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Evaluation of the functionality of mobile wireless sensor networks using stochastic reward nets

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Abstract. In this paper, the functionality of Mobile Wireless Sensor Networks (MWSNs) is analytically modeled and evaluated using Stochastic Reward Nets (SRNs). In MWSNs, mobile nodes can move around to collect data from the environment and send them to the sink. These nodes use a limited battery as the power source which can be charged according to environmental conditions. If the battery does not have enough power, the mobile node is disabled and, therefore, it cannot move around to collect/send data. The data collected by the nodes will expire if they are not received by the sink in a timely manner. In order to avoid data expiration, mobile nodes can send their data to other nodes around themselves, but this also increases the power consumption because of further communication. Furthermore, moving faster in the environment, the power consumption of the nodes increases. Therefore, environmental and movement conditions as well as communication between nodes can have a major impact on the functionality of the MWSNs. These challenges are considered in the paper and the proposed models analyze the impact of different conditions on the functionality of MWSNs. The results obtained from the comparison of different scenarios demonstrate that the environmental and movement conditions have a greater impact on system functionality than the communication conditions.

1. Introduction

Various hardware and software factors can affect the functionality of Mobile Wireless Sensor Networks (MWSNs). One of the most important factors affecting the power and performance of these systems is environmental and movement conditions. In the MWSNs, mobile nodes use rechargeable batteries as the power source. These batteries can be charged according to environmental conditions. If the environmental conditions are not suitable, the battery of mobile nodes will discharge after a while, causing the nodes to be disabled. This degrades the performance of the nodes in doing their job, i.e., delivering data to the sink node. In order to prevent degradation of performance, mobile nodes can send their data to other nodes instead of delivering it to the sink, but this also increases the power consumption because they need to establish further communication. On the other hand, if the nodes want to move faster to collect more data and deliver them to the sink, to increase the performance, the power consumed by the nodes will increase. Therefore, analyzing the tradeoff among environmental, commu-

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nication, and movement conditions is more important when evaluating the performance of mobile nodes in MWSNs.

Both the power consumption and performance of a system depend on the system functionality; hence, the unified power and performance modeling and evaluation can help us understand how various factors affect system functionality. In order to model the MWSNs and evaluate the impact of different environmental, communication, and movement conditions on the system functionality, the Stochastic Reward Nets (SRNs) [1] are used in this paper. SRNs are stochastic extensions of Petri Nets (PNs) that provide a powerful way for modeling complex systems. Various extensions of PNs have been used to model and evaluate different measures in various distributed computing systems [2–6]. The main contribution of this paper can be summarized in the five following categories:

- The SRN formalism is used to model environmental conditions, mobile and sink nodes, and communication between nodes in MWSNs;
- The movement, battery, and energy harvesting are considered in the models proposed for mobile nodes;
- The impact of different environmental, communication, and movement conditions on the system functionality is analyzed using the proposed SRN models;
- The proposed models are used to evaluate and compare different possible scenarios;
- It is proven that by comparing the results, the environmental and movement conditions have a greater impact on system functionality than the communication conditions.

The rest of this paper is organized as follows. Section 2 presents background information on the MWSNs systems, the SRN formalism, and its supporting tool, and SPNP [7,8]. Section 3 introduces the related state of the art in system formal modeling and evaluation. Section 4 presents the proposed SRN models and figures of merit, which can be computed by applying the proposed models. Section 5 compares the results obtained from different environmental, communication, and movement conditions by analytically solving the proposed SRN models. Finally, Section 6 concludes the paper and gives ideas for future work.

2. Background information

2.1. Description of the MWSNs and our assumptions

Wireless Sensor Networks (WSNs) consist of a large number of sensor nodes deployed to observe or measure a certain phenomenon or detect the occurrence of an event. Sensor nodes send their observations to a base station, such as sink node for further processing [9]. In MWSNs, mobile nodes are equipped with locomotive platforms that allow movement after initial deployment [9]. The movement speed of mobile nodes can affect their power consumption and performance. In accordance with the definitions provided by [9,10], Figure 1 represents the structure of an MWSN considered in this paper, which consists of a sink node and several mobile sensor nodes in different layers. We assume that the geographic environment consists of L layers and each layer, except the layer zero, has data that should be collected by mobile nodes. The sink node is in the layer zero and receives data collected by mobile nodes. Mobile nodes move in up and down directions and collect data from the geographic environment in different layers. They can send their data to the sink only when they are in the layer zero. When a mobile node reaches zero and L layers, its direction changes to up and down, respectively.

We assume that each mobile node has a battery that can be in three statuses: low, medium, and high. The status of the battery affects the node functionality. In case of battery low status, the mobile node is disabled and cannot move around and send data. The batteries can be charged at different rates depending on environmental conditions. We assume that environmental conditions can be at three levels, such as suitable, moderate, and unsuitable. For example, if the batteries are charged based on sunlight, sunny and cloudy days are suitable and moderate environmental conditions, respectively. Moreover, nights are unsuitable environmental conditions. Since data collected by mobile nodes and data received by the sink are expired after a specified timed period, mobile nodes can send their data to other nodes around themselves. For example, if the ith node is on the jth layer, it can send its data to nearby nodes that are on the way to the sink in the same layer. We assume that power consumption of active mobile nodes

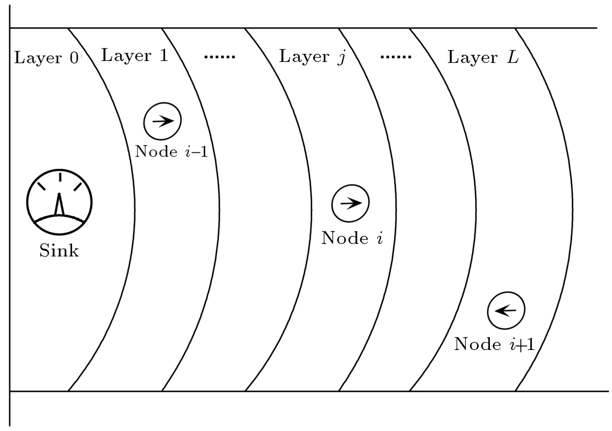

Figure 1. The MWSNs considered in this paper.

increases when they try to communicate with other mobile nodes. Moreover, it is assumed that mobile nodes move at different speeds, affecting their power consumption.

