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Generalized Stochastic Petri Nets Modelling for Energy Harvesting WSNs considering Neighbors with different Vicinity Levels

OUKAS Nourredine
Department of Computer Science
Normal Superior School Kouba, Algiers, Algeria.
LIMOSE laboratory.
M'Hamed Bougara University of Boumerdes.
Independence Avenue, 35000, Boumerdes, Algeria.
oukas@ens-kouba.dz

BOULIF Menouar
Department of Computer Science
M'Hamed Bougara University of Boumerdes
Independence Avenue, 35000, Boumerdes, Algeria
boumen7@gmail.com

***Abstract*—In this paper, we use Generalized Stochastic Petri Nets (GSPN) formalism to model the communication between an SN and its neighbors in wireless sensor networks (WSN). This modelling considers several actual considerations such as sensor vacations and retrial calls phenomenon. Furthermore, given that sensor nodes (SN) consume almost all their energy in the transmission process that varies according to the distance of the neighbors, our model considers different levels of vicinity for communicating neighbors. Our study proves that our modelling, which provides a more realistic approach to describe the actual behavior of the WSN, can identify the input parameter scenario to have a network with a good compromise between longevity and performance.**

***Index Terms*—Wireless sensor network, GSPN, energy harvesting, energy consumption, retrial call, sensor vacation.**

I. INTRODUCTION

A wireless sensor network (WSN) is a large set of small interconnected devices named sensor nodes (SNs). SNs can detect events pertaining to several phenomenon such as temperature, humidity, pressure, speed, acceleration, etc. and send messages that report these events through a wireless communication network. WSNs have various applications, such as agriculture, ambient monitoring, health, construction industry, smart cities, military applications and many others [1], [2].

SNs are powered by batteries with limited energy capacity. Hence, the lifetime of SNs and network operability strongly depends on the battery lifetime. Depending on the type of their duty, SNs may not be easily accessible. A relatively modern solution consists of equipping SNs with harvesters to get energy from the environment (sun, wind, heat, pressure and others) and converting it to electrical energy [3]. Using ambient energy sources and transforming it to an electrical energy by SNs is called energy-harvesting [2], [4], [5] and wireless networks equipped with such SNs are called energy harvesting wireless sensor networks (EH-WSN) [6]–[9].

The recovered energy can be directly used by the components of the SN or accumulated and stored in a rechargeable battery by a DC-DC converter (see Fig.1) which is an electronic circuit or electro-mechanical device that converts a source of direct current (DC) from one voltage level to another [10].

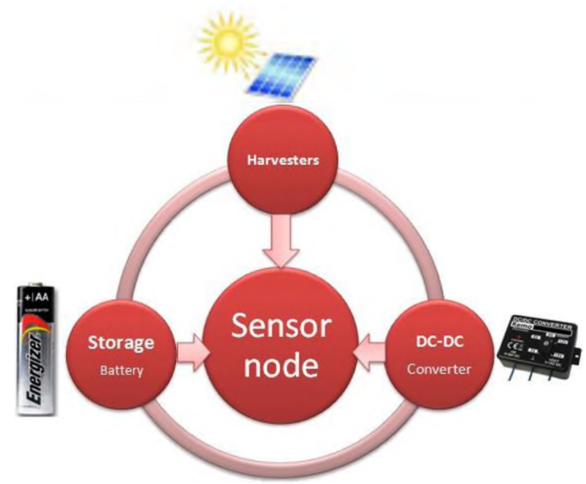

Fig. 1. SN with energy harvesting capability.

