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A New Generalised Stochastic Petri Nets Modelling for Solar Energy Harvesting Sensors in Long Lasting WSNs, Considering Seasonal Sunshine Levels

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Abstract. In this paper, we propose a Generalised Stochastic Petri Net (GSPN) to model the sensor nodes (SNs) interaction in solar Energy Harvesting Wireless Sensor Networks (EHWSNs). Our GSPN formalism models the energy stored in the SN battery by using the quantization principle and takes into account the fact that the EHWSNs deployment territory is susceptible to different sunshine levels. Furthermore, each SN uses the sleeping mechanism to save its energy. The conducted experimental analysis shows that the model is able to predict the parameters of the SNs that insure a long lasting EHWSN.

Keywords and phrases: wireless sensor networks, GSPN modelling, solar energy harvesting, quantization, sunshine levels, sleeping mechanism.

1 Introduction

Wireless sensor networks (WSNs) consist of a number of sensor nodes deployed on a given area to perform a variety of tasks such as sensing data, reporting events, doing simple computation, processing, and communication. WSNs are used in many applications such as: battlefield surveillance, weather monitoring, health monitoring, vehicle tracking, environment monitoring, border surveillance, to cite only a few [1]. The architecture of a WSN typically consists of various scattered sensor nodes, a base station (or sink), external network and end-user. The need of a base station in WSNs is essentially due to the limited power and computing capacity of the sensors [2]. Figure 1 illustrates such a typical WSN architecture.

Commonly, WSNs are deployed in regions that are difficult to access. Therefore, SNs must be energetically autonomous and they must not need to be renewed even if they work for a life-long operation [2]. Several possible solutions to address the problems stemming from these requirements have been suggested like:

- Reducing the power consumption in different levels of the sensor nodes hierarchy.
- Developing energy harvesting techniques that enable an SN to recharge its battery by harvesting energy from its surroundings [3, 4, 5].

Energy harvesting (EH) refers to the ability of collecting renewable energy from the

surrounding area such as sun, wind, body heat, finger strokes, foot strikes or any other source of energy and converting it to electrical energy to power the nodes and increase their lifetime.

Further more, energy harvesting provides numerous benefits to the end user. EH technology can [2]:

1. Reduce the dependency on battery power because harvested ambient/environmental energy may be sufficient to eliminate battery.
2. Reduce maintenance cost by eliminating service visits to replace batteries.
3. Provide long-term solutions. A reliable self-powered sensor node will remain functional virtually as long as the ambient energy is available. Self-powered sensor nodes are perfectly suited for long-term applications looking at decades of monitoring.

Among the environmental renewable energy sources, solar energy is the most suitable for WSNs. Indeed, solar energy is relatively more predictable and it has a higher power density in comparison to other renewable energy sources. Solar energy amount is about $15mW/cm^3$ in direct sun, $150\mu w/cm^3$ outdoor but cloudy day and $6\mu w/cm^3$ indoor [6, 7]. Each SN supervises its local environment, collects data, and share them via a wireless connection. Figure 2 illustrates a standard architecture of an SN equipped with solar energy harvesting system (EHS). EHS consists of a solar panel, a DC-DC converter, rechargeable batteries and a battery charge protection circuit called power management unit [8, 1, 9].