2.2. The SRN formalism and SPNP tool

PNs are an important mathematical formalism to model real systems and evaluate their performance [11]. The advantages of this formalism are simple definition, graphical representation, availability of simulation and analytical solutions, and being supported by various computer tools. The places, transitions, and tokens are three basic elements of the PN formalism [11]. Places are represented by circles and used to model the state variables of a system. Each place can contain zero or several tokens indicating the value of the state variable modeled by the place. Transitions are represented by rectangles and used to model the events/actions that change the values of the state variables. The transitions are divided into two types, namely timed and immediate, which are represented by the hollow and solid rectangles, respectively. There is no waiting time associated with immediate transitions and they fire as soon as they are enabled, while the time taken by timed transitions to fire follows an exponential distribution function.

Stochastic Reward Nets (SRNs) are an important extension of PNs providing a powerful modeling environment to analyze the performance, dependability, and performability of systems [1]. In the SRN formalism, the transitions can have a guard function, a Boolean function, to examine whether a transition is enabled or not. An arc can be marking dependent to specify the number of tokens that should be manipulated in the places during firing of its corresponding transition [7]. The Stochastic Petri Net Package (SPNP) is a well-known tool supporting the SRN formalism to compute a variety of transient, steady-state, cumulative, and sensitivity measures [8]. In this paper, the proposed SRN models are constructed and analyzed by the SPNP tool in the steady state. In order to analytically solve the models and compute measures in the steady state, it is assumed that the transition times of the proposed SRNs follow exponential distributions. The same assumption has been made in related works to model various events in real-world systems, e.g. [2–6].

3. Related work

Some approaches have been proposed to investigate energy harvesting in the MWSNs. These approaches introduce various energy sources, technologies, and challenges that must be addressed to develop reliable energy harvesting systems. Furthermore, there have been other proposed approaches that model MWSNs and evaluate the impact of various factors on power and performance measures, but most of them usually ignore the impact of one of the environmental, communication, and movement conditions on power consumption and system functionality. Table 1 compares our proposed approach against the state-of-the-art approaches.

Table 1. Comparison between previous methods and the models presented in this paper.

Ref.	WSN	Battery	Environmental conditions	Communication conditions	Movement conditions	Migration	Power & performance	Stochastic model
[12]	✓	×	×	✓	×	×	✓	×
[13]	✓	×	×	✓	×	×	×	×
[14]	✓	✓	×	✓	✓	×	✓	×
[15]	✓	✓	×	✓	✓	×	✓	×
[16]	✓	✓	×	✓	✓	×	✓	×
[16]	✓	✓	✓	×	×	×	✓	✓
[17]	✓	✓	✓	✓	×	×	✓	✓
[18]	✓	✓	✓	✓	✓	×	×	✓
[19]	✓	✓	×	✓	×	×	×	✓
[20]	✓	✓	×	✓	×	×	✓	✓
[21]	✓	×	×	×	✓	×	×	✓
[22]	✓	×	×	×	✓	×	×	✓
[23]	✓	✓	✓	✓	✓	×	×	×
[24]	✓	×	×	×	×	×	✓	✓
The proposed models	✓	✓	✓	✓	✓	✓	✓	✓

In [12], different types of wireless smart sensors and communication technologies were reviewed. Sensors must consume less power and reduce the noise produced by wireless communication. In [13], a framework was introduced to evaluate efficient, timely, reliable, and ubiquitous inference of information obtained by nodes in intelligent WSNs. In [14], two mathematical models were introduced to maximize the network lifetime through the controlled mobility of a sink with nonzero travel times without considering energy harvesting and environmental conditions. In [15], the sensor deployment problem was modeled to find an optimal sensor relocation to optimize the sensing quality, energy consumption, and connectivity. However, the impact of energy harvesting on it was not been considered. In [16], a probabilistic algorithm to analyze the network connectivity by taking into account the parameters like network probability, detection area, radius of the individual nodes, and whole detection area was proposed to ensure the network connectivity and communication sustainability. This algorithm optimizes the energy consumption at the utmost level. In [17], by using fuzzy PNs, an energy harvesting aware algorithm for selecting cluster heads was introduced to keep the WSN alive for much longer time. However, its impact on the functionality of WSNs was not considered. In [18], a sensor node with energy harvesting capability was modeled with a new generalized stochastic PN to determine performance parameters and to predict the energy consumption of a sensor node. In this model, a sensor node can be in different modes, such as active, listening, and standby, and it analyzes the impact of the harvesting and sleeping rates on the mean battery charge and mean response time. However, this model ignores the impact of movement conditions. In [19], a PN-based modeling framework was presented for the evaluation of sensing, communication, and movement factors that contribute to energy dissipation in mobile wireless sensor nodes. The model provided by this framework ignores the system functionality. In [20], an approach was proposed for evaluating the WSN lifetime using a set of reusable colored PN models that expressed the power consumption of communication protocols. This approach only evaluates the impact of communication protocols on power consumption of WSN nodes and ignores the impact of environmental and movement conditions. In [21], a methodology that consists of a set of power consumption and reliability models was presented to estimate the power consumption of WSN applications. This methodology also ignores the impact of energy harvesting and movement conditions. In [22,23], the road traffic flows were considered as WSNs, and PNs were used to model the transportation system and the movement of each vehicle. In [24], the ways to increase the network lifetime, while satisfying the full target coverage in the WSNs, consisting of both non-rechargeable and rechargeable sensors, were studied and, then, a lifetime-enhancing method for this purpose was proposed. In [25], the WSNs were modeled using the colored PNs in order to capture the effect of data aggregation on the overall performance.

4. The proposed SRN models

In this section, various parts of an MWSN, such as mobile and sink nodes, environmental conditions, and communication between nodes are modeled first using the SRN formalism. Then, measures of interest on the proposed models are defined.

