IEEE/ACM Transactions on*, v. 12, n. 4, p. 609–619, August 2004.

[12] CHANG, J.-H.; TASSIULAS, L. Energy conserving routing in wireless ad-hoc networks. In: *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*. [S.l.: s.n.], 2000. v. 1, p. 22–31 vol.1. ISSN 0743-166X.

[13] LUO, J.; HUBAUX, J.-P. Joint sink mobility and routing to maximize the lifetime of wireless sensor networks: The case of constrained mobility. *IEEE/ACM Trans. Netw.*, v. 18, p. 871–884, 2010.

[14] GUIMARAES, D. A. et al. Increasing the lifetime of mobile WSNs via dynamic optimization of sensor node communication activity. *Sensors*, 2016. ISSN 1424-8220. Submitted.

[15] HCF. *WirelessHART Specification 75: TDMA Data-Link Layer*. [S.l.], 2008.

[16] ISA. *ISA-100.11a-2011: Wireless Systems for Industrial Automation: Process Control and Related Applications*. [S.l.], 2011.

[17] PETERSEN, S.; CARLSEN, S. Wirelesshart versus isa100.11a: The format war hits the factory floor. *IEEE Industrial Electronics Magazine*, v. 5, n. 4, p. 23–34, Dec 2011. ISSN 1932-4529.

[18] IEEE. *802.15.4e-2012: IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer*. [S.l.], 2012.

[19] MARTINEZ, B. et al. When scavengers meet industrial wireless. *IEEE Transactions on Industrial Electronics*, v. 62, n. 5, p. 2994–3003, May 2015. ISSN 0278-0046.

[20] GUIMARAES, D. A. *Digital Transmission: A Simulation-Aided Introduction with VisSim/Comm*. [S.l.]: Springer, 2009. (Signals and Communication Technology). ISBN 9783642013591.

[21] GILLI, M.; MARINGER, D.; SCHUMANN, E. *Numerical Methods and Optimization in Finance*. Elsevier/Academic Press, 2011. Disponível em: <http://nmof.net>.

[22] DIETRICH, I.; DRESSLER, F. On the lifetime of wireless sensor networks. *ACM Transactions on Sensor Networks (TOSN)*, ACM, v. 5, n. 1, p. 1–39, February 2009.

[23] MAK, N. H.; SEAH, W. How long is the lifetime of a wireless sensor network? In: *Advanced Information Networking and Applications, 2009. AINA '09. International Conference on*. [S.l.: s.n.], 2009. p. 763–770. ISSN 1550-445X.