SNs consume almost up to 90% of their overall energy in the transmission process [11]. By considering sensor-neighbors relationship, the amount of energy consumed by the sending of a message depends on the degree of proximity of the neighbor. This consideration is, to the best of our knowledge, neglected by the literature. In this paper, we propose a GSPN modelling to address this shortcoming by considering different levels of vicinity of the neighbors. Particularly, our neighbor vicinity aware modelling uses the sleeping mechanism technique to configure the SNs in a way that decreases the consumption of energy. In addition to this consideration, our modelling takes into account several circumstances that are schematized in Fig. 2

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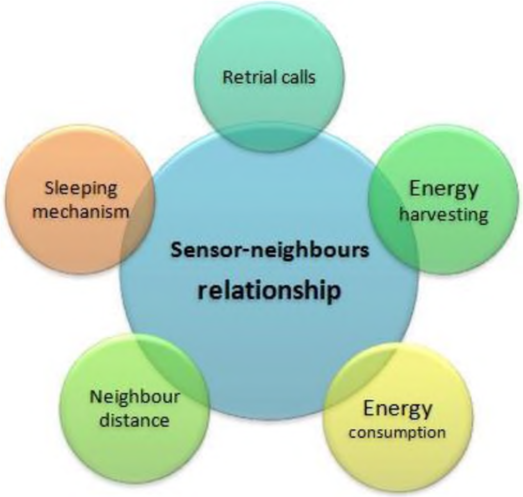


Fig. 2. Considered circumstances in the proposed model

The rest of this paper is organized as follows: In section 2, we present some related works. In the next section, we give a short description of the GSPN modelling tool. In section 4, we construct a GSPN model for EH-WSN. In the next section, we show and discuss some possible scenarios. Finally, we draw our conclusion as well as some directions for future works.

II. Related works

Using GSPN for WSN modelling allows to consider several phenomenon. In [12], the authors introduced the sleeping mechanism. They proposed a model based on the GSPN formalism to predict the energy consumption. Sleeping mechanism is also used in [13].

In [14], the author develops a Petri nets model to evaluate the energy consumption of an SN. The model considers critical components of a sensor node, including processors with emerging energy-saving features, wireless communication components, and an open or closed workload generator. Boutoumi and Gharbi [15] considered normal vacation and working vacation policy, that they called the two thresholds working vacation policy. They propose the modelling and the performance analysis of the system using the GSPN formalism. Gharbi and Charabi [16] propose an algorithmic approach based on GSPN for modelling and analyzing finite-source wireless networks with retrial phenomenon and two server classes. The retrial calls phenomenon is considered in [17] too where the authors model and analyses the radio frequency transmission in WSNs by using a GSPN.

Retrial call phenomenon, server vacations, breakdowns and repairs are combined in [18]. The authors used a GSPN formulation to model the effect of the communication traffic in a WSN with energy harvesting capability on the battery energy level. In [19], the authors took into account the effect of the energy recovery and energy consumption to model the battery of an SN. In [20] the authors introduced message losses, retrial Calls and sensor vacation phenomenon together to develop a GSPN model for EH-WSNs. In this paper we use the GSPN formalism to address the energy consumption by considering three distinct neighbor distances. We consider also retrial calls and sleeping mechanism. Such model allows to adjust input parameters to determine the values that ensure the longevity of a good performing network.

III. GSPN tool

Generalized Stochastic Petri Nets are a powerful tool for modelling and evaluating the performance of systems involving concurrency, non-determinism and synchronization, such as parallel and distributed computer architectures and communication networks [21], [22].

A Petri net is a triple N = (P, T, W) where P and T are disjoint sets of places and transitions, with $W: (P \times T) \cup (T \times P) \rightarrow N$; defines the weighted flow relation. A Petri net can be viewed as a bipartite weighted graph, hence several graph concepts can be extended to them. In the graphical presentation of a GSPN (see Fig.3), places are represented by circles. Usually, a place contains a number that represents the number of tokens. There is three types of arcs: input arcs, output arcs and inhibitor arcs. An inhibitor is also an input arc with the particularity that it forbids the firing of the associated transition.

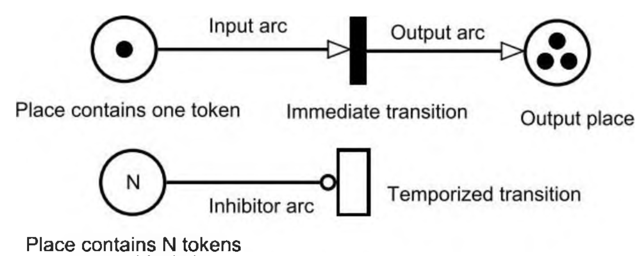


Fig. 3. GSPN graphical elements.

