Modeling the Performance and the Energy Usage of Wireless Sensor Networks by Retrial Queueing Systems [*] [†]

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ABSTRACT

This paper deals with wireless transmission problems in sensor networks. In order to study the performance measures and characteristics, a finite source retrial queueing model is introduced. Two classes of sensors are considered: "time driven" sensors for normal requests and "event driven" sensors with high priority for special, eg. emergency requests.

The main goal is to investigate the relationship between the performance and the energy usage of the sensor network. Two operations are compared. In the first case only the event driven requests can initiate reaching the radio transmission (RF) unit. Time driven requests have to wait for a listening period of RF unit. In the second case the time driven requests also are able to access the sleeping RF unit, which will go to power save (sleeping) state immediately after the job is served.

The steady-state performance measures and probabilities are given by the help of the MOSEL-2 tool.

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Performance modeling; Finite-source retrial queues; Sensor networks

1. INTRODUCTION

Wireless sensor networks contain low cost sensors to monitor some parameters of the environment. The sensed data are transmitted to a sink node (called Base Station) by using radio transmission technology (see e.g. [1], [4]). Concerning the data transmission periodicity, there are different solution ideas. The time driven solution technology schedules the measured data (e.g. temperature, humidity) transmission from the sensor to the sink according to a well defined (but not necessarily constant) time-interval. The event driven solution (see [9]) follows a quite different philosophy: the data transmission is performed only if a special event or situation occur (e.g. fire alarm). The investigation of the performance and energy efficiency of the sensor networks is a hot research area today (see e.g. [6],[7]). Markov chain based modeling is a useful technology to study the behavior and the performance of sensor networks, especially to investigate the performance measurements using special assumptions or conditions (see [5], [1], [4], [2]) This paper establishes a new retrial queueing system for the performance and energy efficiency evaluation of wireless sensor networks from the viewpoint of radio transmission. The time driven sensors are considered as the standard class of operation. The event driven sensors are considered as the high priority class (e.g. fire alarm). The event driven sensors have priority in the radio transmission system over the time driven sensors. After an idle period the radio transmission system goes into power save mode. The power save mode can be used to spare energy. The idle period is a critical factor of

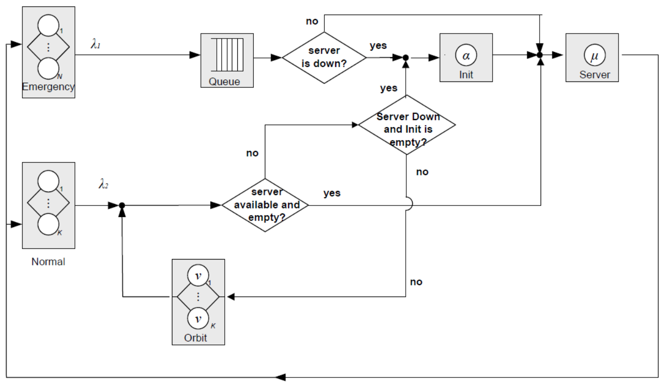

Figure 1: A retrial queue with components

energy efficiency: in this state there is no transmitted data, but the RF unit uses energy. In this paper we would like to investigate the system performance related to the energy usage efficiency, using different service strategies at the RF unit.

2. SYSTEM MODEL

The model of the system described above is a finite source queueing model. A single server unit represents the radio transmission module (RF unit), and the sources play the role of the sensors. The sources are divided into two classes. The first one models the event driven sensors generating emergency requests, while the other one stands for the time driven sensors generating normal requests. The emergency jobs have priority over the normal ones. The number of the event driven and the time driven sensors are denoted by N and K, respectively. Each sensor can send a new request to be served at the RF unit. Normal sensors can measure eg. temperature, while the high priority event driven sensors can indicate emergency situations, eg. illegal intrusions to a location. The inter-request times are assumed to be exponentially distributed with parameter λ_1 for event driven and λ_2 for time driven sensors.

The radio transmission system can be in two states:

- *Available state:* The server is on, and either there is a request under service or the server is waiting for incoming jobs.
- *Power save (sleeping) state:* The server is down, there is only a minimal energy consumption.

