Performance Analysis of a Hierarchical Discovery Protocol for WSNs with Mobile Elements

Francesco Restuccia*†, Giuseppe Anastasi*, Marco Conti†, and Sajal K. Das‡

*Department of Information Engineering
University of Pisa, Italy
{f.restuccia, g.anastasi}@iet.unipi.it

†IIT-CNR
National Research Council, Italy
marco.conti@iit.cnr.it

‡CReWMaN Lab
University of Texas at Arlington, USA
das@cse.uta.edu

***Abstract*—Wireless Sensor Networks (WSNs) are emerging as an effective solution for a wide range of real-life applications. In scenarios where a fine-grain sensing is not required, sensor nodes can be sparsely deployed in strategic locations and special *Mobile Elements* (MEs) can be used for data collection. Since communication between a sensor node and a ME can occur only when they are in the transmission range of each other, one of the main challenges in the design of a WSN with MEs is the energy-efficient and timely discovery of MEs. In this paper, we consider a hierarchical ME discovery protocol, namely *Dual beacon Discovery* (2BD) protocol, based on two different beacon messages emitted by the ME (i.e., Long-Range Beacons and Short-Range Beacons). We develop a detailed analytical model of 2BD assuming a sparse network scenario, and derive the optimal parameter values that minimize the energy consumption at sensor nodes, while guaranteeing the minimum throughput required by the application. Finally, we compare the energy efficiency and performance of 2BD with those of a traditional discovery protocol based on a single beacon. Our results show that 2BD can provide significant energy savings, especially when the discovery phase is relatively long.**

***Keywords:* Wireless Sensor Networks, Sparse sensor networks, Mobile Node Discovery, Energy Efficiency.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are emerging as an effective solution for a wide range of real-life applications, including environmental monitoring, object location and tracking, health monitoring, industrial applications, and smart buildings, just to name a few. In traditional application scenarios, sensor nodes are densely deployed over the sensing area, and data collection is carried out through multi-hop communications towards the sink node. However, a large number of applications does not require a dense deployment of sensor nodes (e.g., air quality monitoring in urban areas). Instead, sensor nodes can be strategically deployed in some specific locations, i.e., a sparse network configuration can be used to reduce economic costs. In a sparse WSN, the distance between neighboring nodes is (much) larger than the transmission range, and data collection is thus carried out through special *Mobile Elements* (MEs) that visit sensor nodes at regular times, gather sensed data, and transport them to a sink node [1]. MEs can be either part of the external environment (e.g., cars, buses, persons), or part of the networking infrastructure (e.g., mobile robots). Also, MEs can have different mobility patterns, ranging from deterministic to completely random mobility [2].

Since sensor nodes and MEs can communicate only when they are in the transmission range of each other, unless the ME mobility pattern is deterministic, each sensor node has to *discover* the presence of the ME in the nearby area before starting to exchange data with it. Therefore, one of main challenges to be faced in the design of a WSN with MEs is the definition of an appropriate protocol for efficient ME discovery by sensor nodes. Typically, a simple approach known as *periodic listening* is exploited to this purpose. In this approach, the ME emits periodic beacon messages to announce its presence in the area, while sensor nodes wake up periodically and for a very short time – thus using a duty cycle – to check for possible beacons from the ME [2]. The duty cycle should be as low as possible, to minimize the energy consumed during the discovery phase. On the other hand, using a very low duty cycle may compromise the performance of the discovery process, i.e., contacts could be missed or detected very late (thus resulting in a short time available for data exchange with the ME).

To reduce the energy consumption of the discovery process without affecting its performance, in this paper we consider a simple but effective *Dual Beacon Discovery* (2BD) protocol that leverages a hierarchical approach. 2BD uses two different beacon messages, namely a *Long-Range Beacon* (LRB) and a *Short-Range Beacon* (SRB), transmitted by the ME with different transmission ranges. Basically, LRBs announce the presence of the ME in the area, while SRBs inform the sensor node that the data exchange can actually take place. Sensor nodes can thus use a very low duty cycle for most of the time, and increase it only upon receiving a LRB.

The main contribution of this paper is a thorough performance analysis of the 2BD protocol, and its comparison – in terms of performance and energy efficiency – with a traditional discovery protocol based on a single beacon (throughout referred to as SB). Specifically, we derive a

978-1-4673-1239-4/12/$31.00 ©2012 IEEE

detailed analytical model of 2BD that characterizes its energy consumption and performance (mainly in terms of throughput). Based on this analytical model, we determine the optimal parameter values that minimize the energy consumption of the sensor node, while guaranteeing the minimum throughput required by the application. Finally, we compare the 2BD protocol with the traditional SB protocol. Our analytical results show that 2BD is able to provide a significant energy saving, while guaranteeing the same (or even better) performance than SB, especially when the discovery phase is relatively long.

The rest of the paper is organized as follows. Section II discusses the related work. Section III briefly describes the 2BD protocol. Section IV introduces the scenario considered in our analysis. Section V is devoted to the analysis of the discovery process. The energy consumptions during the discovery and data transfer phases are derived in Section VI and VII, respectively. Numerical results are presented in Section VIII and conclusions are drawn in Section IX.

II. Related Work

A classification and detailed description of possible approaches to ME discovery is reported in [2]. As anticipated in the Introduction, the most commonly used approach is periodic listening with fixed duty cycle. One of the first discovery algorithms belonging to this class was proposed in [3]. A fixed duty-cycle scheme is also exploited in [4], [1]. Although this approach is quite simple, it proves to be inefficient, especially when sensor nodes spend a long time in the discovery state.

To improve the energy efficiency of the discovery process, adaptive solutions that dynamically adjust the duty cycle of sensor nodes – depending on the estimated probability that the ME is nearby – have been proposed [5], [6]. In [5], time is divided in slots and, for each slot, the probability to come in contact with a mobile node is predicted, using reinforcement learning. The duty cycle of the sensor node is adjusted at the end of each time slot, according to the estimated contact probability. A similar approach is exploited in [6] where, however, a more complex technique based on Q-Learning is used to predict the contact probability. Learning-based adaptive solutions are, in general, more effective than algorithms based on a fixed duty cycle. However, they work very well when the ME mobility has some regularity that can be learned and exploited. Instead, they are unsuitable in scenarios where the ME motion is random (and, thus, unpredictable).