Furthermore, transitions are classed into two types: temporized transitions which need an amount of time to fire and immediate transitions. For each timed transition is associated a firing rate. If for all timed transitions an exponential random law is associated to represent the firing delay, the GSPN is called Markovian and the firing rates of transitions are linked to the underlying Markovian approach [23]. GSPNs have been proven to be equivalent to Continuous Time Markov Chains (CTMC) and their steady state analysis can thus be expressed as the solution of a system of equilibrium equations, one for each possible marking of their reachability set [21].

The firing of a transition needs a number of tokens in the input place equal to the weight of the input arc. As a result, a number of marks is added to the output place equal to the weight of the output arc.

In general, places can represent resources, the number of marks in a place being the number of copies of this resource. Transitions can represent actions, the firing of a transition corresponding to the realization of this action. After the construction of a Petri net, two kinds of analysis can be conducted on it. Qualitative analysis that covers liveliness, boundedness, strong connectivity, ergodicity and others. Quantitative analysis is achieved after the qualitative analysis and consists of calculating the performance parameters after solving the net in the stationary state. After deriving the reachability marking graph, the solution of the net in the equilibrium state provides the vector of stationary probability denoted π. Hence, several performance parameter laws are defined and proved [21 – 24] such as:

- The mean number of marks in a place P :

$$\bar{p} = \sum_{i:Mi\in M} M_i(p) * \pi_i \quad (1)$$

- The probability of an event A denoted *prob (A):*

$$Prob(A) = \sum_{i:Mi\in M} \pi_i \quad (2)$$

where M_i satisfies A.

- The mean throughput of a transition T with rate α denoted $\bar{\alpha}$:

$$\bar{\alpha} = \alpha * Prob(|P| > 0) \quad (3)$$

where $|P|$ is the number of tokens in the input place P of the transition T .

- The mean sojourn time in a place P denoted *wait(P)*:

  Let P be the input place of the timed transition T and $\bar{\alpha}$ its mean throughput. Then,

$$wait(P) = \frac{1}{\bar{\alpha}} \sum_{i:Mi\in M} M_i(p) * \pi_i \quad (4)$$

IV. Proposed Model

Fig.4 shows the proposed GSPN. When a message arrives, the main sensor attempts to send it to an idle neighbor. We suppose that there are three levels of vicinity: near neighbors, medium neighbors and far neighbors. Firstly, the main sensor tries to send the message to a near neighbor. If there isn't any, it searches for a medium distance neighbor then if it fails, it tries to reach a far neighbor. This sorting is enforced by the priority values of immediate transitions: *Near_start, Medium _start and* Far*_start presented* in Table III. If there is no neighbor at all, the message joins the orbit for further call attempts.

Green colored places: *Near_neighbours*, *Medium_neighbours* and Far_ *neighbours* with initial marking s1, s2 and s3 respectively represent near, medium and far neighbours. Thus, yellow colored places *Near_Msgs*, Medium_*Msgs* and *Far_Msgs* contain messages that have to be sent to near, medium and far neighbours respectively. The firing of red coloured transitions represents a successful sending of a message. Concerning the energy considerations, the presence of a rechargeable battery is represented by the place *Battery*.

That initially contains C quantum of energy. The number of quantum increases when the transition *Harvesting* fires and it decreases when the main sensor is activated. We suppose that the sending of a message to a near, medium and far neighbors consumes 1, 2 and 3 quantum respectively. Table I describes the places of our model. All timed transitions are described in Table II whereas all the immediate transitions are described in Table III.