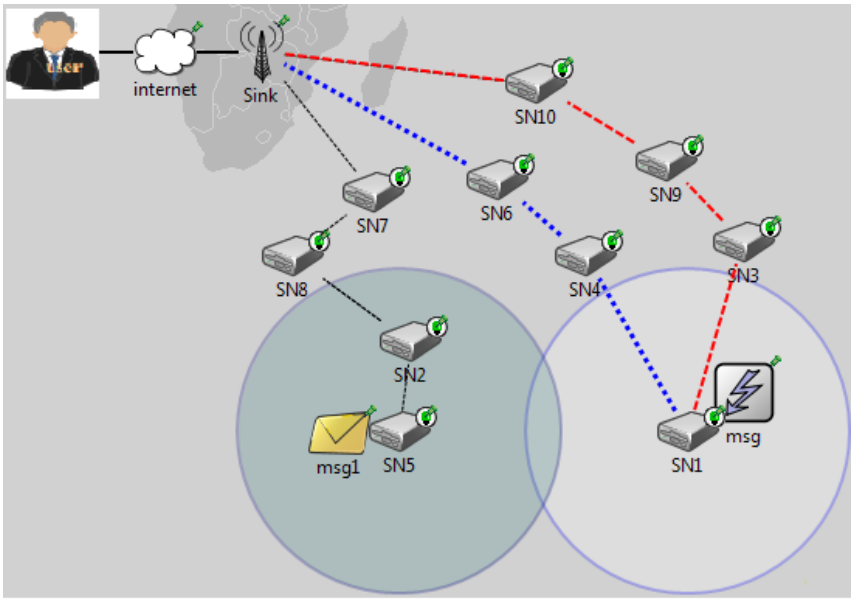

Figure 1: A typical architecture of a WSN.

To evaluate network performances, instead of simulation, we can resort to modelling with mathematical formalism such as Markov chain, queueing systems and Petri nets. Petri nets are a graph tool suitable for modelling dynamic and parallel systems that have been extensively used to model and analyse WSNs behaviour. For example, we have the work of Oukas and Boulif [10] that considers several actual WSN features such as sleeping mechanism, retrial calls, energy harvesting. They propose a model to predict the behaviour of the network. Patrick Wuchner et al. introduced a GSPN model with unreliable orbit [11] to evaluate the performance of WSNs. The Authors also consider the sleeping mechanism and present an analysis that shows the influence of the sleep/awake ratio on the SNs mean response time. In [12], Oukas and Boulif proposed a GSPN modelling that considers different types of neighbours according

to their distances from the sensor. In [13], the same authors presented another GSPN to address the case where the network is divided into clusters and each cluster has two leaders. A coloured GSPN is proposed in [14] to address the differences between messages. The authors conducted an experimental analysis to show the impact of this phenomenon on the performance of the EHWSNs. Boutoumi and Gharbi proposed [15] the two thresholds working vacation policy which is an energy saving and latency efficiency approach constructed over a GSPN model for full-duplex WSNs.

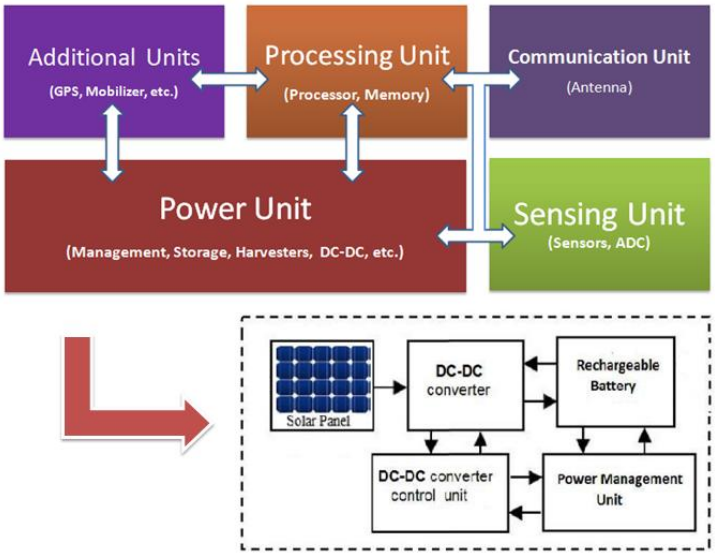

Figure 2: A typical architecture of an EH capable SN.

In [9] Oukas and Boulif proposed a GSPN formulation to model energy harvesting and energy consumption in an SN. They represented the sensor battery energy by quantum and besides the quantization principle, they considered the sleeping mechanism to conserve energy.

In many application scenarios, the lifetime of the sensor node typically ranges from two to ten years depending on the requirement of the specific application. Take for example the case of deploying sensor nodes on remote icy mountains to detect the thickness level of the ice. It will take years for the melting process to be measurable. Hence the lifetime of the sensor nodes has to last for several years before they go into idle state. If that is the case, the lifetime of one or several sensor nodes, depending on the size of the WSN, would affect the performance of the WSN [2].

Deploying a long lasting EHWSN must take into consideration the influence of the seasons on the performance of the network. However, to the best of our knowledge, this has so far been neglected in the related published works.

In this paper we present a new GSPN modelling that takes into account the differences in the seasonal EH rates due to the disparity of sunshine levels.