4.1. Modeling environmental conditions

As mentioned in Section 2.1, we assume three levels for environmental conditions called suitable, moderate, and unsuitable. Figure 2 represents the proposed SRN for different environmental conditions. The number of tokens inside place *Weather* which can be equal to one, two, and three represents the unsuitable, moderate, and suitable levels for the environment to charge the battery of mobile nodes, respectively.

The timed transitions T_U2S and T_S2U model how environmental conditions change from unsuitable to suitable and from suitable to unsuitable, respectively. These timed transitions follow exponential distributions with rates α and β, and guard functions $G1$ and $G2$ listed in Table 2 are assigned to them, respectively. The guard function $G1$ ($G2$) checks the number of tokens inside place *Weather*. If it is smaller (greater) than three (one), function $G1$ ($G2$) returns true to make the timed transition T_U2S (T_S2U) enabled; otherwise, it returns false to prevent the transition from firing. When timed transition T_U2S (T_S2U) fires, a token is deposited into (removed from) place *Weather*.

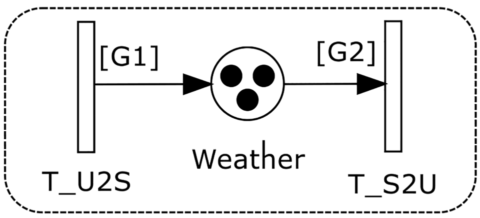

Figure 2. The SRN model proposed for environmental conditions.

Table 2. Guard functions assigned to transitions of the SRN represented in Figure 2 modeling the environmental conditions.

Guard	Function
$G1$	$mark(Weather) < 3$
$G2$	$mark(Weather) > 1$

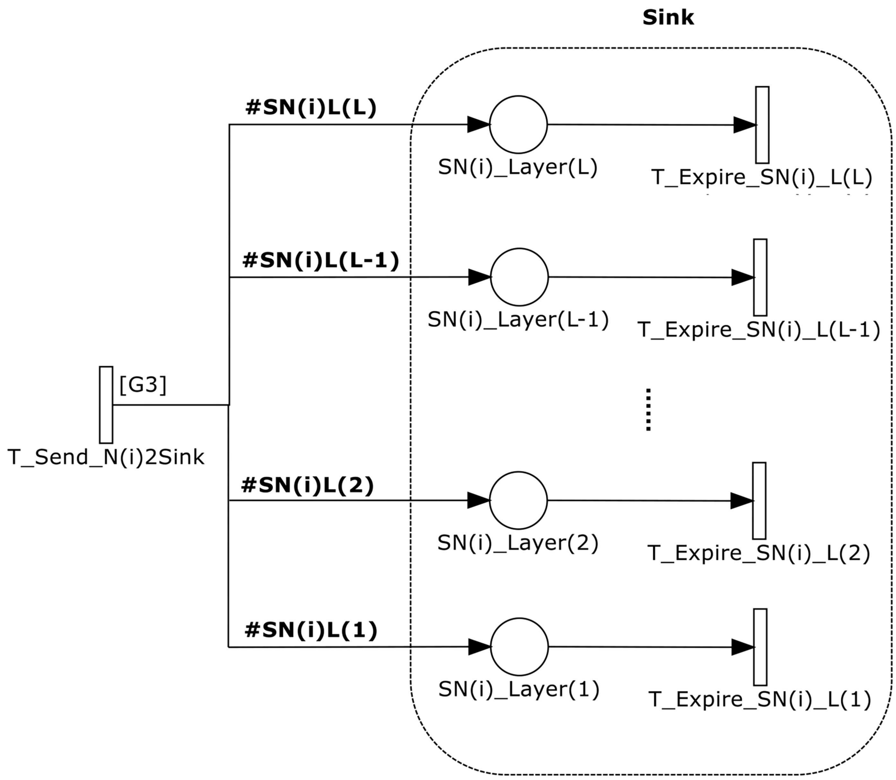

Figure 3. The SRN model proposed for the sink node.

4.2. Modeling the sink node of the MWSNs

As mentioned in Section 2.1, the geographic environment consists of L layers, and each layer, except the layer zero, has data that must be collected by mobile nodes. The sink node receives data collected by mobile nodes in the layer zero. Figure 3 shows the proposed SRN model for the sink node. The place $SN\,(i)\_Layer\,(j)$, $1 \leq i \leq N$, $1 \leq j \leq L$ represents the existence of the jth data of the ith node in the sink node. If the number of tokens inside place $SN(i)\_Layer\,(j)$ is equal to one, the jth data of the ith node is available at the sink node; otherwise, if it is equal to zero, the jth data of the ith node is not available at the sink node due to failure to receive or expire.

The timed transition $T\_Expire\_SN(i)\_L(j)$, $1 \leq i \leq N$, $1 \leq j \leq L$ models the expiration of the jth data of the ith node in the sink node, with rate π. If the number of tokens inside place $SN\,(i)\_Layer\,(j)$ is equal to one, timed transition $T\_Expire\_SN\,(i)\_L(j)$ is enabled and when it fires, a token is removed from place $SN(i)\_Layer(j)$.

The timed transition $T\_Send\_N(i)2Sink$, $1 \leq i \leq N$ sends all data of the ith node to the sink node with rate θ. According to Table 3, the guard function $G3$ assigned to timed transition $T\_Send\_N(i)2Sink$ checks whether the ith node is in the layer zero or not. If it is in the layer zero, guard $G3$ returns true to make transition $T\_Send\_N(i)2Sink$ enabled; otherwise, it returns false to prevent the transition from firing. When timed transition $T\_Send\_N(i)2Sink$ fires, $\#SN\,(i)L(j)$, $1 \leq i \leq N$, $1 \leq j \leq L$ token is deposited into places $SN\,(i)\_Layer\,(j)$. If the jth data of the ith node is available at the ith node and is not available at the sink node, the number $\#SN\,(i)L(j)$ is equal to one; otherwise, it is zero.

Table 3. Functions assigned to transitions and arcs of the SRN represented in Figure 3 modeling the sink node.