Notice that we removed some inhibitor arcs from the model presentation in the Fig.4 in order to enhance clarity. These inhibitors are described as follows:

- An inhibitor arc from *Standby* place to each red colored transition.
- An inhibitor arc from *Standby* place to each immediate transition except *Refuse_recept.*

TABLE I: TIMED TRANSITIONS DESCRIPTION

Name	Signification	Rate
Arrival	Arrival of a message	λ
Send_Near	Successful sending to a near neighbour	$\mu1$
Send_Medium	Successful sending to a medium neighbour	$\mu2$
Send_Far	Successful sending to a far neighbour	$\mu3$
Retrial	Repeated call of a message	ν
Harvesting	Energy recovery	ω
Working	Working energy consumption	γ
Go_sleep	The main sensor joins the sleeping state	α
Be_awake	Activation of the main sensor	δ

TABLE II: IMMEDIATE TRANSITIONS DESCRIPTION

Immédiate transition	Signification	Priority
Near_start	starts sending to a near neighbor	3
Medium_start	starts sending to a medium neighbor	2
Far_start	starts sending to a far neighbor	1
Refuse_recept	message joins the orbit	1

V. Practical Scenarios Analysis

For the following analysis, we use rate values described in Table IV and $(N, C, l, s1, s2, s3) = (10, 25, 10, 2, 2, 2)$.

TABLE III: PLACES DESCRIPTION

Place name	description	initial
Msgs	Source of messages	N
Attempt	message sending attempt	0
Orbit	message waits for an idle neighbor	0
Near_Neighbors	Contains near neighbors	$s1$
Medium_Neighb	Contains medium range neighbors	$s2$
Far_Neighbors	Contains far neighbors	$s3$
Near_Msgs	Contains messages to be sent to a near neighbor	0
Medium_Msgs	Contains messages to be sent to a medium range neighbor	0
Far_Msgs	Contains messages to be sent to a far neighbor	0
Battery	A token in the Battery represents a quantum of energy	C
Standby	main SN is in sleeping sate	0

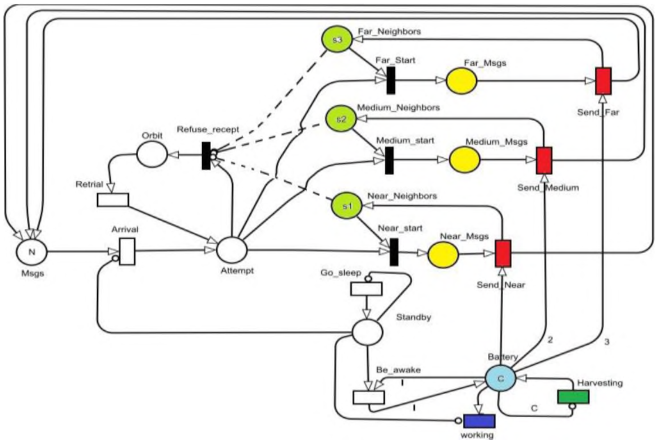


Fig. 4. GSPN model with three types of neighbors for EH-WSN

TABLE IV: INPUT RATE VALUES

Symbol	Signification	Value
λ	Arrival rate	15
v	Retrial rate	10
$\mu 1$	Near send rate	20
$\mu 2$	Medium sending rate	15
$\mu 3$	Far sending rate	10
ω	Harvesting rate	50
γ	Working rate	10
α	Sleeping rate	10
δ	Awake rate	5

A. The mean response time versus the retrial rate

Fig. 5 represents the mean near response time, the mean medium response time, the mean far response time and the global mean response time versus the retrial rate. It is clear from the figure that all mean response time decreases when the retrial rate increases. A big value of retrial rate interdicts messages to stay a large interval of time in the orbit.

Fig. 5. The mean response time versus the retrial rate.

A. mean response time versus sleeping rate

Fig. 6 represents the mean response time versus the sleeping rate. We note that the mean near response time has the smallest values followed by the mean medium response time. The mean far response time has the highest values. The mean response time (with orange color) represents the global state. All mean responses time decreases when the sleeping rate increases. Because when the main sensor is activated in the most interval of time, it serves messages as soon as they are received.