An alternative approach to adaptive discovery is using a hierarchical scheme, like in 2BD. Hierarchical discovery algorithms typically exploit two different radios, for wake-up / discovery and communication, respectively [7], [8], [9]. Both [7] and [8] address the problem of device discovery in mobile opportunistic networks of handheld devices. Also, they both rely on a low power radio (e.g., a Mote radio) for discovery and a higher power radio (e.g., WiFi) for data communication. Unlike the previous solutions, 2BD is specifically targeted to WSNs. In addition, it uses long-range communication for discovery and short-range communication for data exchange, while the previous proposals take the opposite approach. Hierarchical discovery for WSNs, possibly with mobile nodes, is addressed in [9] where the *network interrupt* approach has been proposed. It also relies on two different radios, namely a primary high-power radio (usually in sleep mode) and a control low-power radio (always powered on). A node can activate the primary radio of a another nearby node at any time, just sending a beacon over the low power radio. Unlike the solutions in [7], [8], [9], 2BD does not require multiple radio technologies – typically not available in current sensor platforms – and can thus be implemented on any sensor platform.

The 2BD protocol was originally proposed in [10], where a preliminary performance evaluation, based on simulation, was also included. In this paper we perform a thorough performance analysis, based on Markov chains, to characterize the energy efficiency of 2BD in a sparse network scenario. We also perform an optimization study to derive the parameter values that minimize the energy consumption while guaranteeing the minimum throughput required by the application.

III. Protocol Description

In this section, we briefly describe the 2BD protocol considered in our analysis (additional details can be found in [10]). In 2BD, sensor nodes are assumed to switch between different duty cycles, according to a hierarchical approach. During the discovery phase, sensor nodes operate most of the time with a *low duty cycle* to save energy, and switch to a *high duty cycle* only when the ME is about to enter their transmission range. Information about the ME location is provided to sensor nodes by the ME itself, through a periodic emission of two different beacon messages, namely *Short-Range Beacons* (SRBs) and *Long-Range Beacons* (LRBs). SRBs and LRBs are transmitted in an interleaved way, both with the same period $2 \cdot T_{BI}$ (so that the overall beacon period is T_{BI}), but with different transmission power, and convey different information. Specifically, SRBs are transmitted with the same transmission-power level used during the communication phase for data exchange. They experience a transmission range r – throughout referred to as *communication range* – and are used to notify the sensor node that the ME is within its transmission range and data exchange can, thus, take place. Instead, LRBs are sent with a higher transmission power. Therefore, they have a transmission range R larger than the communication range r – throughout R will be referred to as the *discovery range* – and are used to inform the sensor node that the ME is approaching and a contact could potentially occur in short.

In detail, during the discovery phase, the sensor node is initially in LRB-Discovery state, and wakes up periodically – with a low duty cycle δ_L – to check for possible beacons from ME. Upon receiving a LRB, the sensor node transits to the SRB-Discovery state, increases its duty cycle to δ_H, and waits for a SRB. To avoid energy wastes, if a valid SRB is not received within a pre-defined timeout T_{OUT}, the sensor node transits back to the LRB-Discovery state[1]. Whenever a SRB is received (both in LRB-Discovery and SRB-Discovery state), the sensor node enters the Data Transfer state, increases the duty cycle to 100%, and starts exchanging data with the ME. After transferring all its data, the sensor node transits to the LRB-Discovery state again in order to detect the next contact. However, if the sensor node has a (even partial) knowledge about the mobility pattern of the ME, it can enter a Sleeping state in which the radio is put in sleep mode to save energy. In this case, the sensor node will enter the LRB-Discovery state some time before the estimated next arrival of the ME.

IV. Reference Scenario

In this section we describe the reference scenario considered in our study (shown in Figure 1), and introduce the assumptions on which our analysis is based. We consider a sparse WSN (i.e., the distance between neighboring nodes is very large) and assume that there is a single ME. Therefore, at any time, the ME can communicate with at most one sensor node. We also assume that the ME moves at a constant speed *v* along a linear path, and at a distance *D* from the sensor node.

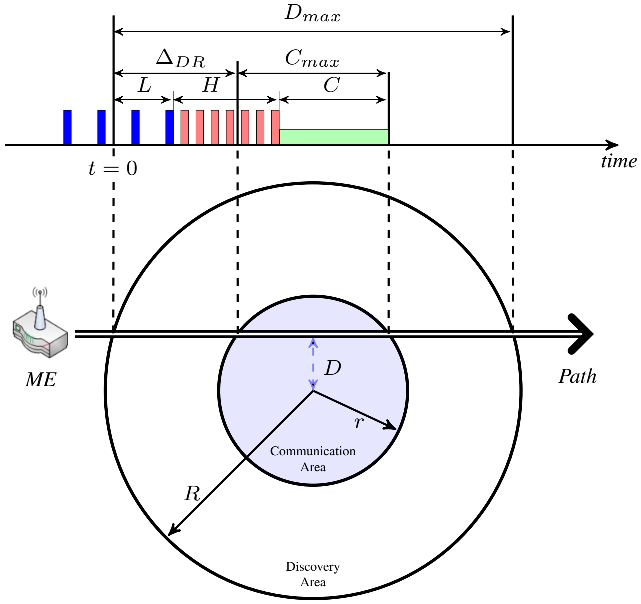

Figure 1. System model.

[1]This timeout has to be set according to the worst case, i.e., when the distance between the sensor node and the ME is zero, so T_{OUT} have to be set to $(R+r)/v$.

The maximum time interval the ME can stay in the communication area and discovery area is denoted by C_{max} and D_{max}, respectively. Also, the maximum time interval the ME can be in the discovery area before entering the communication area is denoted by Δ_{DR}. Messages exchanged between the sensor node and the ME, both in communication and discovery area, may be corrupted due to transmission errors. We assume that LRBs are always accepted (since they just signal the presence of the ME in the region), while corrupted messages/SRBs received within the communication area are discarded. Also, we assume *t=0* as the instant at which the ME enters into the discovery area.

