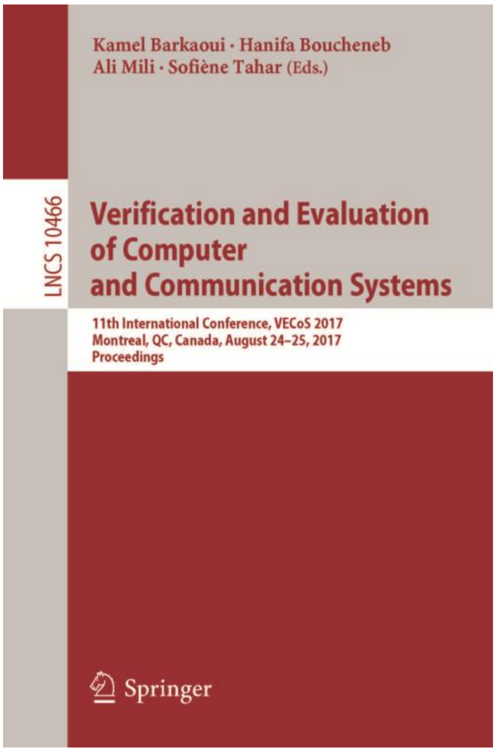

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Abstract. In this paper we model and analyse the radio frequency (RF) transmission in wireless sensor networks using Generalized Stochastic Petri Nets (GSPN). In our model two types of priority requests are considered. In the first type, high priority requests are queued and served according to FIFO discipline. In the second type (case of blocking) low priority requests join the orbit before retrying the request until they find the server free. We consider the preemptive priority to the requests. Indeed, in this study, we highlight the impact of the presence of priority requests on network performances via GSPN formalism. Firstly, we study the case where the high priority requests have non-preemptive priority over lower ones. While, in the second case, we apply the preemptive discipline to the high priority requests. Finally, some numerical examples are given to illustrate our analysis.

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Application of Generalized Stochastic Petri Nets to Performance Modeling of the RF Communication in Sensor Networks

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Abstract. In this paper we model and analyse the radio frequency (RF) transmission in wireless sensor networks using Generalized Stochastic Petri Nets (GSPN). In our model two types of priority requests are considered. In the first type, high priority requests are queued and served according to FIFO discipline. In the second type (case of blocking) low priority requests join the orbit before retrying the request until they find the server free. We consider the preemptive priority to the requests. Indeed, in this study, we highlight the impact of the presence of priority requests on network performances via GSPN formalism. Firstly, we study the case where the high priority requests have non-preemptive priority over lower ones. While, in the second case, we apply the preemptive discipline to the high priority requests. Finally, some numerical examples are given to illustrate our analysis.

Keywords: Radio Frequency (RF) transmission · Wireless sensor network · Generalized Stochastic Petri Nets · Modeling · Performance evaluation · Priority requests

1 Introduction

Wireless sensor networks are rapidly emerging as an important new area in the research community. Their applications are numerous and growing, and range from indoor deployment scenarios in the home and the office to outdoor deployment scenarios in natural, military and embedded settings such as temperature, pressure, fire alarms, motion etc. [8]. Wireless sensor sends such sensed data, usually via radio frequency. Signal processing and communication activities are the main parts of sensor networks. Therefore, optimal organization and management of the sensor network is very crucial in order to perform the desired function with an acceptable level of quality [13]. In order to study the performance of wireless sensor networks, many researchers rely mainly on queueing theory especially retrial or priority queues [9,22].

In the last decades there has been significant contribution in the area of retrial queueing theory. The particularity of these kinds of queueing systems is that arriving requests, which find a server busy, go to some virtual place called

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orbit and try their request after some random time. These queueing models arises in many communication protocols, local area networks, and some other life situations. For a detailed survey one can see [1,2,5–7,10,11,23] and the references therein. Furthermore, there are some situations in sensor networks where some requests are generally considered more important than others such as: fire, explosion sounds in the military field, etc., so the modeling by retrial queue with priority requests arises. In this context of modeling with priority retrial queues, Berczes et al. introduce a non preemptive priority retrial model for the transmission in wireless sensor networks which is based on vacation of the server in [3]. This work is primary based on the works of [9,22]. Later, in [4], Berczes et al. extend this model by adding the fact that at the arrival of high priority requests wake up the Radio Frequency (RF) unit (server) while the low priority requests can not do it.

Motivated by the need for performance models suitable for modeling and evaluating of the Radio transmission in wireless sensor networks, we consider a preemptive priority in order to extend the model of [4]. So, in our model, two types of requests (high priority and low priority requests) arrive at the system and if they find the server unavailable, the high priority requests join the ordinary queue, while the low priority requests have to join the orbit and reattempt after a random period. The server departs for a vacation when there are no requests in the queue or in the orbit upon a service completion. Under this scheme, when a vacation period expires, the server wakes up. If the queue or the orbit are non-empty, the server starts serving requests according to the order of priority. Otherwise, it remains awake for a limited time period, waiting for a possible other request. If no requests arrive during this period, it goes for another vacation. The particularity of our proposed model resides in the fact that any high priority request, upon arrival, interrupts the service of low priority one and begins its service. To analyse this model we used the generalized stochastic Petri nets formalism (GSPN).