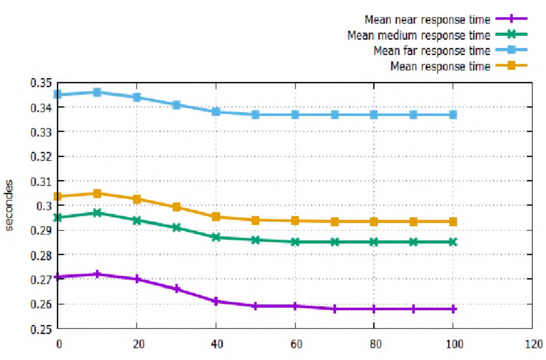


Fig. 6. The mean response time versus the sleeping rate.

B. The mean battery charge versus the harvesting rate

Fig. 7 shows the influence of harvesting rate on the mean battery charge. The mean battery charge increases when the harvesting rate increases. This results are logical and coincides with the actuality. The mean battery charge stabilises near the value of 90% when the harvesting rate value is greater than 60. For example, the energy harvested by a solar panel in the summer is more important when compared with the energy recovered in winter.

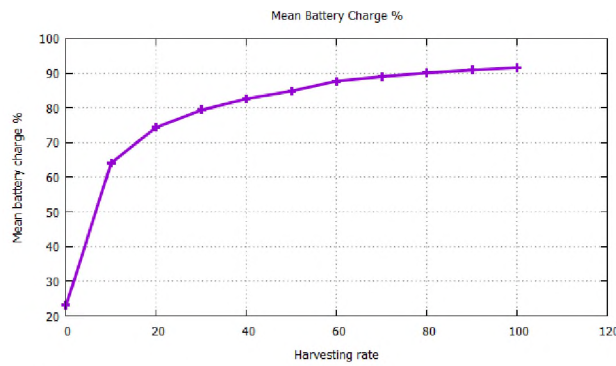
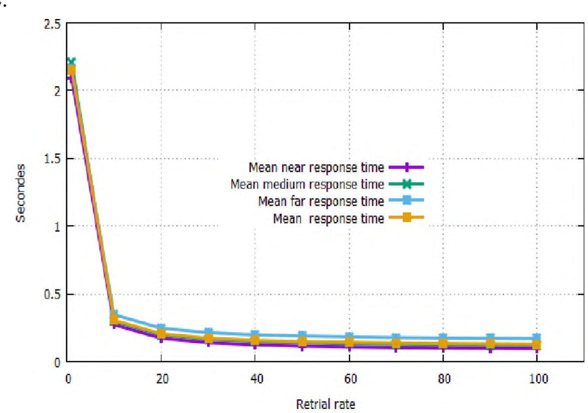


Fig. 7. Mean battery charge versus harvesting rate.

C. mean battery charge versus sleeping rate

Fig. 8 shows the influence of sleeping rate on the mean battery charge. The mean battery charge enhances when the sleeping rate enhances. The SN conserves more energy when it is in the sleeping state.



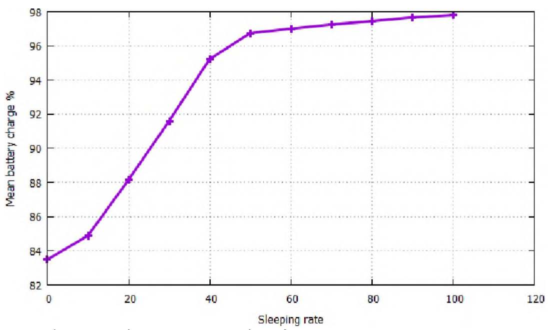


Fig. 8. Mean battery charge versus sleeping rate.

VI. CONCLUSION

In this paper we proposed a GSPN model for EH-WSNs that considers different levels of vicinity to communicate with neighbors. We conducted experimental analysis by using different scenarios proving that our model provide a medium to adjust input values to have the desirable behavior of the network before its actual deployment. In our future work, we want to tackle the case where the modelling is aware of the presence of different types of messages with different energy requirement handling costs.

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