Figure 1 shows both the *discovery area* and the *communication area* (i.e., the regions within which the sensor node can receive a LRB and a SRB, respectively). Also, Figure 1 shows an example of how the radio state of the sensor node (i.e. ON or OFF), can evolve over time. The interaction between the sensor node and the ME can be divided in several phases. In detail, the first phase ranges from when the sensor node enters LRB-Discovery state (thus starting the discovery process) to when the ME enters the discovery area. The next phase, of duration *L*, is terminated by the reception of the first LRB by the sensor node (which, thus, increases the duty cycle, as shown in Figure 1). The third phase corresponds to the time interval *H* between the reception of the first LRB and the reception of a valid SRB. Finally, the communication phase starts with the reception of a valid SRB, and ends when all data have been transmitted or the ME has exited the communication area. Hence, the overall time spent by the sensor node in LRB-Discovery and SRB-Discovery state is *L* and *H*, respectively. Finally, the time available for data communication is *C*. With reference to Figure 1, we can derive C_{max}, D_{max} and Δ_{DR} as follows:

$$C_{max} = \frac{2}{v} \cdot \sqrt{r^2 - D^2}, \;\; D_{max} = \frac{2}{v} \cdot \sqrt{R^2 - D^2},$$
$$\Delta_{DR} = \frac{1}{2} \cdot (D_{max} - C_{max})$$

V. Discovery Phase Analysis

In this section, we derive an analytical model of the discovery phase, based on a *Discrete Time Markov Chain* (DTMC). The purpose of this analysis is to calculate the distribution of both the LRB-Discovery time *L* and SRB-Discovery time *H*, as well as the residual time available for communication after discovery, *C*. The main symbols used in the analysis are summarized in Table I. The analysis is split in two main phases. First, the state of the sensor node (i.e. ON or OFF) over time is derived, by keeping into consideration its duty cycle. Second, the beacon reception process is modeled, i.e. the state transitions of the sensor node are characterized, basing on the probability that a beacon sent by the ME will be correctly received by the sensor node. As beacon transmissions do not depend on when the ME enters into the discovery area (assumed as *t = 0*), the initial LRB transmission within the discovery area is generally affected by a random offset, with respect to the time origin. Let t_0^{LRB} be the time instant at which the ME transmits the first LRB while in the discovery area. t_0^{LRB} is a r.v. uniformly distributed in $[0, 2\ T_{BI})$. Then, the actual instants of subsequent LRB transmissions can be expressed as $t_i^{LRB} = t_0^{LRB} + i \cdot 2\ T_{BI}$, with $i \in [1, N_L - 1]$, where N_L is the maximum number of LRBs the ME can send while in the discovery area, i.e.

$$N_L = \begin{cases} \lceil \frac{D_{max}}{2 \cdot T_{BI}} \rceil & \text{if } D_{max} - (\lceil \frac{D_{max}}{2 \cdot T_{BI}} \rceil - 1) \cdot 2 \cdot T_{BI} > t_0^{LRB} \\ \lfloor \frac{D_{max}}{2 \cdot T_{BI}} \rfloor & \text{otherwise} \end{cases} \quad (1)$$

Since the transmission of SRBs and LRBs are interleaved, and separated by a period T_{BI}, the first SRB transmission in the discovery area by the ME – denoted by t_0^{SRB} – only depends on the t_0^{LRB} value. Thus, t_0^{SRB} can be derived from t_0^{LRB} as follows:

$$t_0^{SRB} = \begin{cases} t_0^{LRB} - T_{BI} & \text{if } t_0^{LRB} \geq T_{BI} \\ t_0^{LRB} + T_{BI} & \text{if } t_0^{LRB} < T_{BI}. \end{cases} \quad (2)$$

The maximum number of SRBs the ME can send while in the discovery area, denoted by N_S, can be expressed as in Equation (1), with t_0^{LRB} replaced by t_0^{SRB}.

Table I
MAIN SYMBOLS USED IN THE ANALYSIS.

Symbol	Description
v	Speed of ME
r	Communication range
R	Discovery range
D	Distance of ME from sensor node
C_{max}	Time spent by ME in the Comm. Area
D_{max}	Time spent by ME in the Disc. Area
Δ_{DR}	Time spent by ME in the Disc. Area before entering the Comm. Area
δ_L	Low Duty Cycle (LDC)
δ_H	High Duty Cycle (HDC)
T_{BI}	Beacon Interval
T_{BD}	Beacon Duration
T_{ON}	Active Time
T_{OFF}^{LDC}	LDC inactivity time
T_{OFF}^{HDC}	HDC inactivity time
$RS(t)$	Current Radio State at time t
H	SRB-Discovery r.v.
L	LRB-Discovery r.v.
t_0^{LRB}	Time of first LRB transmission into the Disc. Area
t_0^{SRB}	Time of first SRB transmission into the Disc. Area
t_L	Average LRB-discovery time
t_H	Average SRB-discovery time
$X(k)$	State probability vector
$\mathbb{P}\{CD\}$	Complete Discovery probability
$\mathbb{P}\{PD\}$	Partial Discovery probability
$\mathbb{P}\{CM\}$	Complete Miss probability
$\mathbb{P}\{PM\}$	Partial Miss probability
P_{RX}	Receiving radio power
P_{TX}	Transmission radio power
P_{SL}	Sleep radio power

Finally, the instants of subsequent SRB transmissions occur at times $t_i^{SRB} = t_0^{SRB} + i \cdot 2\ T_{BI}$, with $i \in [1, N_S - 1]$. Therefore, if the ME is discovered by means of the m-th SRB, the discovery time is $d = t_0^{SRB} + m \cdot T_{BI}$, and the corresponding residual time available for data transfer is *C* = $C_{max} - (d - \Delta_{DR})$.

Let t_k denote the time instant when the *k*-th beacon is received, $k \in [1, N_B]$, where $N_B = N_S + N_L$ is the total number of transmitted beacons. To characterize the radio state at beacon reception times t_k, we introduce the function $RS(t)$, that assumes the value ON/OFF if the radio is active/inactive at time *t*. We denote by S_0 the radio state (i.e., ON/OFF) at time 0. Also, we indicate by r_0 the residual time, at time *t = 0*, in which the radio will remain in that particular state. Finally, we define an auxiliary function $R_{LRB}(t)$ such as $R_{LRB}(t)$ = *True* if a LRB has already been received at time t. The following claim holds.