Guard/arc	Function
$G3$	$mark(N(i)\_Layer(0)) == 2$

$\#SN(i)L(j)$	$if(mark(N(i)\_Layer(j)) == 1)$
	  $if(mark(SN(i)\_Layer(j)) == 0)$
	    $return\ 1$
	  $else$
	    $return\ 0$
	$else$
	  $return\ 0$

4.3. Modeling a mobile node of the MWSNs

As mentioned in Section 2.1, mobile nodes use batteries as the power source and they can move in up and down directions and collect data from the geographic environment in different layers except the layer zero. Figure 4 represents the proposed SRN model for a

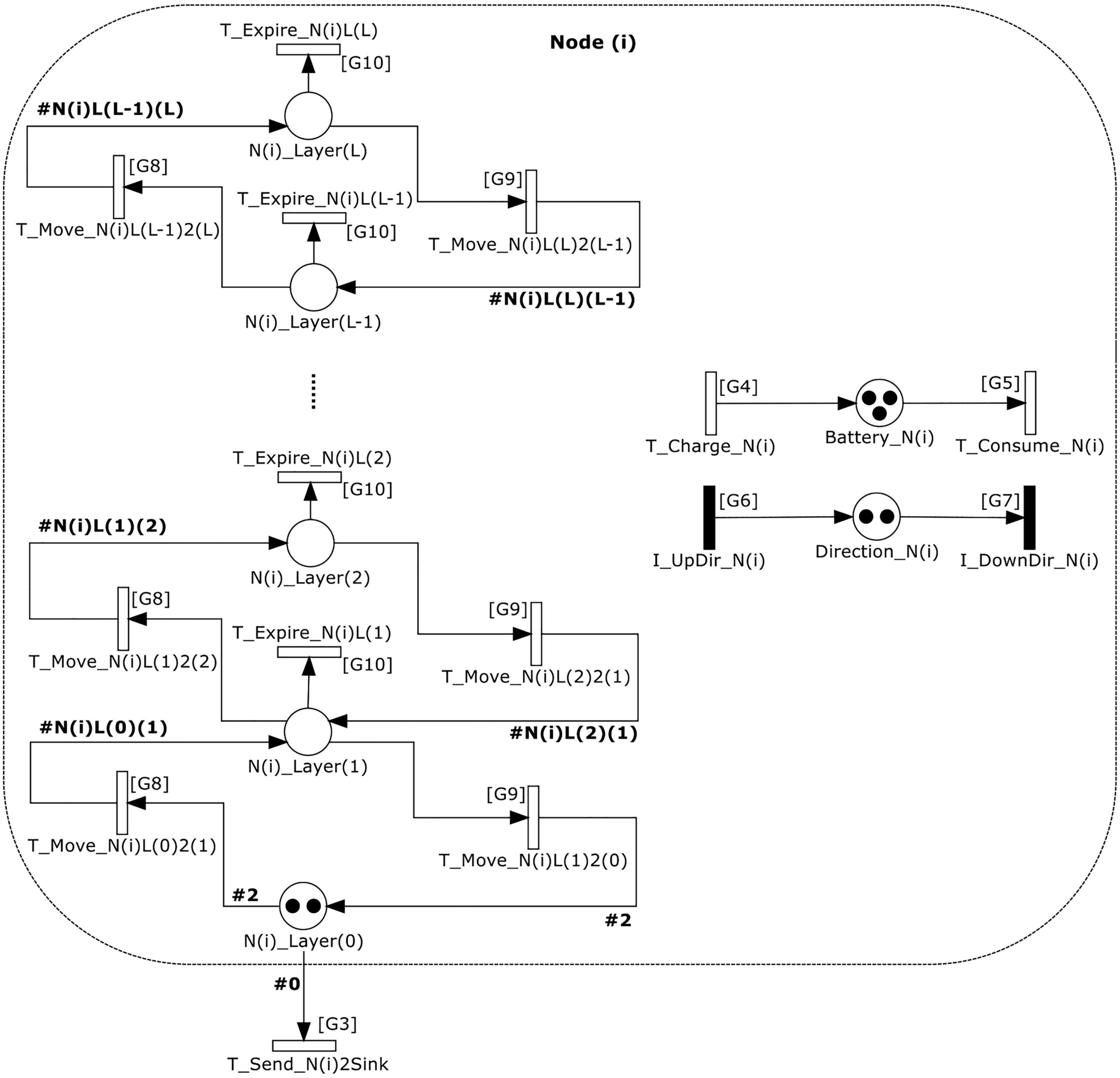

Figure 4. The SRN model proposed for a mobile node.

mobile node. The number of tokens inside place *Battery_N*(i) that can be equal to one, two, and three represents the low, medium, and high statuses of the battery of the ith mobile node, respectively. Furthermore, the number of tokens inside place *Direction_N*(i) which can be equal to one and two represents the down and up directions of the ith mobile node, respectively. The place $N(i)\_Layer\,(j)$, $1 \leq i \leq N$, $1 \leq j \leq L$ represents the existence of the jth data in the ith node. If the number of tokens inside this place is two, it shows that the ith node is in the jth layer and the jth data is being collected by it. If this number is one, the jth data is available at the ith node and if it is zero, the jth data is not available at the ith node due to expiration.

The timed transitions $T\_Charge\_N(i)$ and $T\_Consume\_N(i)$ model how to charge and consume the battery of the ith mobile node, respectively. These timed transitions follow an exponential distribution with rates shown in Eqs. (1) and (2), respectively. Two guard functions $G4$ and $G5$, listed in Table 4, are assigned to transitions $T\_Charge\_N(i)$ and $T\_Consume\_N(i)$, respectively.

$$(mark(Weather) - 1) \times \omega, \tag{1}$$

$$Communication\ done?\,(\omega + 1) : \omega. \tag{2}$$

According to Eq. (1), when environmental condition is suitable, i.e., $mark(Weather) == 3$, the batteries are charged at twice the rate ω. If environmental conditions are moderate, i.e., $mark(Weather) == 2$, the batteries are charged with rate ω and finally, if environmental conditions are unsuitable, i.e., $mark(Weather) == 1$, the batteries are not charged. According to Eq. (2), if the mobile nodes communicate with each other, the

Table 4. Functions assigned to transitions and arcs of the SRN represented in Figure 4 modeling the mobile node.