To highlight priority impact of priority requests on sensor networks performances, we have considered two models. In the first model we considered the case where the requests are served under the non-preemptive priority policy. Whereas in the second model, the requests are served under the preemptive priority. For the numerical application, we compared the performance indices of the models above for different parameters values. We considered the non preemptive case where the high and the low priority requests have the same service rates to compare our results with those in [4]. Furthermore, we considered different service rates in the preemptive priority case to illustrate the influence of these parameters on the performance indices of our model.

This paper is organized as follows: In Sect. 2, we introduce the proposed models of the RF transmission in wireless sensor networks in detail. In Sect. 3, we give an overview of Petri Nets. The generalized Stochastic Petri Net models describing the RF transmission in wireless networks for the two cases: non preemptive and preemptive priority are investigated in Sect. 4. Section 5 is devoted to the performance characteristics where we give the main steady-state characteristics of the studied models. In Sect. 6, we provide various numerical results which are presented and discussed in detail. We finally conclude and give some envisaged further works.

2 The Basic Models

Our motivation is the need for performance models suitable for modeling and evaluating of the Radio Frequency transmission in wireless sensor networks. Thus, we consider in the RF transmission two types of requests: high priority and low priority requests. The sources represent two classes of sensors: the emergency class like fire alarms (high priority requests) while the second one refers to the standard case like temperature measurement (low priority requests). The basic operation of the model can be described as:

- **Arrival and retrial process:** Two types of requests high priority (resp. low priority) requests arrive from two groups of finite sources with capacity N_1, resp. N_2. The high priority (resp. low priority) requests follow Poisson process with mean arrival rate λ_1 (resp. λ_2). Upon blocking, low priority requests immediately join a pool of unsatisfied requests, called the orbit. Any orbiting request tries to connect with the RF (server) after an exponential time period with rate $\nu > 0$, until it finds the server free.
- **Service process:** The RF unit (server) can be in two states: in ON state (accessible), it is able to start processing the incoming requests, or in OFF state, the RF unit can be asleep. The distribution of this ON state times is exponential with parameter α. If there are no incoming requests during this time period, the RF unit switches to OFF state. The distribution of this OFF state times is exponential with parameter β. A listening session starts when the server is in ON state and there are not requests waiting in the queue or in the orbit.

  If the server RF is in ON state at the arrival time of a low priority request, it will be served according to exponential distribution with rate μ_2. Any high priority request in non preemptive case, which upon arrival finds the server busy is queued up in an ordinary queue and will be served according to exponential distribution with rate μ_1. In the case of preemptive priority, the service of a lower-priority request will be interrupted and begins its service immediately with rate μ_3. The interrupted request joins the orbit and will restart service later. Indeed, in these two priorities cases, when the high priority request arrives when the server is at the OFF state, it wakes up the RF unit and starts its service with an exponentially distributed initialization time with parameter γ. In the following, we present the GSPN models describing the RF transmission in wireless sensor networks for the two cases of non preemptive and preemptive priority.

3 An Overview of Generalized Stochastic Petri Nets

Petri nets (PNs) are a powerful modeling tool, introduced in 1962 by Carl Adam [21]. In fact, they combine a well defined mathematical theory with a graphical representation of the systems dynamic behavior. PNs are widely studied and successfully applied in different discrete event dynamic systems in computers networks, real-time computing systems, telecommunication networks, etc. [12,14–17]. The strong mathematical foundation of Petri nets and the amiability of a wide range of supporting tools have made them popular among academic researchers. A Petri Net is a collection of directed arcs connecting places and transitions. Places may hold tokens, so the state or marking of a net is its assignment of tokens to places. A transition is enabled when the number of tokens in each of its input places is at least equal to the arc weight going from the place to the transition. When fired, the tokens in the input places are moved to output places, according to arc weights and place capacities.

In this paper, we use Generalized Stochastic Petri Nets (GSPN) formalism [19,20], which is a modeling formalism that can be conveniently used for analyzing the complex models of discrete event dynamic systems and study their performances or reliability evaluations. This formalism allows us to define two classes of transitions: immediate transitions and timed transitions. Immediate transitions fire in zero time, this means they occur instantaneously, so they always have priority over any enabled timed transitions. While timed transitions fire after a random exponentially distributed enabling time. A marking in which immediate transitions are enabled is known as a vanishing marking, while a marking in which only timed transitions are enabled is known as a tangible marking. The use of GSPN has several advantages due to the memoryless property of the exponential distribution of firing times. [19,20] has shown that the stochastic Petri nets are isomorphic to a Continuous-Time Markov Chain (CTMC). Thus, solving GSPN models consists first to eliminate the vanishing states in order to obtain an equivalent CTMC which contains only tangible states. In this way, the performance measures of this GSPN model can be evaluated by a simple computation of the steady-state distribution $\pi = (\pi_1, \pi_2, \pi_3, \cdots, \pi_n)$, which is the solution of the following linear system:

$$\begin{cases} \pi.Q = 0; \\ \sum\limits_{i \in E} \pi_i = 1; \end{cases} \tag{1}$$

where: π_i denotes the steady-state probability that the process is in the state M_i and E is the set of the tangible states. Q is the infinitesimal generator matrix of the Markov process and its elements are computed as a function of the timed transitions firing rates [18].