Claim. *The state of the sensor node at time t_k is given by*

$$\begin{array}{c} RS(t_k) \\ S_0 = ON \\ R_{LRB}(t_k) = \mathit{False} \end{array} = \begin{cases} ON & 0 \leq t'_k < r_0 \\ OFF & r_0 \leq t'_k < r_0 + T_{OFF}^{LDC} \\ ON & r_0 + T_{OFF}^{LDC} \leq t'_k < T_{ON} + T_{OFF}^{LDC} \end{cases}$$

$$\begin{array}{c} RS(t_k) \\ S_0 = OFF \\ R_{LRB}(t_k) = \mathit{False} \end{array} = \begin{cases} OFF & 0 \leq t'_k < r_0 \\ ON & r_0 \leq t'_k < r_0 + T_{ON} \\ OFF & r_0 + T_{ON} \leq t'_k < T_{ON} + T_{OFF}^{LDC} \end{cases}$$

$$\begin{array}{c} RS(t_k) \\ R_{LRB}(t_k) = \mathit{True} \end{array} = \begin{cases} ON & 0 \leq t''_k < T_{ON} \\ OFF & T_{ON} \leq t''_k < T_{ON} + T_{OFF}^{HDC} \end{cases}$$

$$\begin{aligned} t'_k &= t_k \bmod (T_{ON} + T_{OFF}^{HDC}) \\ t''_k &= (t_k - t_{R-LRB}) \bmod (T_{ON} + T_{OFF}^{HDC}) \end{aligned} \quad (4)$$

Proof. *Omitted for the sake of space. See [11].*

Once the radio state at beacon reception times has been fully characterized, we can now model the beacon reception process. The evolution of the system at beacon reception times can be modeled by a *Discrete Time Markov Chain* (DTMC), where (as it will be clarified in the following) each macro state L_i (S_i) corresponds to several different states of the DTMC, all representing the same LRB (SRB) reception process. Specifically, we denote by L_i (S_i) the macro state that represents all possible radio states just before the reception of the *i*-th LRB (SRB).

Figure 2 shows the DTMC when the first beacon emitted into the discovery area is a LRB (i.e., $t_0^{SRB} > t_0^{LRB}$). A similar representation is obtained when $t_0^{SRB} < t_0^{LRB}$. For the sake of space, in the following we will analyze only the former case. The latter case is almost similar and is discussed in [11]. Initially, the system is in state L_0, and eventually converges to one of the absorbing states defined in Table II. *Complete Discovery (CD)* and *Partial Discovery (PD)* characterize a success, i.e., the ME is discovered by the sensor node. *Complete Miss (CM)* and *Partial Miss (PM)*,

$$
\mathbf{P} = \begin{array}{c} \\ L_0 \\ S_0 \\ L_1 \\ \vdots \\ L_{N_L} \\ CM \\ PM \\ CD \\ PD \end{array}
\begin{array}{c} \begin{array}{ccccccccc} L_0 & S_0 & L_1 & S_1 & \cdots & CM & PM & CD & PD \end{array} \\
\left(\begin{array}{ccccccccc}
0 & T_{L_0 S_0} & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\
0 & 0 & T_{S_0 L_1} & 0 & \cdots & 0 & 0 & T_{S_0 CD} & T_{S_0 PD} \\
0 & 0 & 0 & T_{L_1 S_1} & \cdots & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \ddots & T_{S_{N_S} CM} & T_{S_{N_S} PM} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & T_{L_{N_L} CM} & T_{L_{N_L} PM} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{array} \right) \end{array} \tag{3}
$$

on the other hand, characterize a failure, i.e., the sensor node does not discover the ME.

$$
\begin{aligned}
& t_{S_i L_j}^{(sx_k)} = \begin{cases} p(t_i) & \text{if } j = i+1 \text{ AND } sx_k = ON \\ 1 & \text{if } j = i+1 \text{ AND } sx_k = OFF \\ 0 & \text{if } j \neq i+1 \end{cases} \\
& t_{L_i S_j}^{(sx_k)} = \begin{cases} 1 & \text{if } j = i \\ 0 & \text{if } j \neq i \end{cases} \\
& t_{S_i PD}^{(sx_k)} = \begin{cases} 1 - p(t_i) & \text{if } R_{LRB}(t_i) = \textit{False} \text{ AND } sx_k = ON \\ 0 & \text{otherwise} \end{cases} \\
& t_{S_i CD}^{(sx_k)} = \begin{cases} 1 - p(t_i) & \text{if } R_{LRB}(t_i) = \textit{True} \text{ AND } sx_k = ON \\ 0 & \text{otherwise} \end{cases} \\
& t_{L_{N_L} CM}^{(sx_k)} = \begin{cases} 1 & \text{if } R_{LRB}(t_i) = \textit{False} \\ 0 & \text{otherwise} \end{cases} \\
& t_{L_{N_L} PM}^{(sx_k)} = \begin{cases} 1 & \text{if } R_{LRB}(t_i) = \textit{True} \\ 0 & \text{otherwise} \end{cases} \\
& t_{S_{N_S} CM}^{(sx_k)} = \begin{cases} 1 & \text{if } R_{LRB}(t_i) = \textit{True} \\ 0 & \text{otherwise} \end{cases} \\
& t_{S_{N_S} PM}^{(sx_k)} = \begin{cases} 1 & \text{if } R_{LRB}(t_i) = \textit{True} \\ 0 & \text{otherwise} \end{cases} \\
& i \in [0, N_S - 1], \;\; j \in [0, N_L - 1], \;\; k \in [1, M]
\end{aligned} \tag{5}
$$

The different absorbing states are characterized by different energy consumptions. From a generic state L_i, the system always transits to state S_i, irrespective of the i-th LRB reception status. Instead, from state S_i, the system can evolve to the following states: L_{i+1}, if the i-th SRB has been missed because the radio is OFF (i.e., $RS(t_i^{SRB}) = OFF$), or a transmission error has occurred, which happens with probability $p(t_i^{SRB})$; CD, if a LRB has already been received, i.e., $R_{LRB}(t_i^{LRB}) = \textit{True}$; PD, otherwise. Finally, at the end of the process, i.e., when in state L_{N_L} or S_{N_S}, the system transits to the absorbing state PM or CM, depending on whether a LRB has been already received or not.

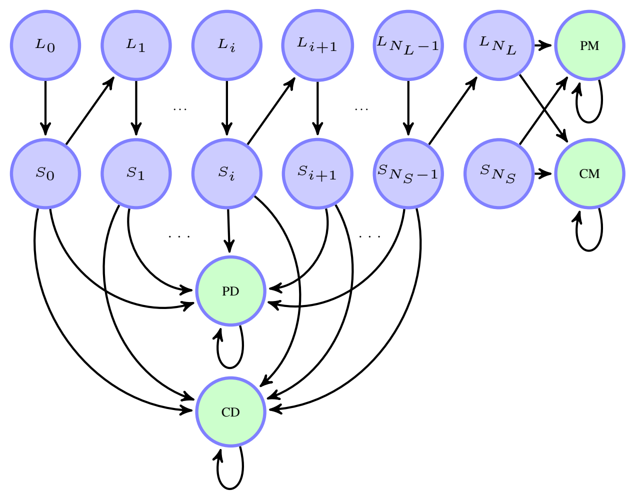

Figure 2. State diagram when $t_0^{SRB} > t_0^{LRB}$.