The rest of this paper is organised as follows: In section 2, we present a short description of the GSPN formalism. In section 3, we explain the proposed GSPN modelling. The next section presents the results of the experimental analysis. Finally, we draw our conclusion as well as some directions for future works.

2 GSPN Formalism

Petri Nets are commonly used for modelling and evaluating the performance of systems involving concurrency, non-determinism and synchronisation, such as parallel and distributed computer architectures and communication networks.

A Petri net is composed of events called transitions, resource containers called places and arcs which link them. Places contain marks (or tokens) that usually represent conditions, resources or products. A GSPN is a special kind of Petri nets. Its transitions can be one of two types: immediate transitions and timed transitions. The transitions of the first type, do not need time to fire, whereas timed transitions need a period of time to fire. For example, in Figure 3, the transition Go_sleep is an immediate transition, whereas the rest are all timed transitions.

In the other hand, an inhibitor arc is a mean to forbid the firing of an event. When a place is linked with a transition by an inhibitor arc, this transition stays inactive until the number of marks in the place becomes lower than the weight of the inhibitor arc. In Figure 3, the transition $Send$ cannot fire if there is a token in the place $Standby$. For further details on GSPNs, we refer the readers to [16, 17].

3 Proposed Model

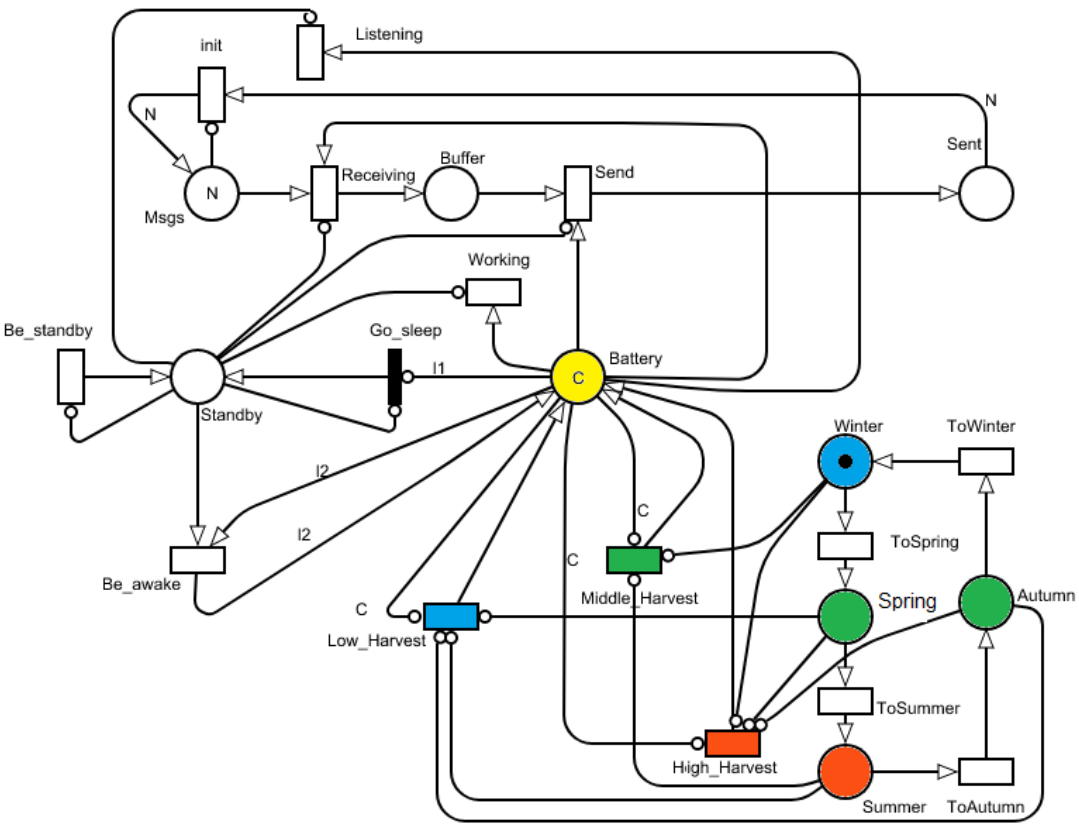

Figure 3: A GSPN model of an SN with various sunshine levels

Figure 3 shows the proposed model and Table 1 gives a description to the associated places. All the transitions are described in the Table 2.