4 GSPN Models of the RF Transmission in Wireless Sensor Networks

The two GSPN models that we proposed to describe the RF transmission with non preemptive (resp. preemptive) priority are depicted in Fig. 1 (resp. Fig. 2).

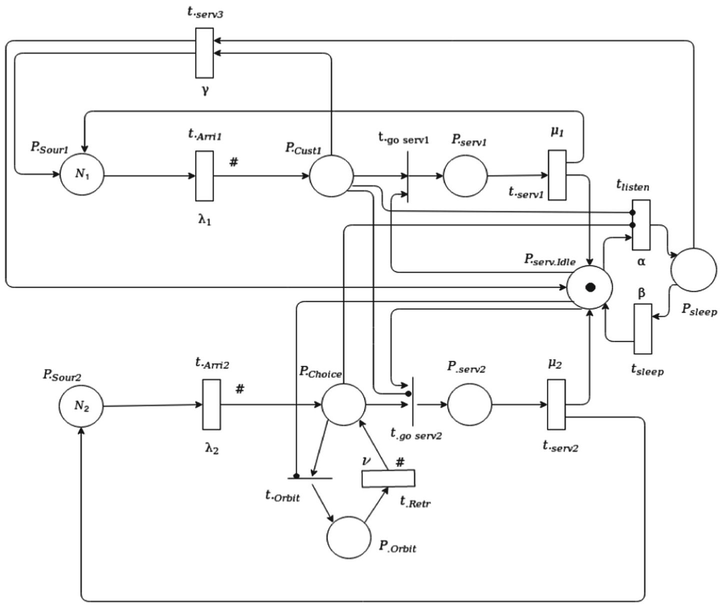

Fig. 1. The non preemptive GSPN Model of the RF transmission in wireless sensor networks.

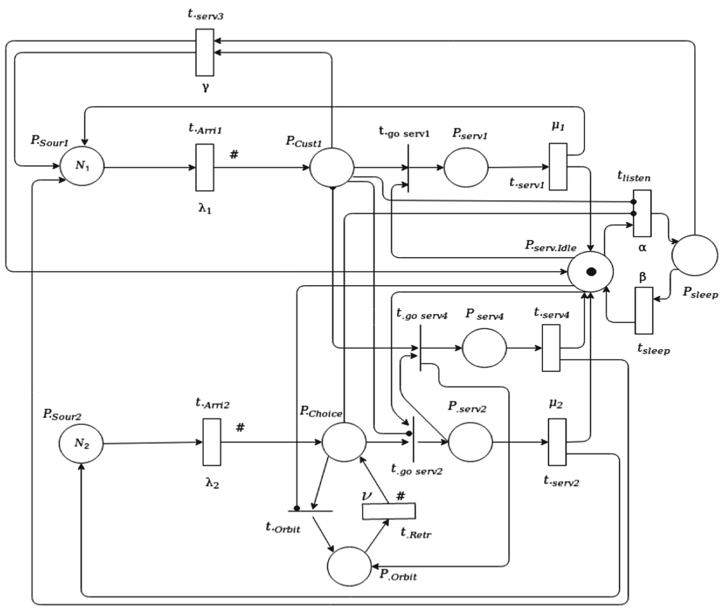

Fig. 2. The preemptive GSPN Model of the RF transmission in wireless sensor networks.

▶ In both GSPN models:

- The place $P._{Sour1}$ (resp. $P._{Sour2}$) contains the high priority (resp. low priority) requests, represented by N_1 (resp. N_2) tokens, which represents the condition that none of the N_1 and N_2 requests has arrived for service;
- The place $P._{Cust1}$ contains the high priority requests;
- The place $P._{Choice}$ represents the condition that a primary or a repeated call is ready for service;
- The place $P._{Orbit}$ represents the orbit;
- The place $P._{serv1}$ (resp. $P._{serv2}$) represents the condition that the server is busy by the high priority (resp. low priority) request;
- The place $P._{sleep}$ represents the fact that the RF sleeps for power saving purposes.
- The place $P._{serv.Idle}$ represents the condition that server is idle, represented by one token.
- When the transition t_{Arri1} fires, one token is taken from P_{Sour1} and is deposited in P_{Cust1}. The firing of t_{Arri1} indicates the arrival of a high priority request. This firing is marking dependent. Thus, the firing rate of t_{Arri1} depends on the number of tokens in P_{Sour1}. If we have N_1 tokens in P_{Sour1}, the firing rate is $N_1\lambda_1$. The condition of marking dependent firing is represented by the symbol # placed next to the transition t_{Arr1}.
- If the arrived request is a low priority one, the transition t_{Arri2} will fire, then P_{Choice} receives a token. Because the transition t_{Arri2} is a marking dependent, so the firing rate is $N_2\lambda_2$.
- The immediate transition $tgo.serv1$ is enabled when $P_{Serv.Idle}$ contains one token (i.e. the server is idle), and P_{Cust1} is not empty (i.e. there is at least one priority request). Once the transition $tgo.serv1$ is fired, a token is removed from each of the two places $P_{Serv.Idle}$ and P_{Cust1}, and it is placed in P_{Serv1}. This token represents a high priority request in service.
- The immediate transition $t._{Orbit}$ fires at the arrival of a low priority request which finds no operational free server i.e. $P_{Serv.idle}$ is empty. Hence, it joins immediately the orbit represented by the place P_{Orbit}. Once in orbit, the request starts generation of a flow of repeated calls exponentially distributed with rate ν. The firing of transition t_{Retr} represents the arrival of a repeated call from the orbit.
- The immediate transition $t_{go.serv2}$ is fired if the place P_{Cus1} is empty (This condition is expressed by the inhibitor arc from place P_{Cust1} to the transition $t_{go.serv2}$.), $P_{Serv.idle}$ contains one token represents the idle server and P_{Choice} contain one token. So, P_{Serv2} receives a token representing a low priority request in service.
- When there are no requests in P_{Cus1} and P_{Choice} a listening session is commencing which is expressed by the inhibitor arcs. So, the firing of the transition t_{listen} represents the event that an idle server is in OFF state.
- The firing of transition t_{sleep} represents the end of the OFF period. Hence, the server is returned to the available state (ON state).
- Once in the OFF state, the server can serve the high priority requests if there is at least one high priority request in P_{Cus1}.

- The timed transition t_{Serv2} (resp. t_{Serv1} and t_{Serv3}) is fired to determine the end of the low priority (resp. high priority) requests period service. Thus, P_{sour2} (resp. in P_{sour1}) receives a token which represents the condition that a low priority request or a high priority one will be returned to be idle, and a second token is deposited in $P_{Serv.idle}$ which represents the condition that the server is ready to serve another request.

▶ **In the preemptive GSPN model:**

- $P_{.serv4}$ represents the condition that the server is busy by the high priority request after interruption of low priority request service. So, the interrupted request joins the orbit and will restart service later.
- At the end of a service period of the preemptive requests, timed transition $t_{go.Serv4}$ fires. The request under service returns to free state P_{sour2} and the server becomes idle.

5 Performance Measures

The aim of this section is to derive the formulas of the most important stationary performance indices corresponding to a RF transmission. As all the proposed models are bounded their initial markings are home states. Accordingly, their steady-state probability distributions exist. In this case, several performance indices can be computed by the formulas given in the following subsections.

▶ **The mean arrival rate of the high priority requests η_1 (resp. low priority requests η_2 are:**

$$\eta_1 = \sum_{j\in(SM_j)_1} \lambda_1(M_j)\pi_j, \quad \eta_2 = \sum_{j\in(SM_j)_2} \lambda_2(M_j)\pi_j; \tag{2}$$

with: $(SM_j)_k$ is the set of markings where the transition t_{Arri_k} is enabled, and $\lambda_k(M_j)$ is the firing rate associated with the transition t_{Arri_k} in the marking M_j, with $k = \overline{1,2}$.

▶ **The mean retrial rate of low priority requests:**
The throughput of the transition t_{Retr} gives the mean retrial rate of low priority requests:

$$\eta_o = \sum_{j\in(SM_j)o} \nu(M_j).\pi_j; \tag{3}$$

with: $(SM_j)_o$ is the set of markings where the transition t_{Aretr} is enabled, and $\nu(M_j)$ is the firing rate associated with the transition t_{retr} in the marking M_j.

▶ **The mean rate of listening period:**
This represents the throughput of the transition t_{listen}:

$$\bar{\alpha} = \sum_{j\in(SM_j)} \alpha(M_j).\pi_j; \tag{4}$$

with: (SM_j) is the set of markings where the transition t_{listen} is enabled, and $\alpha(M_j)$ is the firing rate associated with the transition t_{listen} in the marking M_j.

▶ **The mean rate of sleeping period:**
This represents the throughput of the transition t_{listen}:

$$\bar{\beta} = \sum_{j \in (SM_j)} \beta(M_j).\pi_j; \tag{5}$$

with: (SM_j) is the set of markings where the transition t_{sleep} is enabled, and $\beta(M_j)$ is the firing rate associated with the transition t_{sleep} in the marking M_j.

▶ **The mean number of the high priority requests η_{01} (resp. low priority requests η_{02}) in the queue:**

$$\eta_{01} = \sum_j M_j(P_{Cust1}) + M_j(P_{Serv4})\pi_j, \qquad \eta_{02} = \sum_j M_j(P_{Orbit}).\pi_j; \tag{6}$$

where, $M_j(P_{Cust1})$ is the number of tokens in place P_{Cust1} in the marking M_j and $M_j(P_{Orbit})$ is the number of tokens in place P_{Orbit} in the marking M_j. The sum in this formula is made on all the accessible markings.