In available state the server can be busy or idle depending on whether there is a request under service or not. In power save state the server is sleeping until an incoming job wakes it up. The server starts in available state. The service of an incoming event driven request begins immediately. The distribution of service times for each job coming from both classes are exponential with parameter μ. Additional arriving high priority requests join to the FIFO queue. After the current job is served, two possible operation modes are distinguished and compared:

- The server is switched to power save mode immediately.
- The server remains in available mode for a time period, which is described with an exponential distribution with parameter β

When the server is down (power save mode) and there is an incoming job, it will launch an initiation process for the RF unit. This initiation time is modeled by an exponentially distributed random variable with parameter γ . The time driven (low priority) requests are handled by the help of retrial queueing. A job arriving from the normal source checks the availability of the radio transmission unit. If the unit is on and idle, the request goes directly to the server. The service begins immediately. Because of the event driven requests have non-preemptive priority over the time driven ones, the jobs are directed to the orbit when the server is up and busy. The requests retry to reach the server again from the orbit after an exponentially distributed time period with parameter ν. A normal priority request can only reach the server when it is available, idle, and there is no job in the FIFO queue. When the incoming low priority job finds the RF unit to be under an initialization process, the request joins to the orbit. If the RF unit is found in power save mode and there is no initialization process in progress, two cases are compared for time driven jobs:

- A time driven job can also wake up the server and put it into the available mode.
- A time driven job cannot wake up the server. The service begins only that case, when the available server is in listening mode (ie. the server is up for a while after a job is served). Any other case the job goes to the orbit.

In this paper we would like to analyze the performance of the system, especially investigating how the "wake-up" feature influences the performance and the energy usage efficiency parameters of the system. The most important factor of the energy usage efficiency is the "idle" state: In the idle state the RF unit does not transmit data, but does use energy.

The operational dynamics of the system can be seen in the corresponding queueing model, see Fig. 1.

We introduce the following notations (see the summary of the model parameters in Table 1):

- $k_1(t)$ is the number of active sensors in the emergency source at time t,
- $k_2(t)$ is the number of active sensors in the normal source at time t,
- $q(t)$ denotes the number of emergency requests in the queue at time t,
- $o(t)$ is the number of jobs in the orbit at time t.
- $y(t) = 0$ if there is no job in the server and the server is available, $y(t) = 1$ if the server is busy with a job coming from the emergency class, $y(t) = 2$ when the server is busy with a job coming from the normal sensor class, $y(t) = 3$ if the server is in sleeping state at time t.
- $c(t) = 1$ when the server is in sleeping state at time t and one emergency request has started the initialization procedure, $c(t) = 2$ when the server is in sleeping

state at time t and one normal request has started the initialization procedure and $c(t) = 0$ in the other cases.

It is ease to see that:

$$k_1(t) + k_2(t) = \begin{cases} K + N - q(t) - o(t), & y(t) = 0 \\ K + N - q(t) - o(t) - 1, & y(t) = 1, 2 \\ K + N - q(t) - o(t) - c(t), & y(t) = 3 \end{cases}$$

.

Table 1: Overview of model parameters

Parameter	Maximum	Value at t
Active emergency sensors	N	$k_1(t)$
Active normal sensors	K	$k_2(t)$
Emergency generation rate		λ_1
Normal generation rate		λ_2
Total gen. rate	$\lambda_1 N + \lambda_2 K$	$\lambda_1 k_1(t) + \lambda_2 k_2(t)$
Requests in queue	N	$q(t)$
Service rate		μ
Busy servers	1	$c(t)$
Cust. in service area	$N+1$	$c(t)+q(t)$
Requests in Orbit	K	$o(t)$
Retrial rate		ν
Mean time of sleeping period		$\frac{1}{\beta}$
Mean time of listening period		$\frac{1}{\alpha}$

To maintain theoretical manageability, the distributions of inter-event times (i.e., request generation time, service time, retrial time, available state time, sleeping state time, listening state time) presented in the network are by assumption exponential and totally independent. The state of the network at a time t corresponds to a Continuous Time Markov Chain (CTMC) with 4 dimensions:

$$X(t) = (y(t); c(t); q(t); o(t))$$

The steady-state distributions are denoted by

$$P(y, c, q, o) = \lim_{t\to\infty} P(y(t) = y, c(t) = c, q(t) = q, o(t) = o)$$

Note, that the state space of this Continuous Time Markovian Chain is finite, so the steady-state probabilities surely exist. For computing the steady-state probabilities and the system characteristics, we use the MOSEL-2 software tool in this paper. These computations are described in papers of Bolch and Wüchner et al. [3], [8].

