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Modeling the RF Communication in Sensor Networks by using Finite-Source Retrial Queueing System

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Abstract* – In this paper we study the radio frequency (RF) transmission in wireless sensor networks. A new finite source retrial queueing model is introduced in order to calculate the most important system performance characteristics (e.g. mean waiting time, mean number of requests waiting for transmission). The sensors form the "sources" and the RF unit represents the "service station" of the queueing model. The sensors are classified according to their working purposes: The first class is the "Emergency" class, which is responsible to notify special emergency situations (e.g. fire alarms). The second class is the "Standard" class, which performs the measurement of standard environmental data (e.g. humidity, temperature). The RF unit may enter into energy saving (or "sleeping") working mode in order to spare energy and have longer battery life. The RF communication is stopped in the sleeping mode. Concerning the "wake up" mechanism from the energy saving mode we differentiate two cases and create two models to compare their steady-state system performance measures: In the first model the RF transmission possibility will be available randomly for the sensor nodes (Non Controlled case). In the second model the RF transmission requests coming from the emergency class, will access the wireless channel immediately (Controlled case).

***Keywords:* wireless sensors, performance evaluation, retrial queueing, stochastic simulation.**

I. INTRODUCTION

Wireless sensor networks are widely used to implement low cost unattend monitoring of different environments. Baronti et al. [5] showed that the technology limits are far beyond the current usage. Chiang [9] represented the wireless sensor networks as a system containing three main components see Figure 1. Buchmann showed ([8], [14]) that the operation mechanisms depending on the vendor implementations can be totally different, but also common features are observable. For example, power saving is a standard requirement to achieve long time operation of the wireless nodes. Similarly, a common feature that can appear in the wireless data transmission is a bottleneck in the operation (see [10]).

To categorize the literature on retrial queues and applications, the assumption on traffic sources is an important aspect. That is, there is an infinite (see [3], [11]) number of sources or a finite ([4], [2], [13], [16]) number of sources that are assumed to generate load to a system under investigation.

In this paper we introduce a retrial queueing model to investigate the performance characteristics of the wireless transmission problem in the sensor networks. We divide the sensors into two classes. The first one is the "Emergency" class, which performs the notification of special emergency situations (eg. fire alarms). The second one is the "Standard" class, which measures and transmits environmental data (e.g. temperature).

The emergency class has priority over the standard class in the operation. For the performance evaluation of the wireless transmission we study and compare two cases: In the first model the RF transmission possibility will be available randomly for the sensor nodes (Non Controlled case). In the second model the RF transmission requests coming from the emergency class will access the wireless channel immediately (Controlled case).

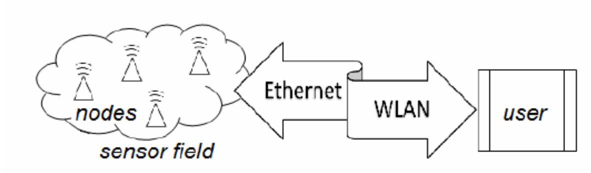

Fig. 1 Wireless sensor network

The rest of this paper is organized as follows. In Section II we present the corresponding queueing model. Numerical results and their discussion are provided in Section III. Finally, Section IV concludes the paper.

II. SYSTEM MODEL

Let us consider a queueing model with a single server unit (RF unit), where the jobs come from two groups of finite sources. These sources represent the sensors. The first class of sensors corresponds to the emergency case alerts (e.g. fire alarms), while the second one refers to the standard case (e.g. temperature, humidity measurement).

The number of sensors of the first class is denoted by *N*, and the number of sensors of the second class is denoted by *K*. The sensors send a new service request (i.e. to send the measured value through the radio interface). The distribution of the inter-request times is exponential with parameter λ_1 for the emergency sensors and with parameter λ_2 for the standard class. Two states are considered for the radio transmission unit (server) in the model:

- ON state: If the RF unit is ON (accessible) it is able to start processing the incoming jobs.
- OFF state: The RF unit can be in OFF state (it sleeps for power saving purposes).

The RF unit is engaged when it is in ON state and there are more than zero jobs in the servicing environment. The RF unit is inactive when it is in OFF state and there are no jobs in the servicing environment.

The RF unit begins to work with an ON state period. The distribution of this ON state times is exponential with parameter α. If there are no incoming jobs during this time period, the RF unit switches to OFF state. The distribution of this OFF state times is exponential with parameter β.

When the OFF state period is over, the RF unit enters in ON state. If there are emergency requests waiting in the queue, the RF unit begins to serve them. In the other situation, when there are not any emergency requests waiting in the queue, a listening session will be started.

When the RF unit is in ON state, the incoming jobs can access the RF unit. The RF unit will switch to OFF state, if there are no incoming jobs during the ON state. A request of the emergency class goes directly to a FIFO queue waiting to be served (i.e. transmitted through the radio interface).

If an emergency request arrives to the RF unit being in OFF state we consider two operation possibilities:

- The request waits for the end of the OFF state period.
- The request wakes up the RF unit, which will start the service after an exponentially distributed initialization time with parameter γ.

If a request from the second class finds the RF unit busy or in OFF state then the requests goes to the orbit. These requests waiting in the orbit retry to find the RF unit idle according to a Poisson flow with retrial rate ν. We assume that emergency requests have non-preemptive priority over standard requests.

The distribution of service times for each request coming from both classes is exponential with parameter μ. The functionality of this sensor network is presented in Fig. 2.