▶ **The mean number of high priority requests η_{S1} (resp. low priority requests η_{S2}) in the system:**

$$\eta_{S1} = \sum_j [M_j(P_{Cust1}) + M_j(P_{Serv1}) + M_j(P_{Serv4})]\pi_j; \tag{7}$$

$$\eta_{S2} = \sum_j [M_j(P_{Orbit}) + M_j(P_{Serv2})]\pi_j. \tag{8}$$

The sum in this formula is made on all the accessible markings.

▶ **The mean waiting time of high priority W_1 (resp. low priority W_2) the requests:**

$$W_1 = \frac{\eta_{01}}{\eta_1}; \qquad W_2 = \frac{\eta_{02}}{\eta_2}. \tag{9}$$

▶ **The mean response time of high priority τ_1 (resp. low priority τ_2) requests:**

$$\tau_1 = \frac{\eta_{S1}}{\eta_1}; \qquad \tau_2 = \frac{\eta_{S2}}{\eta_2}. \tag{10}$$

▶ **The blocking probability of low priority requests:**

$$B_p = \sum_i Prob\{M(P_{Orbit}) \geq 1 \;\; and \;\; M(P_{\cdot serv.Idle}) = 0\}. \tag{11}$$

▶ **The probability that the server is busy by high priority request P_{s1} (resp. low priority requests P_{s2}):**

$$P_{s1} = \sum_i Prob\{(M(P_{serv1}) = 1) \; or \; (M(P_{serv4}) = 1)\}; \tag{12}$$

$$P_{s2} = \sum_i Prob\{M(P_{serv2}) = 1\}. \tag{13}$$

► **The probability of sleeping period:**

$$Pr_s = \sum_i Prob\{M(P_{sleep}) \geq 1\}. \tag{14}$$

6 Numerical Results

In the present section, we study the effect of several parameters on the performance measures in the sensor networks for the two cases: preemptive and non preemptive priority. The results of this study are displayed in different figures. On each figure the blue lines correspond to the non preemptive priority and the red lines correspond to the preemptive priority. In Table 1, we considered the same parameters as those used by Berczes et al. [4] in order to compare the results.

Figure 3 displays the mean queue length versus the λ. We see that as the arrival rate increases, the mean queue length increases. We note that the mean queue length for the preemptive priority is less than in the non preemptive priority. In the case of preemptive priority, the requests spend less time compared to non preemptive case.

On Fig. 4 the mean orbit size of low priority requests is displayed as a function of λ. We see that the mean number of requests in the orbit is an increasing function of arrival rate. However, the mean orbit size in preemptive priority is almost close to the mean orbit size in non preemptive priority. For high request generation rates mean orbit size approaches N_2 i.e. the low priority requests are blocked. These results are useful for choosing the parameters that fine tuning the size of the orbit.

In Fig. 5, mean waiting time spent in the queue are plotted versus arrival rates. We remark that increasing of the arrival rates increases the mean waiting time spent in the queue by the high priority requests. But the mean waiting time in preemptive case is smaller than mean waiting time in the non preemptive

Table 1. Network parameters.

Parameter	Symbol	Value
Population size	(N_1, N_2)	$(50, 50)$
Arrival rates	(λ_1, λ_2)	$(\frac{\lambda}{10}, \frac{9\lambda}{10})$
Service rates	(μ_1, μ_2)	$(20, 20)$, $(20, 10)$, $(10, 20)$
Retrial rate	ν	2
Initialization rate	γ	10
Mean time of sleeping period	$\frac{1}{\beta}$	0.5
Mean time of listening period	$\frac{1}{\alpha}$	1.5

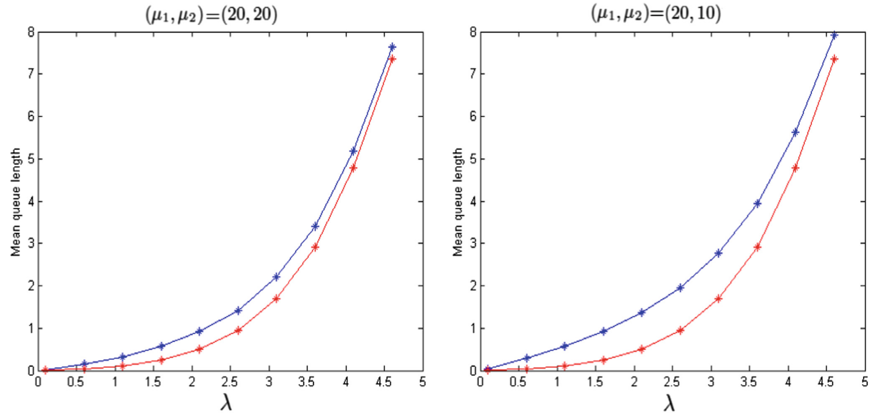

Fig. 3. Mean queue length versus λ.