Guard/arc	Function
$G4$	$mark(Battery\_N(i)) < 3$ & $mark(Weather) > 1$
$G5$	$mark(Battery\_N(i)) > 1$
$G6$	$mark(N(i)\_Layer(0)) == 2$ & $mark(Direction\_N(i)) == 1$
$G7$	$mark(N(i)\_Layer(L)) == 2$ & $mark(Direction\_N(i)) == 2$
$G8$	$mark(Battery\_N(i)) > 1$ & $mark(N(i)\_Layer(j)) == 2$ & $mark(Direction\_N(i)) == 2$
$G9$	$mark(Battery\_N(i)) > 1$ & $mark(N(i)\_Layer(j)) == 2$ & $mark(Direction\_N(i)) == 1$
$G10$	$mark(N(i)\_Layer(j)) == 1$

$\#N(i)L(j)L(j+1)$	$if(mark(N(i)\_Layer(j+1)) == 0)$
	    $return\ 2$
	$else$
	    $return\ 1$

$\#N(i)L(j)L(j-1)$	$if(mark(N(i)\_Layer(j-1)) == 0)$
	    $return\ 2$
	$else$
	    $return\ 1$

batteries are consumed with the rate $(\omega+1)$; otherwise, they are consumed with the rate ω. The guard function $G4$ checks the situation that the battery is not high and environmental conditions are not unsuitable. If it is, function $G4$ returns true to make timed transition $T\_Charge\_N(i)$ enabled; otherwise, it returns false to prevent the transition from firing. When timed transition $T\_Charge\_N(i)$ fires, a token is deposited into place $Battery\_N(i)$. The guard function $G5$ checks if the battery is not low. If it is evaluated to true, timed transition $T\_Consume\_N(i)$ is enabled; otherwise, it cannot fire. When timed transition $T\_Consume\_N(i)$ fires, a token is removed from place $Battery\_N(i)$.

The immediate transition $I\_UpDir\_N(i)$ and $I\_DownDir\_N(i)$ model how the direction of the ith mobile node changes from down to up and from up to down, respectively. The guard functions $G6$ and $G7$ listed in Table 4 are assigned to transitions $I\_UpDir\_\ N(i)$ and $I\_DownDir\_N(i)$, respectively. According to guard function $G6$ ($G7$), if the mobile node is in the zero (Lth) layer and its direction is down (up), immediate transition $I\_UpDir\_\ N(i)$ ($I\_DownDir\_N(i)$) is enabled. When immediate transition $I\_UpDir\_N(i)$ ($I\_DownDir\_N(i)$) fires, a token is deposited into (removed from) place $Direction\_N(i)$ ($Direction\_N(i)$).

The timed transition $T\_Expire\_N(i)\_L(j)$, $1 \leq i \leq N$, $1 \leq j \leq L$ expires the jth data in the ith node with rate π. According to the guard function $G10$, if the number of tokens inside place $N(i)\_Layer(j)$ is equal to one, timed transition $T\_Expire\_N(i)\_L(j)$ is enabled and when it fires, a token is removed from place $N(i)\_Layer(j)$.

The timed transitions $T\_Move\_N(i)L(j)2L(j+1)$ and $T\_Move\_N(i)L(j)L(j-1)$, $1 \leq i \leq N$, $1 \leq j \leq L$ model upward and downward movements of the ith node in different layers, respectively. These timed transitions follow an exponential distribution with rate μ, and guard functions $G8$ and $G9$, listed in Table 4, are assigned to them, respectively. The guard function $G8$ ($G9$) checks whether the battery is not low, the ith node is in the jth layer and the direction of the ith node is up (down). If it is, function $G8$ ($G9$) returns true to make timed transition $T\_Move\_N(i)L(j)2L(j+1)$ ($T\_Move\_N(i)L(j)2L(j-1)$) enabled; otherwise, it returns false to prevent the transition from firing.

When timed transition $T\_Move\_N(i)L(j)2L(j+1)$ fires, a token is removed from place $N(i)\_Layer(j)$ and $\#N(i)L(j)L(j+1)$, $1 \leq i \leq N$, $1 \leq j \leq L$ tokens are deposited into places $N(i)\_Layer\,(j+1)$. If the $(j+1)$th data is not available at the ith node, the number $\#N(i)L(j)L(j+1)$ is equal to two; otherwise, it is equal to one. Similarly, when timed transition $T\_Move\_N(i)L(j)2L(j-1)$ fires, a token is removed from place $N(i)\_Layer(j)$ and the $\#N(i)L(j)L(j-1)$, $1 \leq i \leq N$, $1 \leq j \leq L$ token is deposited into places