When the SN is activated, it receives messages ($Receiving$ transition), sends messages to its neighbours ($Send$ transition), listens to the network ($Listening$ transition) and, achieves its basic operations ($Working$ transition). To conserve energy, the SN joins the sleeping state periodically by the firing of the transition $Be\_standby$.

Place name	Description	Initial value
Msgs	Source of messages	N
Buffer	The SN buffer	0
Standby	SN standby state	0
Sent	Daily sent messages	0
Battery	SN battery charge	C
Winter	Winter season	1
Spring	Spring season	0
Summer	Summer season	0
Autumn	Autumn season	0

Table 1: Description of model places

In this model, we utilise the quantization principle. In fact, we suppose that the amount of energy stocked in the battery is divided into C levels. Each level or quantum is a small quantity of energy. We suppose that a quantum is sufficient enough to send or receive a message, to listen to the network for a predefined time, and to achieve a basic operation ($working$ transition).

Energy harvesting is modelled by the transitions $Low\_Harvest$, $Middle\_Harvest$ and $High\_Harvest$ which represent three levels of sunshine.

1. The low harvesting level is associated to the winter season.
2. The middle harvesting level concerns both spring and autumn seasons.
3. The high harvesting level concerns the summer season.

Figure 4 and Figure 5 show the mean sunshine time of the Algerian territory in summer and winter. For example, the province of Illizi has a high level of sunshine in summer (greater than 10.8 hours per day) compared with that of winter (under 9.8 hours per day).

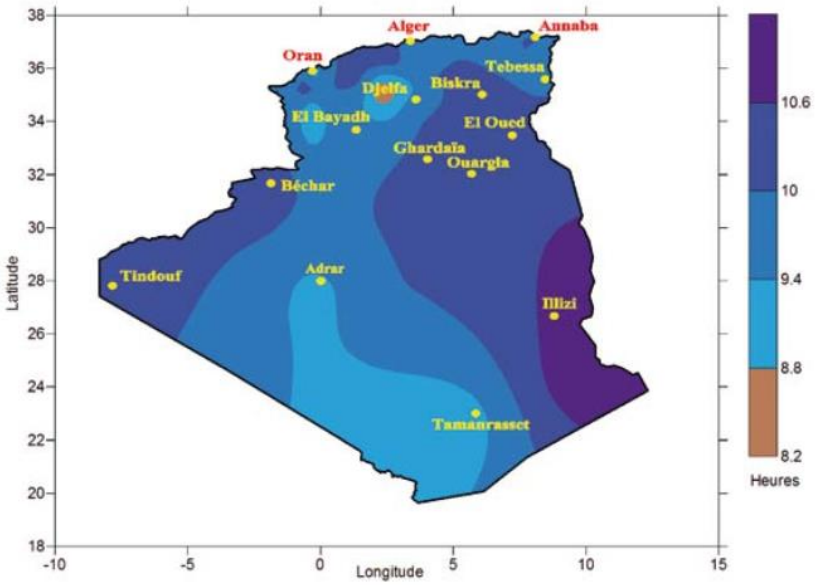

Figure 4: Mean sunshine time of Algerian territory in summer [18]

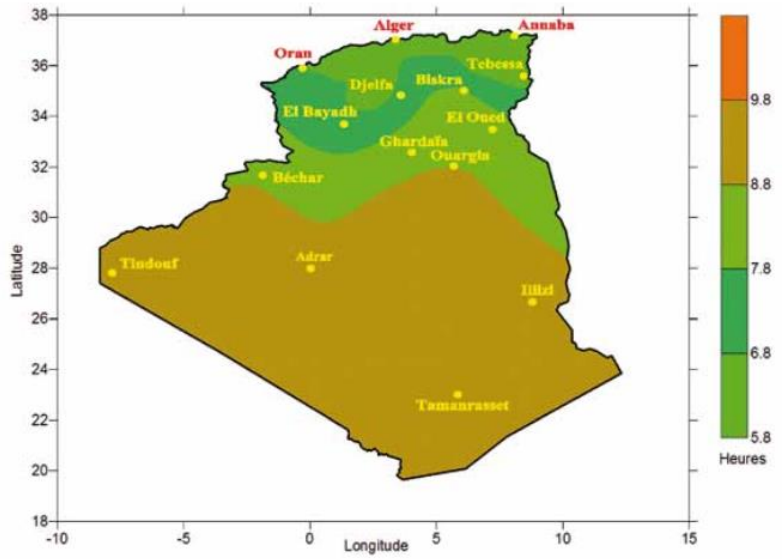

Figure 5: Mean sunshine time of Algerian territory in winter [18]