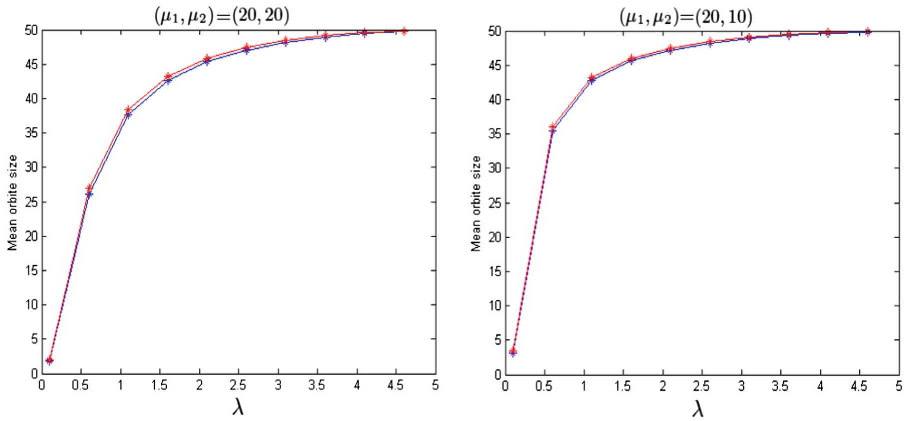

Fig. 4. Mean orbit size versus λ.

case. We remark also that the waiting time in the case of non preemptive priority increases with the decreases of the service rate of low priority requests, contrary to the case of preemptive priority where waiting time remains almost the same.

Figure 6 illustrates the behavior of mean waiting time in the orbit versus the arrival rates. The curves show the increases of the waiting time in the orbit with the increases of λ. We can see that for small values of $\lambda \leq 2$ mean waiting time in the orbit given by the preemptive case is close to mean waiting time in the orbit given by the non preemptive one. But after this value, the requests spend more time in the orbit. This is because the server interrupt the non preemptive requests (which join the orbit) and serve the high priority requests.

Figures 7 and 8 show how much the increases of the arrival rate affects the mean response time, especially for the low priority requests. We can also see

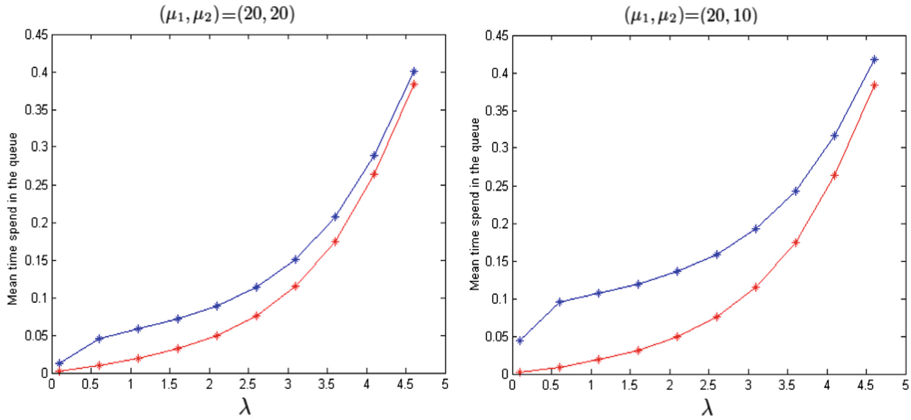

Fig. 5. Mean waiting time in the queue versus λ.

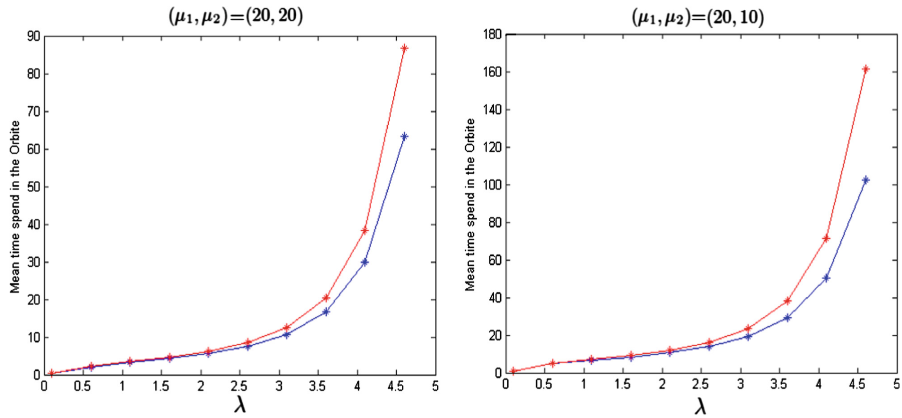

Fig. 6. Mean waiting time in the orbit versus λ.

the influence of service rates, for example, the difference between the response times for $\lambda = 4.5$ in the case of $(\mu_1, \mu_2) = (20, 20)$ and $(\mu_1, \mu_2) = (20, 10)$ is significant. Furthermore, we remark that the mean response time of low priority requests in non preemptive case is almost close to the mean response time in the preemptive case for a lower values of the arrival rates ($\lambda \leq 2.3$). But priority requests response time in the case of preemptive case gives the best results. This is because the server is busy a lot more with priority requests.