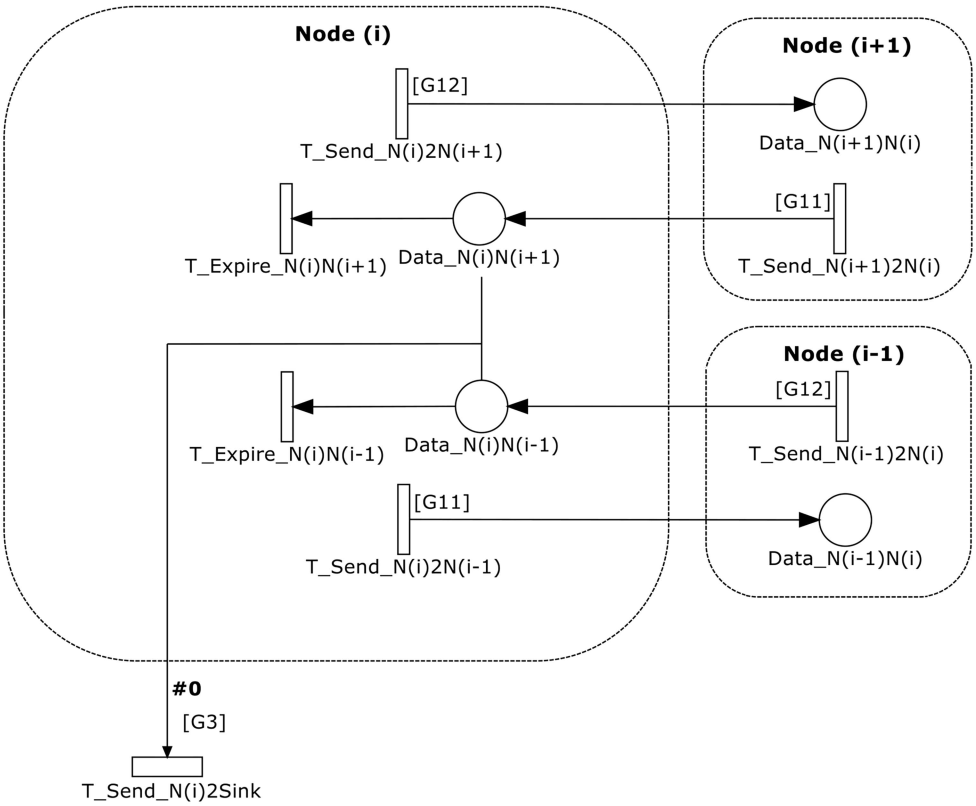

Figure 5. The SRN model proposed for the communication between mobile nodes.

$N(i)\_Layer(j-1)$. If the $(j-1)$th data is not available at the ith node, the number $\#N(i)L(j)L(j-1)$ is equal to two; otherwise, it is equal to one.

4.4. Modeling communication between mobile nodes

As mentioned in Section 2.1, mobile nodes can send their data to other nodes around themselves. For example, if the ith node is in the jth layer, it can send its data to the $(i+1)$th and $(i-1)$th nodes which are on the way to the sink in the same layer. Figure 5 represents the proposed SRN model to ensure a communication between mobile nodes. The places $Data\_N(i)N(i-1)$ and $Data\_N(i)N(i+1)$, $1 \leq i \leq N$ represent the existence of the data of the $(i-1)$th and $(i+1)$th nodes in the ith node, respectively. If the number of tokens inside place $Data\_N(i)N(i-1)$ ($Data\_N(i)N(i+1)$) is equal to one, all data of the $(i-1)$th ($(i+1)$th) node is available at the ith node; otherwise, if it is equal to zero, the data is not available at the ith node.

The timed transitions $T\_Send\_N(i)N(i-1)$ and $T\_Send\_N(i)N(i+1)$, $1 \leq i \leq N$ send the data of the ith node to the $(i-1)$th and $(i+1)$th nodes, respectively. These timed transitions follow an exponential distribution with rate θ, and guard functions $G11$ and $G12$ listed in Table 5, are assigned to them, respectively. In case the data of the ith node are

Table 5. Functions assigned to transitions of the SRN represented in Figure 5, modeling the communication between mobile nodes.

Guard/arc	Function
$G11$	$mark(Data\_N(i)N(i-1)) == 0\&$ $mark(Battery\_N(i)) > 1 \ \& \ mark(Battery\_N(i-1)) > 1 \ \&$ $mark(Direction\_N(i)) == 2 \ \& \ mark(Direction\_N(i-1)) == 1 \ \&$ $(\exists_{(1\leq j\leq L)} \ mark(N(i)\_Layer(j)) == mark(N(i-1)\_Layer(j)) == 2)$
$G12$	$mark(Data\_N(i)N(i+1)) == 0 \ \&$ $mark(Battery\_N(i)) > 1 \ \& \ mark(Battery\_N(i+1)) > 1 \ \&$ $mark(Direction\_N(i)) == 2 \ \& \ mark(Direction\_N(i+1)) == 1 \ \&$ $(\exists_{(1\leq j\leq L)} \ mark(N(i)\_Layer(j)) == mark(N(i+1)\_Layer(j)) == 2)$

not available at the $(i-1)$th ($(i+1)$th) node, the battery of the $(i-1)$th ($(i-1)$th) and ith nodes is not low and the direction of the $(i-1)$th ($(i+1)$th) and ith nodes is down and up, respectively, and they will be in the same layer. Function $G11$ ($G12$) returns true to make timed transition $T\_Send\_N(i)N(i-1)$ ($T\_Send\_N(i)N(i+1)$) enabled; otherwise, it returns false to prevent the transition from firing. When timed transition $T\_Send\_N(i)N(i-1)$ ($T\_Send\_N(i)N(i+1)$) fires, a token is deposited into place $Data\_N(i-1)N(i)$ ($Data\_N(i+1)N(i)$).

The timed transitions $T\_Expire\_N(i)N(i-1)$ and $T\_Expire\_N(i)N(i+1)$, $1 \leq i \leq N$ expire the data of the $(i-1)$th and $(i+1)$th nodes in the ith node with rate π, respectively. If the number of tokens inside place $Data\_N(i)N(i-1)$ is one, timed transition $T\_Expire\_N(i)N(i-1)$ is enabled and empties this place upon firing. The same happens for transition $T\_Expire\_N(i)N(i+1)$ and place $Data\_N(i)N(i+1)$.

As mentioned in Section 4.2, the timed transition $T\_Send\_N(i)2Sink$, $1 \leq i \leq N$ sends all data of the ith node to the sink node with rate θ. If the mobile nodes can communicate with each other, this transition also sends all data of the $(i-1)$th and $(i+1)$th nodes to the sink node. Therefore, when timed transition $T\_Send\_N(i)2Sink$ fires, the $\#SN(i-1)L(j)$ and $\#SN(i+1)L(j)$, $1 \leq i \leq N$, $1 \leq j \leq L$ tokens are deposited into places $SN(i-1)\_Layer(j)$ and $SN(i+1)\_Layer(j)$, respectively. If the jth data of the $(i-1)$th ($(i+1)$th) node is available at the ith node and is not available at the sink node, the number $\#SN(i-1)L(j)$ ($\#SN(i+1)L(j)$) is equal to one; otherwise, it is zero.