Notice that the proposed model contains several inhibitor arcs described as follow:

- From the place *Battery* to each harvesting transitions to prevent their firing if the battery is full i.e. the number of quantum is equal to C.
- From $Standby$ to the transitions $Be\_standby, Go\_sleep, Listening, Send$ and *Receiving* to forbid their related events to occur when the SN is sleeping.
- From the places associated to the four seasons *Spring*, *Summer*, *Autumn* and *Winter* to the transitions associated to the level of harvesting $Low\_Harvest, Middle\_Harvest$ and $High\_Harvest$ in order to prevent the firing of an unsuitable EH transition as explained earlier.

We define two thresholds for the sleeping mechanism: $l1$ and $l2$. If the battery energy is lower than $l1$ quanta, the SN joins the standby state immediately by the firing of the transition Go_sleep. The SN awakes by the firing of the transition Be_awake if its energy level is greater than or is equal to the threshold $l2$.

Transition	Signification	Firing rate
Receiving	The SN receives a message	$receive\_r$
Send	Successful message sending	$send\_r$
Working	Working energy consumption	$working\_r$
Listening	The SN listens to the network	$listen\_r$
$Be\_standby$	To the sleeping state	$Sleep\_r$
GO_sleep	Directly on sleeping state	/
Be_awake	The SN becomes active	$awake\_r$
$Low\_Harvest$	Low energy recovery	low_r
$Middle\_Harvest$	Middle energy recovery	$middle\_r$
$High\_Harvest$	High energy recovery	$high\_r$
ToSpring	Spring season comes	$season\_r$
ToSummer	Summer season comes	$season\_r$
ToAutumn	Autumn season comes	$season\_r$
ToWinter	Winter season comes	$season\_r$
Init	New day	$init\_r$

Table 2: Description of the model transitions.

4 Numerical Results

We use the *TimeNet* tool to calculate the performance parameters of the system in the steady state [17]. In Table 3, we define some performance parameters formulas derived from the Little law and others [17, 19] in accordance with the *TimeNet* tool syntax.

Measure	Formula	Signification
$EBattery$	$(\#Battery)$;	Mean battery charge
$Response\_time$	$((\#Buffer))/(receive\_r)$	Mean response time
$TransceiverU$	$(\#Buffer > 0)$	Transceiver utilization

Table 3: Some performance parameter measures.

4.1 Influence of energy harvesting rate on the performance parameters

Herein, we variate the energy harvesting rate to show the behaviour of the network. We obtained the results illustrated in Figure 6.