In Fig. 9 the blocking probability of retrial requests curves are plotted versus the arrival rate λ. From this figure it is shown that this probability increases as λ increases and approaches one. The increasing of this blocking probability is rapid for a small value of μ_2. This figure also shows that the optimal choice of

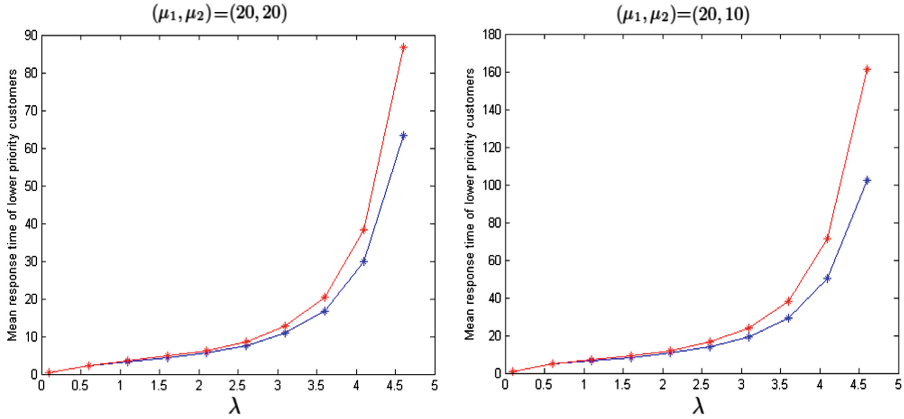

Fig. 7. Mean response time of low priority requests versus λ.

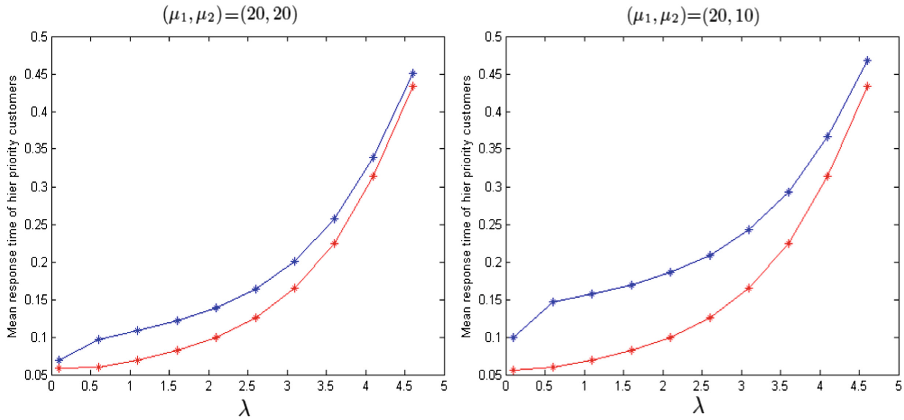

Fig. 8. Mean response time of high priority requests versus λ.

blocking probability for the retrial requests corresponds to the case of preemptive discipline.

Figure 10 illustrates the behavior of the probability that the server is busy versus the arrival rate λ. We have presented two curves which correspond to the probability that the server is busy by the high priority (resp. low priority) requests. These curves show the probability that RF is busy by the low priority request increases until the maximum and decreases to approaches zero. The observed peak in curve indicates that from the $\lambda = 0.5$ corresponding to this point, the high-priority requests are strongly constrained to be preferred over low-priority requests. We notice that this probability approaches zero with the increases of λ. The zero is reached rapidly for a lower values of μ_1. We can

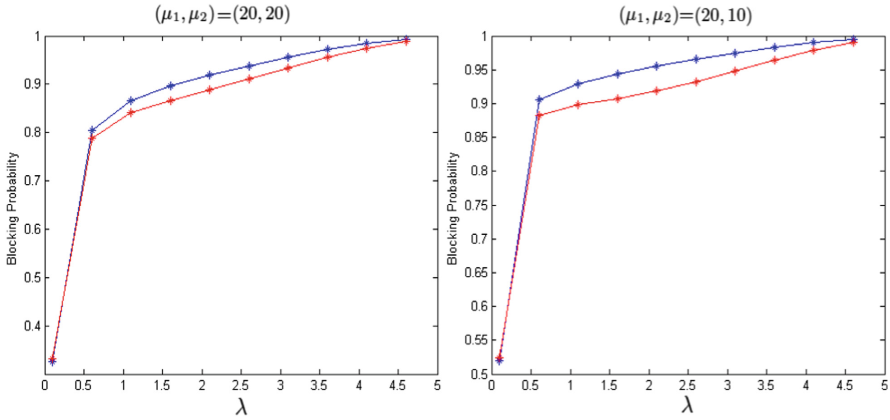

Fig. 9. Blocking probability of retrial requests versus λ.

see also that in the case of preemptive discipline this probability is less than in preemptive case.