4.5. Interesting measures

In order to assess the functionality of the MWSNs, we define some reward functions in the proposed SRN models. The expected cumulative rewards can be computed as $\sum_i \rho_i \times \pi_i$, where ρ_i is a reward assigned to marking i of the SRN model and π_i is the probability of being in marking i in the steady state [2,3]. The interesting measures in the proposed SRN models are as follows:

- **Average status of the battery of each mobile node ($AB\_Node(i)$).** As mentioned earlier, the battery of each mobile node can be in three statuses, such as low, medium, and high. Since the number of tokens inside place $Battery\_N(i)$ represents three statuses of the battery of the ith mobile node, we compute the measure $AB\_Node(i)$ by defining reward function in Eq. (3):

$$AB\_Node(i) = \sum_{k=1}^{3} \pi(mark(Battery\_N(i)) == k) \times k. \tag{3}$$

- **Availability of environment data at each mobile node ($AD(j)\_Node(i)$).** As mentioned earlier, the geographic environment consists of the L layers and each layer except the layer zero has data that should be collected by mobile nodes.Furthermore, the data collected by each mobile node are expired after a while. Since the number of tokens inside place $N(i)\_Layer(j)$ represents the existence of the jth data in the ith node, we compute the measure $AD(j)\_Node(i)$ by defining reward function in Eq. (4):

$$AD(j)\_Node(i) = \pi(mark(N(i)\_Layer(j)) == 1) + \pi(mark(N(i)\_Layer(j)) == 2). \tag{4}$$

- **Availability of environment data at the sink node $AN(i)D(j)\_Sink$).** As mentioned earlier, the sink node is in the layer zero and receives data collected by mobile nodes. Furthermore, the data received by the sink node are expired after a while. Since the number of tokens inside place $SN(i)\_Layer(j)$ represents the existence of the jth data of the ith node in the sink node, we compute the measure $AN(i)D(j)\_Sink$ by defining reward function in Eq. (5):

$$AN(i)D(j)\_Sink = \pi(mark(SN(i)\_Layer(j)) == 1). \tag{5}$$

5. Numerical results

In this section, the results obtained by numerically solving the proposed SRN models in the steady state using the SPNP tool [8] are discussed in three parts. In Section 5.1, we compare the results obtained from six different environmental conditions regardless of the communication between mobile nodes. In Section 5.2, the results of the previous sub-section are compared against the results that consider communication between mobile nodes. In Section 5.3, new movement conditions are defined and the results of the previous subsections, following the same movement conditions, are compared to the results of new movement conditions.

5.1. Comparison of different environmental conditions

Herein, we define six different environmental conditions and evaluate their impact on interesting measures. These conditions are listed below:

- **Suitable.** The environmental conditions are always suitable;
- **Moderate.** The environmental conditions are always moderate;
- **Unsuitable.** The environmental conditions are always unsuitable;

- $\boldsymbol{\alpha = \beta}$. The occurrence rates of suitable and unsuitable environmental conditions are equal;
- $\boldsymbol{\alpha = 2 \times \beta}$. The occurrence rate of suitable environmental conditions is twice that of unsuitable environmental conditions;
- $\boldsymbol{\alpha = \frac{1}{2} \times \beta}$. The occurrence rate of suitable environmental conditions is half that of unsuitable environmental conditions.

Table 6 provides the value of input parameters used in all of the following experiments. Furthermore, Table 7 represents the results obtained from the proposed SRN models in different environmental conditions regardless of the communication between mobile nodes.

As can be seen in Table 7, the environmental conditions can affect the battery status and availability of environmental data at each mobile node. In suitable environmental conditions, the battery of mobile nodes is lower, making them more active. This makes it less likely that the data collected by the mobile nodes will expire, because the nodes arrive at the desired layers in time. Furthermore, the sink node receives more data from mobile nodes in suitable environmental conditions. The opposite of the above is true for unsuitable environmental conditions.

As can be seen in Table 7, the data of middle layers is more up-to-date at mobile nodes, because the nodes reach those layers in a shorter amount of time. However, the data of the first layers are more up-to-date at the sink node, because they are sent to the sink sooner after collection.

5.2. Comparison of different communication conditions

The previous section evaluates the impact of six different environmental conditions on the system functionality without considering the communication between mobile nodes. In this section, the results in the previous section are compared to those that consider communication between mobile nodes. Table 8 represents the results obtained from the proposed SRN models in different environmental conditions considering the communication between mobile nodes.

As can be seen in Tables 7 and 8, since the

Table 6. Input parameters of the proposed SRN models.

Parameter	Value
Number of layers (L)	5
Rate of changing conditions from suitable to unsuitable (α)	Conditional
Rate of changing conditions from unsuitable to suitable (β)	1 event/h
Rate of changing status of the battery of each mobile node (ω)	4 event/h
Movement rate of each mobile node (μ)	10 layer/h
Sending rate of data (θ)	100 data/h
Expiration rate of data (π)	2 data/h

Table 7. Results obtained from different environmental conditions regardless of the communication between mobile nodes.

Node	Environmental conditions	Availability of environmental data					Battery status
		Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	
Mobile	Suitable	0.62	0.68	0.68	0.62	0.48	2.61
	Moderate	0.60	0.66	0.66	0.60	0.46	2.42
	Unsuitable	0	0	0	0	0	1
	$\alpha = \beta$	0.51	0.57	0.57	0.51	0.37	2.08
	$\alpha = 2 \times \beta$	0.58	0.64	0.64	0.58	0.44	2.38
	$\alpha = \frac{1}{2} \times \beta$	0.43	0.48	0.48	0.43	0.30	1.73
Sink	Suitable	0.41	0.34	0.29	0.24	0.20	—
	Moderate	0.39	0.32	0.26	0.22	0.18	—
	Unsuitable	0	0	0	0	0	—
	$\alpha = \beta$	0.30	0.24	0.20	0.16	0.13	—
	$\alpha = 2 \times \beta$	0.37	0.30	0.25	0.21	0.17	—
	$\alpha = \frac{1}{2} \times \beta$	0.22	0.17	0.13	0.10	0.08	—

Table 8. Results obtained from different environmental conditions considering the communication between mobile nodes.