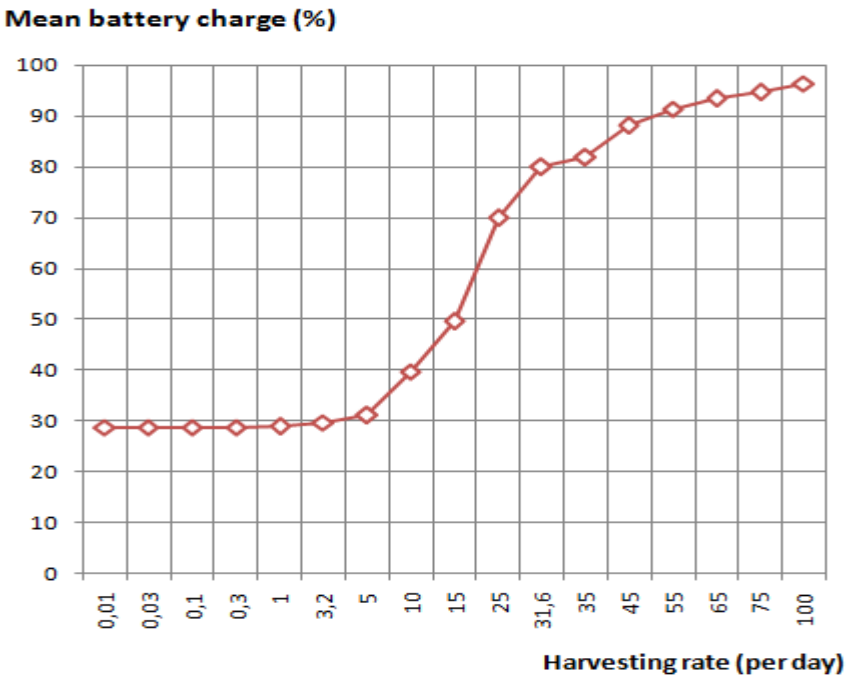

Figure 6: Mean Battery charge versus harvesting rate

Figure 6 shows how the mean battery charge clearly grows when the harvesting rate increases. For the two thresholds $l1$ and $l2$, we used the two values 20% and 40% of the total charge stored in the SN battery in order to bound the the energy level in this interval. We can also realise from the same figure that the mean battery charge stabilises near the value of 30% until the harvesting rate is equal to 5 quantum per day. Next, it starts growing thanks to the big amount of energy harvested in summer season.

Figure 7 illustrates the influence of the harvesting rate on the mean response time. When the energy harvesting rate increases, the mean response time decreases. This is due to the sufficient amount of energy stored in the battery that allows to the SN to promptly achieve its duty. Indeed, the messages are directly sent as soon as they are received, and hence do not need to wait.

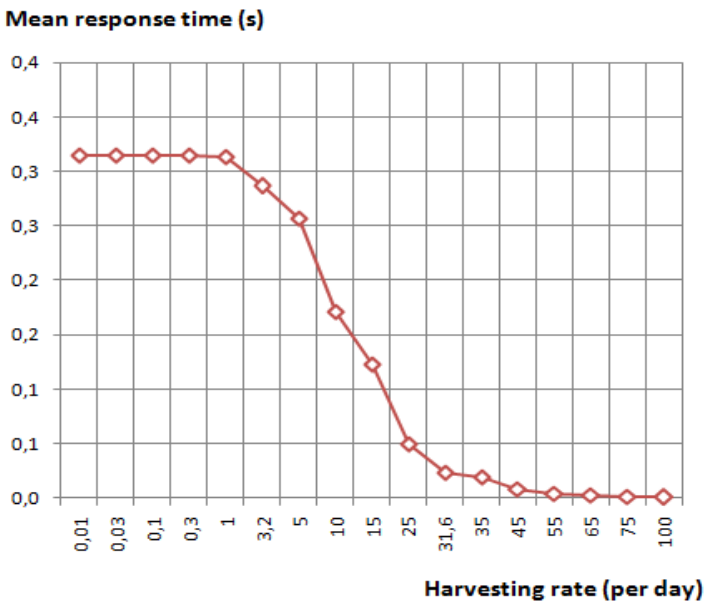

Figure 7: Mean response time versus harvesting rate

4.2 Influence of Sleep/Awake ratio on the performance parameters

By following the same approach, we show the influence of the $Sleep/Awake$ ratio on the performances of the system. The obtained results are as follows:

Figure 8 illustrates the influence of the sleeping mechanism on the mean battery charge. The mean battery charge increases when the SN is sleeping most of the time (i.e. $Sleep/Awake > 1$) which allows to conserve more energy.