Table II
DEFINITION OF DTMCS ABSORBING STATES.

State	Description	LRB Received	SRB Received
CD	Complete Discovery	YES	YES
PD	Partial Discovery	NO	YES
CM	Complete Miss	NO	NO
PM	Partial Miss	YES	NO

Equation (3) shows the transition matrix referred to Figure 2, while Equation (5) details the transition probabilities. In the following we assume that time is discretized, with slot time of duration Δ. Hence, the residual time in a radio state can assume M different values, with $M = \lceil (T_{ON} + T_{LDC}^{OFF})/\Delta \rceil$. As anticipated, since the initial radio state and the initial residual time can assume all possible values, sub-blocks T_{XY} in matrix P have size $M \times M$ and keep track of all possible transition probabilities from the generic state X to the generic state Y, assuming all possible radio states at the time t_i of the evaluation of state X. Let $sx_k, \; k = 1, 2, \; \ldots, M$ be the set of all possible radio states at time t_i, obtained by using the $RS(t)$ function calculated at time t_i and by considering all the M initial radio states. In detail, the elements of the T_{XY} blocks are

$$t_{XY}^{(sx_k)} = \mathbb{P}\{Y \mid X(sx_k)\}, \; k=1,2,\;\dots,M \quad (6)$$

In Equation (5) we detail the expression of all T sub-blocks.

Let $N_T = N_S + N_L + 2$ be the number of the transient macrostates of the DTMC (i.e., L_i/S_i). Let $\mathbf{X}^{(0)}$ be the initial state probability vector of the sensor node and $\mathbf{X}^{(k)}$ the state probability vector after the k-th beacon transmission, with $k \in [1, N_T]$, i.e.,

$$\begin{aligned} \mathbf{X}^{(k)} &= \begin{pmatrix} X_0^{(k)} & X_1^{(k)} & \cdots & X_{N_T-1}^{(k)} & X_{N_T}^{(k)} \end{pmatrix} \\ \mathbf{X}^{(0)} &= \begin{pmatrix} X_0^{(0)} & 0 & \cdots & 0 & 0 \end{pmatrix} \end{aligned} \quad (7)$$

Note that only the $X_0^{(0)}$ component of the initial state vector is not zero, since when the ME enters into the contact area, the sensor node is waiting for the first beacon. Moreover, $X_{N_T-1}^{(k)}$ and $X_{N_T}^{(k)}$ represent the cumulative probability that ME has been detected after *k* beacon transmissions, by either a complete discovery or a partial discovery. According to the theory of DTMCs, it follows that

$$\underset{k \in [0, N_T]}{\mathbf{X}^{(k+1)}} = \begin{cases} \mathbf{X}^{(k)} \cdot \mathbf{P} & \text{if } t_0^{SRB} > t_0^{LRB} \\ \mathbf{X}^{(k)} \cdot \mathbf{Q} & \text{if } t_0^{SRB} < t_0^{LRB} \end{cases} \quad (8)$$

Where Q is the transition matrix in the case $t_0^{SRB} < t_0^{LRB}$, detailed in [11] (it is similar in structure to matrix *P*). Now we can derive the time spent by the sensor node in low and high duty cycle. To this end, we define two r.v.s, namely *L* and *H*, denoting the time spent by the sensor node (starting from the time origin) until the reception of the first LRB and SRB, respectively. We denote by $l(i)$ and $h(i)$ the probability mass functions (p.m.f.s) of *L* and *H*, respectively. Equation (8) allows us to derive $h(i)$ given that the first SRB transmission occurs at time t_0^{SRB}, i.e., $h(i|t_0^{SRB})$,

$$\begin{aligned} h(i|t_0^{SRB}) = \\ \mathbb{P}\{D = t_i^{SRB}|t_0^{SRB}\} \end{aligned} = \begin{cases} \mathbf{X}_{N_T}^{(2)} + \mathbf{X}_{N_T-1}^{(2)}, \; i = 0 \\ \\ \left(\mathbf{X}_{N_T}^{(2i+2)} + \mathbf{X}_{N_T-1}^{(2i+2)}\right) - \\ \left(\mathbf{X}_{N_T}^{(2i)} + \mathbf{X}_{N_T-1}^{(2i)}\right), \\ i \in [1, N_S - 1] \\ \\ 0, \; \text{otherwise} \end{cases} \quad (9)$$

Equation (9) holds only if $t_0^{SRB} < t_0^{LRB}$. The equation for $t_0^{SRB} > t_0^{LRB}$ is similar and detailed in [11]. In Equation (9), $h(i|t_0^{SRB})$ includes the probability of having either a complete discovery, i.e., $X_{N_T-1}(k)$, or a partial discovery, i.e., $X_{N_T}(k)$. Note that only even iterations are considered, since SRBs are interleaved with LRBs. We will eliminate the dependency from t_0^{SRB} in Equation (9) later. Let us derive $l(i|t_0^{SRB})$ first.

$$l(i|t_0^{SRB}) = \mathbb{P}\{L = t_i^{LRB}|t_0^{SRB}\} = \begin{cases} 1 & i = i^* \\ \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

Equation (10) can be explained as follows. Since we assumed that LRBs are never discarded, given the initial radio state (S_0, r_0) and the first SRB transmission time t_0^{SRB}, the time of the first LRB reception can be deterministically derived as the t_{i*}^{LRB} such that the radio is ON (i.e., $RS(t_{i*}^{LRB}) =$ *True*).

Finally, in order to eliminate the dependency of $h(i)$ and $l(i)$ from t_0^{SRB}, we need to consider all possible values of t_0^{SRB} and the corresponding probabilities. Since we are assuming that time is discrete, with time slot Δ, let us denote by $\Lambda \equiv \{0,\; \Delta, \cdots,\; n\cdot\Delta\},\; n = \lfloor T_{BI}/\Delta \rfloor$ the set of possible values that can be assumed by t_0^{SRB}. Assuming that each value in Λ can occur with probability Δ/T_{BI}, and by definition of conditional probability, the p.m.f.s of the LRB discovery time $l(i)$ and the SRB discovery time $h(i)$ can be expressed as follows.