As soon as we have calculated the distributions defined above, the most important steady-state system characteristics can be obtained in the following way:

- *Utilization of the server*

$$U_S = \sum_{y=1}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} P(y, 0, q, o)$$

- *Availability of the server*

$$A_S = \sum_{y=0}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} P(y, 0, q, o)$$

- *Average number of jobs in the orbit*

$$\overline{O} = E(o(t)) = \\ = \sum_{y=0}^{3}\sum_{c=0}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} oP(y, c, q, o)$$

- *Average number of jobs in the FIFO*

$$\overline{Q} = E(q(t)) = \\ = \sum_{y=0}^{3}\sum_{c=0}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} qP(y, c, q, o)$$

- *Average number of jobs in the network*

$$\overline{M} = \overline{O} + \overline{Q} + \\ + \sum_{y=1}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} P(y, 0, q, o) + \\ + \sum_{c=1}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} P(3, c, q, o)$$

- *Average number of active emergency sensors*

$$\overline{\Lambda_1} = N - \overline{Q} - \sum_{q=0}^{N-1}\sum_{o=0}^{K} P(1, 0, q, o) - \\ - \sum_{q=0}^{N-1}\sum_{o=0}^{K} P(3, 1, q, o)$$

- *Average number of active normal sensors*

$$\overline{\Lambda_2} = K - \overline{O} - \sum_{q=0}^{N}\sum_{o=0}^{K-1} P(2, 0, q, o) - \\ - \sum_{q=0}^{N}\sum_{o=0}^{K-1} P(3, 2, q, o)$$

- *Average generation rate of emergency sensors:*

$$\overline{\lambda_1} = \lambda_1 \overline{\Lambda_1}$$

- *Average generation rate of normal sensors:*

$$\overline{\lambda_2} = \lambda_2 \overline{\Lambda_2}$$

3. NUMERICAL RESULTS

To illustrate the effect of the wake up property of the low priority requests on some of the most important measures in sensor networks, we present numerical results. The corresponding parameters are summarized in Table 2. The most interesting results are displayed in the following figures. In each Figure the blue lines (dotted with circles) represent the cases, when the time driven requests can not wake up the RF unit, they have to wait in orbit for an idle period. The average listening period is 1.5 sec here. The red lines (dotted with triangles) represent the cases, when the low priority requests are able to wake up the server. The RF unit switches to power save mode immediately after a request is served.

On Figure 2 the mean queue length of the FIFO (event driven requests) can be observed. It can be seen, that there is no significant difference between the two modes. The queue length is slightly higher in case, when low priority request can switch the server into available mode.

Figure 3 shows how orbit fills up at different request generation rates. At lower rates the orbit size is smaller for the cases, when time driven jobs can wake up the server. At higher rates it is changed, but the difference is very small.