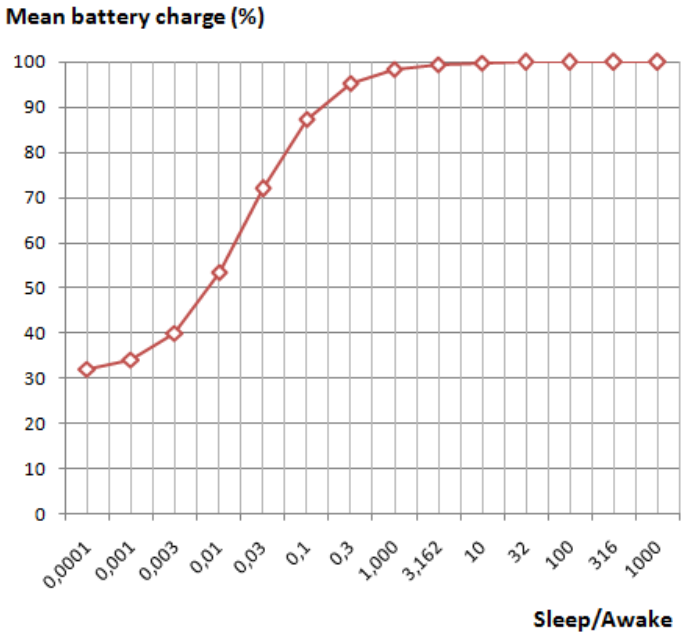

Figure 8: Mean Battery charge versus Sleep/Awake ratio

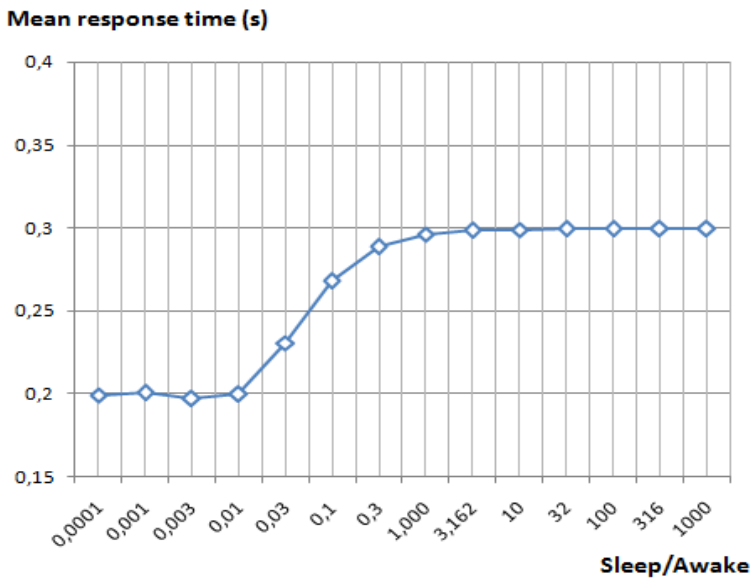

Figure 9: Mean response time versus Sleep/Awake ratio

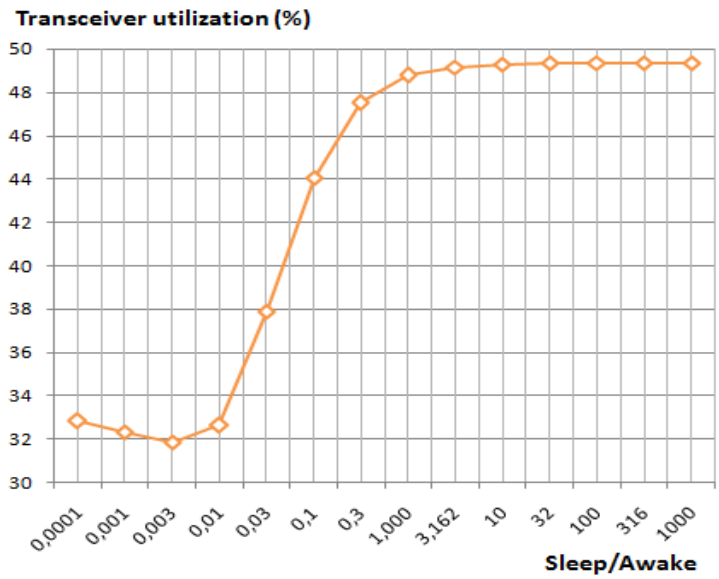

Figure 10: Transceiver utilisation versus Sleep/Awake ratio

As shown in the Figure 9, the mean response time increases when the SN is in the standby state most of the time, because the received messages must wait for a long time until they are sent.

The percentage of utilisation of the communication unit (transceiver) versus the $Sleep/Awake$ ratio rate is shown in Figure 9. We see that the utilisation increases when the SN is in the standby state most of the time, and then it stabilises near the value of 50%.

5 Conclusion and Future Works

In this paper, we proposed a GSPN modelling to analyse the sensor node behaviour in a long lasting EHWSN. This model considers several actual circumstances such as the sleeping mechanism and the energy harvesting with seasonal sunshine levels. We derived various results concerning the daily mean battery charge, the mean system time and, the transceiver utilisation. The conducted experiments show the behaviour of the system in various actual cases which

help WSN deployment decision makers to predict the performances of the network before its actual deployment.

In our future researches, we want to consider other renewable energy sources such as wind, mechanic and thermal.

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