$$h(i) = \frac{\Delta}{T_{BI}} \cdot \frac{\sum_{\hat{t}_0^{SRB}\in\Lambda} h(i|\hat{t}_0^{SRB})}{\sum_{i=1}^{N_S}(\sum_{\hat{t}_0^{SRB}\in\Lambda} h(i|\hat{t}_0^{SRB}))} \quad (11)$$

$$l(i) = \frac{\Delta}{T_{BI}} \cdot \frac{\sum_{\hat{t}_0^{SRB}\in\Lambda} l(i|\hat{t}_0^{SRB})}{\sum_{i=1}^{N_L}(\sum_{\hat{t}_0^{SRB}\in\Lambda} l(i|\hat{t}_0^{SRB}))} \quad (12)$$

VI. Energy Consumption Analysis

In this section, we calculate the energy consumed by the sensor node in the discovery phase. Since the discovery process can have four different outcomes, we derive the Average Energy Consumption for: (i) *Complete Discovery* ($\overline{E}_{CD}$), (ii) *Partial Discovery* ($\overline{E}_{PD}$), (iii) *Complete Miss* ($\overline{E}_{CM}$), (iv) *Partial Miss* ($\overline{E}_{PM}$). By definition of L and D and using Equations (11) and (12), the average time spent by sensor node in low duty cycle (t_L) and high duty cycle (t_H) can be obtained, respectively, as

$$t_L = \mathbb{E}\{L\} \quad (13)$$

$$t_H = \mathbb{E}\{H - L\} \quad (14)$$

Finally, the equations for the aforementioned energies are defined in the below equations.

$$\overline{E}_{CD} = \begin{aligned} &P_{SL}\cdot\{(1-\delta_L)\cdot t_L + (1-\delta_H)\cdot t_H\} + \\ &P_{RX}\cdot\{\delta_L\cdot t_L + \delta_H\cdot t_H\} \end{aligned} \quad (15)$$

$$\overline{E}_{PD} = P_{SL}\cdot(1-\delta_L)\cdot t_H + P_{RX}\cdot\delta_L \quad (16)$$

$$\overline{E}_{CM} = P_{SL}\cdot(1-\delta_L)\cdot T_{OUT} + P_{RX}\cdot\delta_L\cdot T_{OUT} \quad (17)$$

$$\overline{E}_{PM} = \begin{aligned} &P_{SL}\cdot\{(1-\delta_L)\cdot t_L + (1-\delta_H)\cdot T_{OUT}\} + \\ &P_{RX}\cdot\{\delta_L\cdot t_L + \delta_H\cdot T_{OUT}\} \end{aligned} \quad (18)$$

Where P_{SL} (P_{RX}) denotes the power consumed by sensor node in sleep (receive) mode, δ_L (δ_H) is the low (high) duty cycle, T_{OUT} is the maximum time the sensor node remains active after receiving a LRB. In case of a Complete Discovery ($\overline{E}_{CD}$), the sensor node remains in low duty cycle for a total time t_L, then, switches to high duty cycle for a time t_H. When a Partial Discovery ($\overline{E}_{PD}$) occurs, the sensor node remains in low duty cycle for a total time t_H, then, begins communicating with the ME. In case of a Complete Miss ($\overline{E}_{CM}$), the sensor node remains in low duty cycle for a time equal to T_{OUT}. Finally, in case of a Partial Miss ($\overline{E}_{PM}$), the sensor node remains in low duty cycle for a total time t_L, then switches to high duty cycle until the timeout expires. The average total energy spent in the discovery phase can be derived as

$$\begin{aligned}\overline{E}_{dsc} = \overline{E}_{CD} \cdot \mathbb{P}\{CD\} + \overline{E}_{PD} \cdot \mathbb{P}\{PD\} + \\ \overline{E}_{CM} \cdot \mathbb{P}\{CM\} + \overline{E}_{PM} \cdot \mathbb{P}\{PM\}\end{aligned} \tag{19}$$

In Equation (19), $\mathbb{P}\{CD\}, \mathbb{P}\{PD\}, \mathbb{P}\{CM\}, \mathbb{P}\{PM\}$ denote the probability to be in each of the absorbing states at the end of the discovery process. According to our terminology and using Equations (8) and (9), the abovementioned probabilities are given by $\mathbf{x}_{N_T}^{N_T}(N_T \cdot M + i)$ where *i = 1, 2, 3, 4* for CD, PD, CM, PM, respectively.

VII. Data Transfer Analysis

In this section we focus on the communication phase and derive (i) the average number of bytes correctly transferred by the sensor node to the ME during a contact, and (ii) the average energy consumed by the sensor node during the data transfer phase. We assume that the data exchange is carried out through a simple ARQ (*Automatic Repeat reQuest*) protocol with selective retransmissions that is briefly outlined below.

Upon receiving a valid SRB, the sensor node enters the communication state and starts transmitting messages of fixed duration T_m to the ME. On the other side, the ME replies with ACK messages "piggybacked" in periodic beacons (both LRBs and SRBs). Specifically, the sensor nodes transmits a window of N_m messages back to back, and then waits for the periodic ACK (N_m is set in such a way that the N_m-th message is received by the ME just before the transmission of the periodic ACK/beacon). ACKs specify which messages in the previous window have been received correctly by the ME. Then, the sensor node transmits another window of N_m messages including both messages not acknowledged by the previous ACK and new messages. If the corresponding ACK is missed, the sensor node retransmits all message sent in the previous window. Since the sensor node cannot know when the ME leaves the communication area, it implicitly assumes that the communication with the ME is lost when it misses N_{ack} consecutive ACKs.

For the analysis of the data transfer phase we took an approach similar to [12]. We just mention here that, leveraging the equations derived in the previous sections, we calculated the average number of messages N_{tot} correctly transmitted during a contact, and the energy $\overline{E}_{com}$ spent by the sensor node during the data transfer phase. It can be shown ([11]) that

$$\begin{aligned}\overline{E}_{com} = P_{TX} \cdot (N_w + N_{ack}) \cdot N_m \cdot T_m + \\ P_{RX} \cdot (N_w + N_{ack}) \cdot T_{BD}\end{aligned} \tag{20}$$

Where $N_w + N_{ack}$ is the total number of windows sent during the contact (each window includes N_m messages of duration T_m). In detail, the sensor node sends $(N_w + N_{ack})$ windows of N_m messages of duration T_m and receives the same number of ACKs.

VIII. Performance Evaluation

To perform an integrated analysis of both the discovery and communication processes, we consider the following performance metrics.