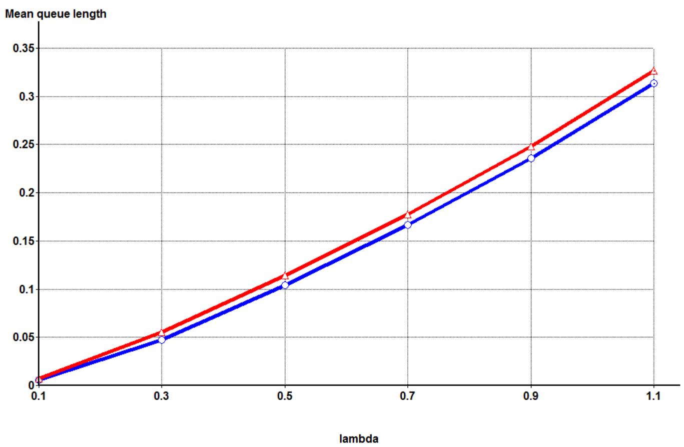

Figure 2: Mean queue length vs generation rate

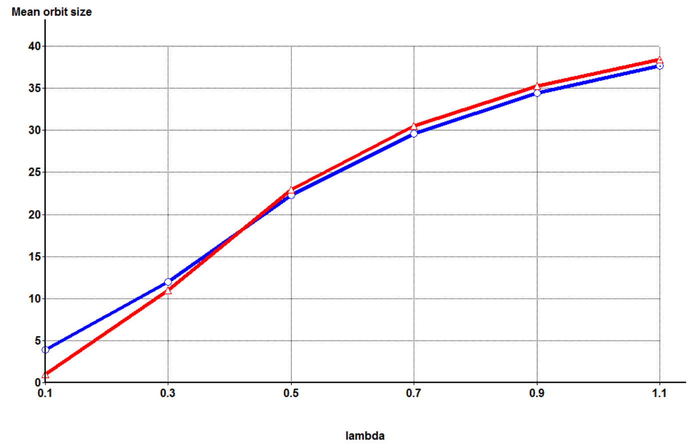

Figure 3: Mean orbit size vs generation rate

Similar effect can be seen on Figure 5. The initially higher average waiting time in queue will be lower for the cases of listening periods.

For the first glance, the Figure 4 shows, that the mean time spent in the FIFO is higher for the "wake up" cases. But if we take a look at this graph, notice that the difference is almost irrelevant.

On Figure 6 the first really interesting result can be observed. The independent variable is still the request generation rate. The figure shows the probability of idle state of RF unit. For the listening mode it is much higher at lower generation rates. Larger generation rates the difference decreases, but still remains significant.

For the remaining figures the independent variable is the average length of listening period. It means, that the other case is a constant line here. Figure 7 shows, that the orbit size is very large for small listening periods. As this period is increasing, this difference fades out. For cases of listening periods greater than 1, the difference turns negative, but the orbit sizes are almost the same.

Figure 8 shows the important result of the power consumption efficiency. On the previous figure you can see, that the orbit size was (hardly) smaller above 1 sec average listening periods. This figure demonstrates, that in this case the idle period of RF unit increases rapidly. The advantages of listening mode are very small, while the disadvantages, regarding the energy efficiency, are much higher.

Table 2: Numerical values of model parameters

Parameter	Symbol	Value
Overall generation rate	λ	[0.1,1.1]
Emergency generation rate	$\lambda_1 = \frac{\lambda}{10}$	[0.01,0.11]
Normal generation rate	$\lambda_2 = \frac{9}{10}\lambda$	[0.09,0.99]
Number of Emergency sensors	N	50
Number of Normal sensors	K	50
Retrial rate	ν	2
Service rate	μ	20
Server's failure rate	δ	[0.001..0.01]
Server's repair rate	τ	[0.01..0.21]
Initialization rate	γ	100
Mean time of sleeping period	$\frac{1}{\beta}$	2
Mean time of listening period	$\frac{1}{\alpha}$	1.5,[0.1,1.5]