Node	Environmental conditions	Availability of environmental data					Battery status
		Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	
Mobile	Suitable	0.61	0.68	0.68	0.61	0.47	2.51
	Moderate	0.58	0.65	0.65	0.58	0.44	2.30
	Unsuitable	0	0	0	0	0	1
	$\alpha = \beta$	0.50	0.55	0.55	0.50	0.36	1.98
	$\alpha = 2 \times \beta$	0.57	0.63	0.63	0.57	0.42	2.27
	$\alpha = \frac{1}{2} \times \beta$	0.42	0.46	0.46	0.42	0.28	1.65
Sink	Suitable	0.45	0.39	0.34	0.28	0.24	—
	Moderate	0.41	0.36	0.31	0.25	0.21	—
	Unsuitable	0	0	0	0	0	—
	$\alpha = \beta$	0.31	0.27	0.23	0.18	0.15	—
	$\alpha = 2 \times \beta$	0.39	0.34	0.29	0.24	0.20	—
	$\alpha = \frac{1}{2} \times \beta$	0.22	0.19	0.15	0.12	0.09	—

Table 9. Results obtained from different environmental and communication conditions in new movement conditions.

Node	Environmental conditions	Availability of environmental data										Battery status	
		Layer 1		Layer 2		Layer 3		Layer 4		Layer 5			
		No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Mobile	Suitable	0.72	0.71	0.77	0.76	0.77	0.76	0.72	0.71	0.60	0.59	2.26	2.18
	Moderate	0.67	0.66	0.73	0.71	0.73	0.71	0.67	0.66	0.55	0.54	2	1.92
	Unsuitable	0	0	0	0	0	0	0	0	0	0	1	1
	$\alpha = \beta$	0.57	0.55	0.61	0.60	0.61	0.60	0.57	0.55	0.45	0.44	1.76	1.71
	$\alpha = 2 \times \beta$	0.66	0.64	0.71	0.70	0.71	0.70	0.66	0.64	0.54	0.53	2.02	1.95
	$\alpha = \frac{1}{2} \times \beta$	0.46	0.45	0.50	0.49	0.50	0.49	0.46	0.45	0.34	0.33	1.48	1.44
Sink	Suitable	0.51	0.56	0.47	0.53	0.42	0.49	0.39	0.45	0.35	0.41	—	—
	Moderate	0.45	0.49	0.41	0.46	0.37	0.42	0.33	0.38	0.29	0.34	—	—
	Unsuitable	0	0	0	0	0	0	0	0	0	0	—	—
	$\alpha = \beta$	0.34	0.38	0.31	0.35	0.27	0.32	0.24	0.28	0.21	0.25	—	—
	$\alpha = 2 \times \beta$	0.44	0.48	0.40	0.45	0.36	0.41	0.32	0.37	0.29	0.33	—	—
	$\alpha = \frac{1}{2} \times \beta$	0.24	0.26	0.20	0.23	0.18	0.21	0.15	0.18	0.13	0.15	—	—

communication between mobile nodes increases their power consumption, the battery of mobile nodes is not that high, thus making them less active. This makes it more likely that the data collected by the mobile nodes will expire, because the nodes do not arrive at the desired layers in time. However, the data of the sink node in Table 8 is more up to date when compared with those shown in Table 7, because the mobile nodes send their data to others. The results of Tables 7 and 8 demonstrate that compared to the communication conditions, the environmental conditions have a greater impact on system functionality and availability of data, because the communication between nodes increases power consumption.

5.3. Comparison of different movement conditions

In this section, the movement rate (μ) of mobile nodes is doubled and if a mobile node communicates with others, its battery is consumed with the rate $(2 \times \omega + 1)$; otherwise, it is consumed with the rate $2 \times \omega$. Table 9 shows the results obtained from different environmental and communication conditions in new movement conditions. In Table 9, the columns labeled with "No" represent the situations where there is no communication between mobile nodes, and inversely, columns labeled with "Yes" stand for the situations in which mobile nodes communicate to each other.

Although power consumption is doubled by doubling the movement rate, the results of Tables 7, 8, and 9 demonstrate that the availability of environmental data at each mobile node increases with increasing the movement rate in different environmental and communication conditions. Furthermore, the data of the sink node in Table 9 are more up to date than those shown in Tables 7 and 8. For example, in Table 7, where the movement rate is μ and there is no communication between nodes, the availability of environmental data of the sink node in Layer 1 in suitable environment conditions is equal to 0.41; however, in Table 8, where the movement rate is μ and there is a communication between nodes, it is equal to 0.45. However, in Table 9, where the movement rate is $2\times\mu$, these results are equal to 0.51 and 0.56, respectively.

The results of Tables 7, 8, and 9 show that the environmental and movement conditions, compared to the communication conditions, have a greater impact on system functionality and data availability.

6. Conclusions and future work

This study presented analytical SRN models to analyze the impact of different environmental, communication, and movement conditions on the functionality of mobile wireless sensor networks. In previously done research, the impacts of all of these conditions had not been simultaneously evaluated in the MWSNs. In the proposed models, the mobile nodes move around to collect data and, then, send it to the sink node. They use the battery as the power source that can be charged according to environmental conditions. The data 9 of the sink and mobile nodes expires after a while and needs to be constantly updated. The results obtained from numerically solving the proposed models demonstrated that the environmental and movement conditions had a greater impact on system functionality and availability of data, compared to the communication conditions.

The routing algorithms and communication between nodes were the most important factors influencing the MWSNs. In this context, the communication constraints, such as the malfunction and noise, can be considered in the communication. Furthermore, the random movement of mobile nodes can be considered in these systems. As a future work, one can model and evaluate the impact of these factors on the power consumption, lifetime, and system functionality. Furthermore, the impact of other factors, e.g., heterogeneity of nodes and different levels of failures, can be modeled and analyzed using SRNs in the MWSNs. In other words, the impact of these factors on other aspects of MWSNs like reliability, availability, and dependability can be assessed in the future.

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