- *Discovery Ratio (DR)*. It is defined as the probability that a contact is detected, i.e., $DR = \mathbb{P}\{CD\} + \mathbb{P}\{PD\}$.
- *Throughput (θ)*, It is defined as the total number of bytes correctly transferred to the ME per contact, provided that a contact is detected. Hence, $\theta = N_{tot} \cdot DR \cdot B_m$, where B_m is the message payload size in bytes.
- *Energy Per Byte Acknowledged*. It is the average total energy spent by the sensor node per acknowledged byte, i.e.,
$$\overline{E}_{byte} = \frac{\overline{E}_{dsc} + \overline{E}_{com}}{N_{tot} \cdot B_m}$$

Now we derive the optimal parameter values δ_L^{opt} and δ_H^{opt} that minimize the Energy per byte acknowledged, while guaranteeing the minimum throughput θ_{min} required by the application. The problem can be formulated as

$$\min_{\delta_L, \delta_H} \left\{\overline{E}_{byte}(\delta_L, \delta_H)\right\} : \theta \geq \theta_{min}$$

It can be proven that, under the assumption that v, T_{BI}, T_{BD}, and R are fixed, the optimization problem is bounded, i.e., a local minimum exists. To solve the optimization problem, we used a modified version of the gradient descent algorithm [13]. Details are in [11].

Below, we compare the performance of the 2BD protocol with that of a traditional, fixed duty-cycle discovery protocol based on a single beacon (SB). To this end, we derived an analytical model for SB similar to the one described above, and performed the same optimization analysis to derive the optimal duty cycle. The performance comparison is carried out in terms of the energy saving S provided by 2BD with respect to SB, i.e., $S = (E_{byte}^{SB} - E_{byte}^{2BD})/E_{byte}^{SB}$.

Unless stated otherwise, we will use the parameter values in Table III. Starting from this basic configuration, we will vary the value of some parameters to investigate their individual impact on *S*. Communication parameters in Table III are inspired from the IEEE 802.15.4 standard [14], while the radio parameters are assumed to be the same of a Chipcon CC2420 radio transceiver [16]. Moreover, we used the same message loss model derived in [15], i.e, a polynomial model in the form

$$p(t) = a \cdot [t - \Delta_{DR} - {}^{C_{max}}/_{2})]^2 + b \quad (21)$$

Equation (21) holds only within the communication area ($\Delta_{DR} \leq t < \Delta_{DR} + C_{max}$). For other t values, *p(t)* is equal to one. We assumed a = 0.4492 and b = 0.0077, as in [15].

Parameter	**Value**
Receive power (P_{RX})	35.46 mW
Transmission power (P_{TX})	31.32 mW
Sleep mode power (P_{SL})	36 μW
Beacon interval (T_{BI})	100ms
Beacon duration (T_{BD})	1ms
Time slot (Δ)	10ms
ME speed (v)	40 ${}^{Km}/_{h}$
ME - sensor distance (D)	15m
Communication range (r)	95m
Discovery range (R)	200m
Bitrate	250 ${}^{Kbit}/_{s}$
Message payload size (B_m)	118byte
Message duration (T_m)	4.256ms

Table III
PARAMETERS CHOSEN FOR ANALYSIS.

In the following analysis, we assume that the sensor node has some information about inter-contact times (e.g., they can be predicted based on the past history), however, it does not know the exact arrival time of the ME. Therefore, sensor node enters the discovery state some time in advance with respect to the predicted arrival time. The time interval from when the sensor node goes to the discovery state to when the ME enters into the communication area will be throughout referred to as *waiting time*. Obviously, the waiting time is related to the uncertainty in the arrival time prediction (the higher the uncertainty, the larger the *waiting time*). Also, it is worthwhile to emphasize that, under the same operating conditions, the waiting time is the same for both SB and 2BD, since the communication range is unchanged.

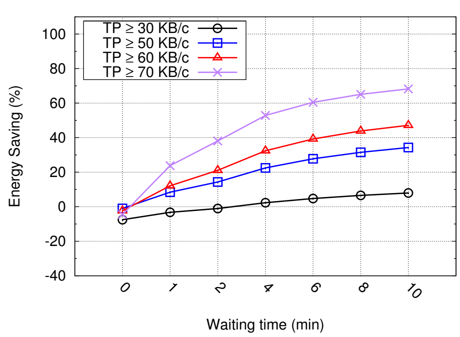

Figure 3. Energy savings of 2BD in function of throughput.

A. Results

Figure 3 shows the energy savings provided by 2BD, with respect to SB, as a function of the waiting time and for different values of (minimum) throughput. When the arrival time of the ME can be exactly predicted (and the waiting time is thus zero), 2BD is less energy efficient than SB, irrespective of the considered throughput. This happens because the 2BD discovery process is slightly longer (it must start when the ME enters into the discovery area, while with SB it can start when the ME enters into the communication area). However, as an aside, if the arrival time is exactly known, the discovery process becomes pointless. As soon as the uncertainty (and hence, the waiting time) increases, the time spent by sensor node in the discovery state increases accordingly and, hence, 2BD tends to be more and more convenient than SB. This happens because 2BD uses a lower duty cycle for most of the time while in the discovery state. In particular, when the ME mobility pattern is random and sensor node is forced to be always in the discovery state, the energy savings achieved by 2BD may be very high. This point is better clarified in Table IV, which shows the optimal duty cycles used by 2BD and SB to guarantee a certain throughput. For all the considered throughput values, the low duty cycle of 2BD is significantly lower than the duty cycle used by SB. Figure 3 also shows that, for a fixed waiting time, the energy savings provided by 2BD are much higher for large throughput values. This happens because a larger throughput requires an earlier discovery of the ME and/or a higher percentage of detected contacts and, ultimately, a higher duty cycle. To this end, 2BD can take advantage of its hierarchical mechanism. As shown in Table IV, when the requested throughput changes from 30 to 70 Kbytes/contact, the duty cycle of SB increases from 1.3% to 10.1%, while the low duty cycle of 2BD only passes from 1.0% to 1.6%.

θ (KBpc)	δ^{opt}	δ_L^{opt}	δ_H^{opt}	DR_{2BD}	DR_{SB}
$\geq$ 30	1.3	1.0	2.7	69.46	66.70
$\geq$ 50	3.0	1.4	5.9	91.54	91.48
$\geq$ 60	4.6	1.5	9.3	97.87	97.76
$\geq$ 70	10.1	1.6	20.8	99.98	99.97

Table IV
OPTIMAL DUTY CYCLE VALUES.

Figure 4 shows the impact of the discovery range on the energy efficiency of 2BD (SB is not affected by this parameter). Since the nominal communication range r is equal to 95m, the results show that even with a discovery range slightly larger than the communication range (e.g., R = 150m), 2BD is able to provide significant energy savings with respect to SB. A further increase in the R value allows to provide the same throughput with a lower low duty cycle, thus resulting in higher energy savings.