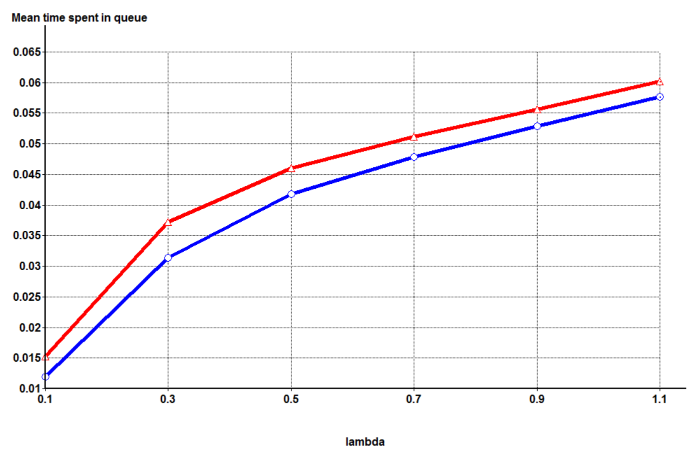

Figure 4: Mean time spent in queue vs generation rate

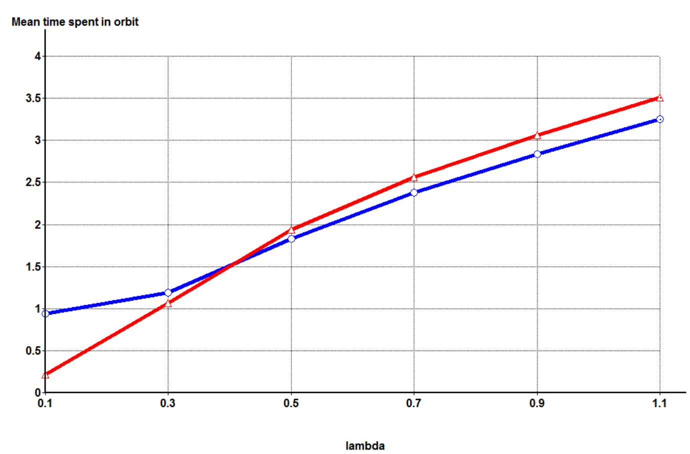

Figure 5: Mean time spent in orbit vs generation rate

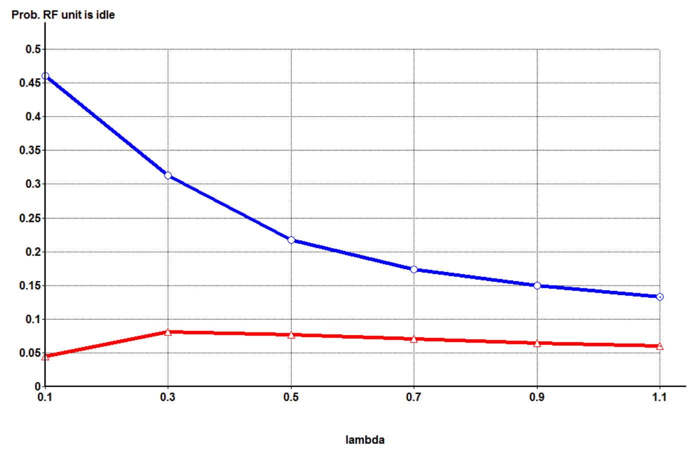

Figure 6: Probability that the server is in idle state vs generation rate

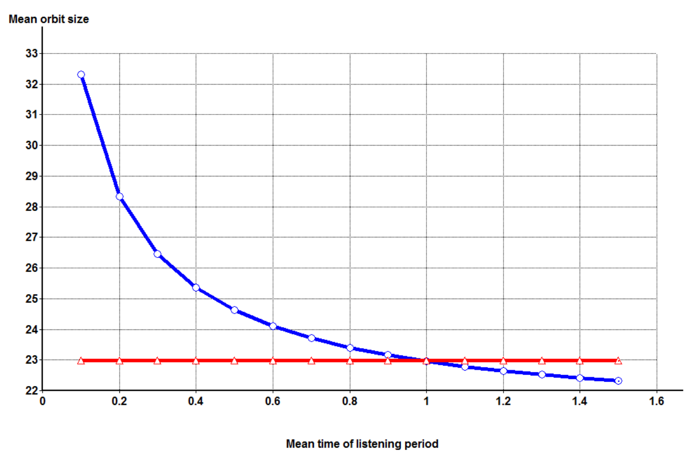

Figure 7: Mean orbit size vs mean time of listening period

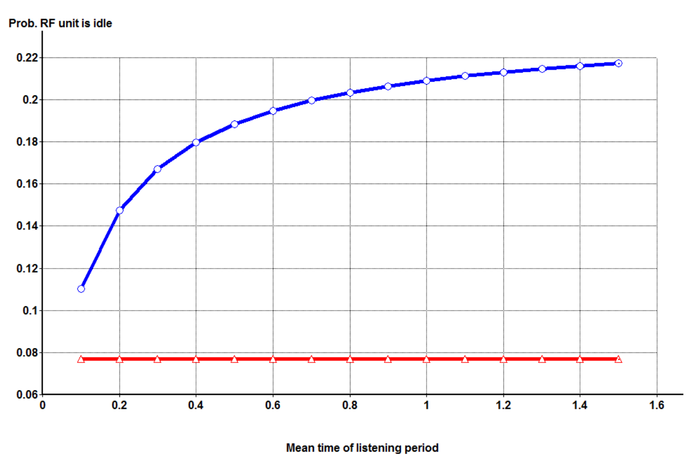

Figure 8: Probability that the server is in idle state vs mean time of listening period

4. CONCLUSIONS

In this paper we investigated the relationship between the performance and the energy usage of sensor networks. Two operation modes were compared. In the first one, the lower priority request can not wake up the RF unit. They have to wait in the orbit, and during a retrial can be served only if the server is up and idle. That means, there is a listening period after a job service. The second case is, when the low priority time driven request can wake up the RF unit (if it is found in sleeping mode). Here there is no listening period. Based on the result it can be stated, that there are some advantages of listening mode, but they are relatively small.

5. ACKNOWLEDGMENTS

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