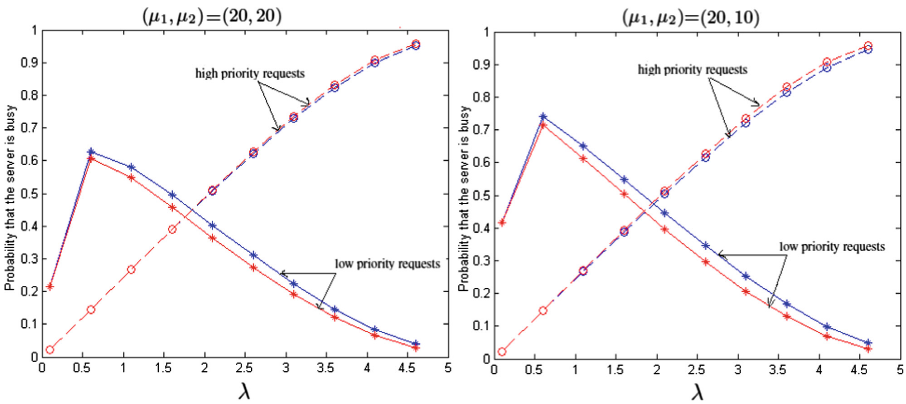

Fig. 10. The probability that the server is busy versus λ.

Figure 11 shows that the increases of the sleeping period rate doesn't influences a lot for the mean queue length and for the orbit size. For example, the mean number of waiting requests is around 0.02 in the case of preemptive priority and around 0.11 in the case of non preemptive priority. Otherwise, the average number of requests in the orbit is between $[21.4, 22.4]$ in the case of preemptive priority, and between $[22.1, 23.4]$ in the case of non preemptive priority. We constat that the number of priority requests in the queue does not depend on the sleeping period rate, this is due the wake up of the server and the preemptive priority of the requests.

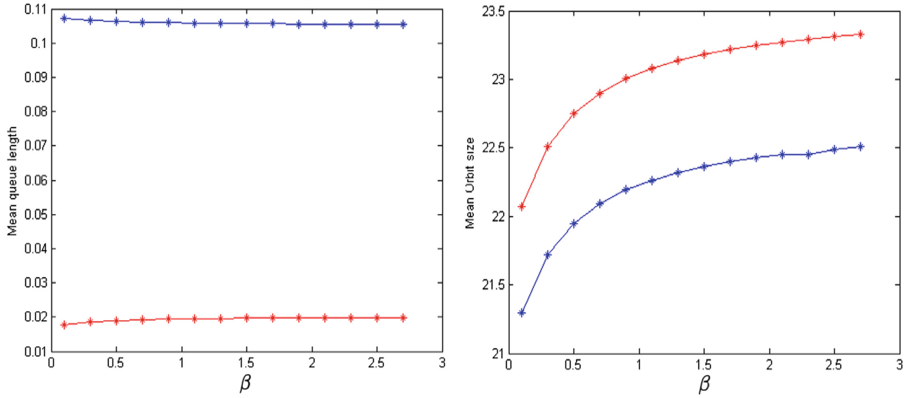

Fig. 11. Mean queue length and mean orbit size versus β.

7 Conclusion

Sensor networks can increase the efficiency of many military and civil applications, such as combat field surveillance, security and disaster management where conventional approaches prove to be very costly and risky [13]. This paper aims at modeling and studying performances of the RF transmission in wireless sensor networks by using Generalized Stochastic Petri Nets (GSPN). We studied two models: in the first the high priority requests have non-preemptive priority over lower ones while, in the second model, we applied the preemptive priority to the high priority requests. According to this study we can see that the preemptive priority is favorable to higher priority customers, because they are not influenced by lower priority customers at all. The advantage of our approach resides in the expressive power that the GSPN formalism offer in order to construct a simple model for the RF transmission in sensor networks. The numerical results are discussed and show the positive and negative effects of parameters on several performance Indices. The performance results obtained and compared to [4] showed that our model based on preemptive priority improves the network performances with better blocking probability compared to non preemptive one, especially for high priority requests. The results show significant performance improvements in the processing of high priority requests. The conclusion is that the proposed model can be implemented in sensor networks situations where some requests are considered more important than others such us: fire, explosions sound in the military field.

In future, we plan to extend our model to mixed priority with more sleeping period schemes.

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Abstract. In this paper we model and analyse the radio frequency (RF) transmission in wireless sensor networks using Generalized Stochastic Petri Nets (GSPN). In our model two types of priority requests are considered. In the first type, high priority requests are queued and served according to FIFO discipline. In the second type (case of blocking) low priority requests join the orbit before retrying the request until they find the server free. We consider the preemptive priority to the requests. Indeed, in this study, we highlight the impact of the presence of priority requests on network performances via GSPN formalism. Firstly, we study the case where the high priority requests have non-preemptive priority over lower ones. While, in the second case, we apply the preemptive discipline to the high priority requests. Finally, some numerical examples are given to illustrate our analysis.

Keywords: Radio Frequency (RF) transmission · Wireless sensor network · Generalized Stochastic Petri Nets · Modeling · Performance evaluation · Priority requests