Finally, Figure 5 shows the impact of the beacon period on both protocols. We can observe a different behavior of the different curves for short and long waiting times. This behavior can be explained as follows. In general, using a larger beacon period (e.g., passing from 50 ms to 200

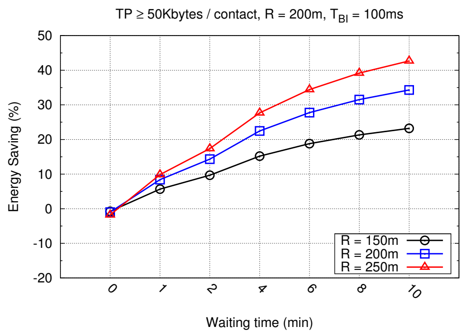

Figure 4. Energy savings of 2BD in function of R.

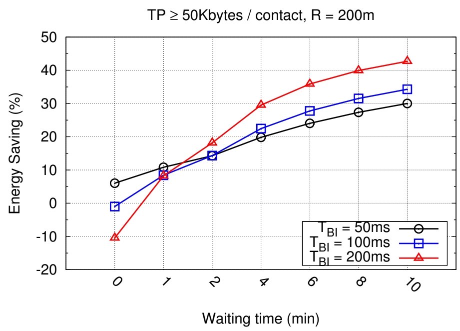

Figure 5. Energy saving of 2BD in function of T_{BI}.

ms) makes the discovery process more difficult. Hence, the sensor node is forced to increase its duty cycle to guarantee the same throughput. When the waiting time is long, 2BD is more energy-efficient than SB, thanks to its hierarchical mechanism. Instead, when the waiting time is short, the additional energy consumed by 2BD in high duty cycle becomes predominant with respect to that consumed in low duty cycle and, overall, SB is more efficient than 2BD. However, unless the waiting time is very small, 2BD is always more efficient than SB, irrespective of the considered beacon period.

IX. Conclusions

In this paper we have analyzed 2BD, a hierarchical discovery protocol for WSNs with Mobile Elements. We have developed a detailed analytical model of 2BD, to characterize both the throughput and the energy consumption of sensor nodes. Then, we have derived the optimal parameter values that minimize the energy consumption, while guaranteeing the minimum throughput required by the sensing application. Finally, we have compared 2BD with a traditional protocol based on a single beacon, in terms of both energy consumption and performance. Our analysis has shown that 2BD is able to provide significant energy savings, especially when the discovery phase is relatively long. For the sake of space, our analysis has been limited to a sparse network scenario only. In a dense scenario, 2BD may cause *false activations* of sensor nodes, resulting in energy wastes (i.e., sensor nodes that fall outside of the MEs communication range can receive a LRB, however, they will never receive a subsequent SRB). Obviously, the number of false activations depends on the discovery range R that is used. Our preliminary results (not reported here for the sake of space) show that, with an appropriate setting of R, 2BD is convenient also in a dense network scenario.

References

[1] S. Jain, R. Shah, W. Brunette, G. Borriello, and S. Roy, “Exploiting Mobility for Energy Efficient Data Collection in Wireless Sensor Networks”, Mobile Networks and Applications, Vol. 11, N. 3, 2006.

[2] M. Di Francesco, S. K. Das, G. Anastasi, “Data Collection in Wireless Sensor Networks with Mobile Elements: A Survey”, ACM Trans. on Sensor Networks, Vol. 8, N. 1, 2011.

[3] R. Mathew, M. Younis, S. Elsharkawy “Energy-Efficient Bootstrapping Protocol for Wireless Sensor Networks”, Innovations in Systems & Software Engineering, Vol. 1, N. 2, 2005.

[4] A. Somasundara, A. Kansal, D. Jea, D. Estrin, M. Srivastava, “Controllably Mobile Infrastructure for Low Energy Embedded Networks”, IEEE Trans. on Mobile Computing, Vol. 5, N. 8, 2006.

[5] V. Dyo, C. Mascolo, “Efficient Node Discovery in Mobile Wireless Sensor Networks”, Lecture Notes in Computer Science. Proc. DCOSS 2008 (LNCS 5067).

[6] K. Shah, M. Di Francesco, G. Anastasi, M. Kumar, “A Framework for Resource-Aware Data Accumulation in Sparse Wireless Sensor Networks”, Computer Communications, Vol. 34, N. 17, 2011.

[7] T. Pering, V. Raghunathan, R. Want, “Exploiting Radio Hierarchies for Power-Efficient Wireless Device Discovery and Connection Setup”, Proc. Int’l Conf. on VLSI Design, 2005.

[8] H. Jun, M. Ammar, M. Corner, E. Zegura, “Hierarchical Power Management in Disruption Tolerant Networks Using Traffic-aware Optimization”, Computer Communications, Vol. 32, N. 16, 2009.

[9] J. Brown, J. Finney, C. Efstratiou, B. Green,N. Davies, M. Lowton, G. Kortuem, “Network Interrupts: Supporting Delay Sensitive Applications in Low Power Wireless Control Networks”, Proc. ACM CHANTS, 2007.

[10] K. Kondepu, G. Anastasi, M. Conti, “Dual-Beacon Mobile-Node Discovery in Sparse Wireless Sensor Networks”, Proc. IEEE ISCC, 2011.

[11] F. Restuccia, G. Anastasi, M. Conti, S. Das, “Performance Analysis of a Hierarchical Discovery for WSNs with Mobile Elements (Extended Version)”, Technical Report DII-2011-12, Univ. Pisa, Italy, 2011. http://www.iet.unipi.it/∼anastasi/papers/tr-11-12.pdf

[12] G. Anastasi, M. Conti, M. Di Francesco “Reliable and Energy-efficient Data Collection in Sparse Sensor Networks with Mobile Elements”, Performance Evaluation, Vol. 66, N. 12, 2009.

[13] Mordecai Avriel. Nonlinear Programming: Analysis and Methods. Dover Publishing. ISBN 0-486-43227-0, 2003.

[14] IEEE 802.15.4 standard. http://standards.ieee.org/getieee802/download/802.15.4-2006.pdf.

[15] G. Anastasi, M. Conti, E. Monaldi, and A. Passarella, “An adaptive data- transfer protocol for sensor networks with Data Mules”, Proc. IEEE WoWMoM, 2007.

[16] Chipcon, 2.4 GHz IEEE 802.15.4/ZigBee-Ready RF Transceiver, Chipcon Products from Texas Instruments, 2004, CC2420 Data Sheet.