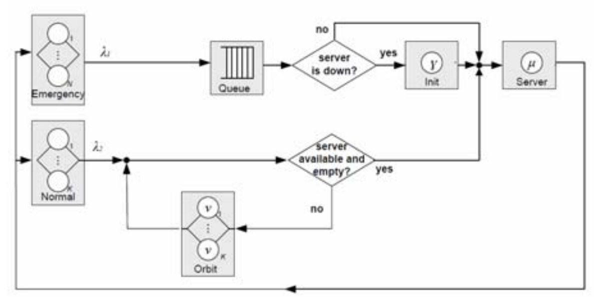

Fig. 2 A retrial queue with components

The notations described below are introduced, and Table 1 contains the overview of parameters of the network:

- $k_1(t)$ is the number of active sensors in the emergency source at time *t*,
- $k_2(t)$ is the number of active sensors in the standard 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 RF unit and the RF unit is available, $y(t)=1$ if the RF unit is engaged with a job coming from the emergency class, $y(t)=2$ when the RF unit is servicing a job coming from the standard sensor class, and $y(t)=3$ if the server is in OFF state at time \$t\$
- $c(t)=1$ when the RF unit is in OFF State at time *t* and one emergency request has started the initialization procedure, $c(t)=0$ in the other cases.

It is easy to see that

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

To maintain theoretical manageability, the distributions of inter-event times (i.e., request generation time, service time, retrial time, ON state time, OFF 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: $X(t) = (y(t); c(t); q(t); o(t))$.

TABLE 1. List of network parameters.

Parameter	Maximum	Value at *t*
Active emergency sensors	*N* (population size)	$k_1(t)$
Active standard sensors	*K* (population size)	$k_2(t)$
Emergency generation rate		λ_1
Standard generation rate		λ_2
Requests in queue	*N*	$q(t)$
Service rate		μ
Busy servers	*1* (number of servers)	$c(t)$
Cust. in service area	*N+1*	$c(t)+q(t)$
Requests in orbit	*K*	$o(t)$
Retrial rate		ν

The steady-state distributions are denoted by

$$P(y,c,q,o) = \\ = \lim_{t\to\infty} P(y(t)=y, c(t)=c, q(t)=q, o(t)=o). \quad (1)$$

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 e.g. [7], [15].

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

- Utilization of the RF unit

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

- Availability of the RF unit

$$A_S = \sum_{y=0}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} P(y,0,q,o). \quad (3)$$

- Average number of jobs in the orbit

$$\overline{O} = E(o(t)) = \\ = \sum_{y=0}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} oP(y,0,q,o) + \\ + \sum_{c=0}^{1}\sum_{q=0}^{N}\sum_{o=0}^{K} oP(3,c,q,o). \quad (4)$$

- Average number of jobs in FIFO

$$\overline{Q} = E(q(t)) = \\ = \sum_{y=0}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} qP(y,0,q,o) + \\ + \sum_{c=0}^{1}\sum_{q=0}^{N}\sum_{o=0}^{K} qP(3,c,q,o) \quad (5)$$

- Average number of jobs in the network

$$\overline{M} = \overline{O} + \overline{Q} + \\ + \sum_{y=1}^{2}\sum_{q=0}^{N}\sum_{o=0}^{K} P(y,0,q,o) + \\ + \sum_{q=0}^{N}\sum_{o=0}^{K} P(3,1,q,o) \quad (6)$$

- Average number of active emergency sensors

$$\overline{\Lambda_1} = N - \overline{Q} - \sum_{q=0}^{N-1}\sum_{o=0}^{K} P(1,0,q,o). \quad (7)$$

- Average number of active standard sensors

$$\overline{\Lambda_2} = N - \overline{O} - \sum_{q=0}^{N}\sum_{o=0}^{K-1} P(2,0,q,o). \quad (8)$$

- Average generation rate of emergency sensors

$$\overline{\lambda_1} = \lambda_1 \overline{\Lambda_1}. \quad (9)$$

- Average generation rate of standard sensors

$$\overline{\lambda_2} = \lambda_2 \overline{\Lambda_2}. \quad (10)$$

- Average waiting time in FIFO

$$ET_q = \frac{\overline{Q}}{\overline{\lambda_1}}. \quad (11)$$

- Average waiting time in orbit

$$ET_q = \frac{\overline{Q}}{\overline{\lambda_1}}. \quad (12)$$

III. NUMERICAL RESULTS

To demonstrate the efficiency of sleeping period in sensor networks in graphs, some computational results are presented in this section.

The corresponding parameters can be overviewed in Table 2. Numerous interactions of parameters were investigated by using the model. The most interesting results are displayed on the following figures. On each figure the blue lines (dotted with circles) and the red lines (dotted with triangles) represent the Non Controlled and the Controlled cases, respectively.

TABLE 2. Numerical values of model parameters.

Parameter	**Maximum**	**Value at *t***
Overall generation rate	λ	[0.1, 4.6]
Emergency generation rate	$\lambda_1=\lambda/10$	[0.01, 0.46]
Standard generation rate	$\lambda_2=9\lambda/10$	[0.09, 4.14]
Number of Emergency sensors	N	50
Number of Standard sensors	K	50
Retrial rate	ν	2
Service rate	μ	20
Initialization rate	γ	10
Mean time of sleeping period	$1/\beta$	[0.5, 2.5]
Mean time of listening period	$1/\alpha$	1.5

On Fig. 3 one can see the effect of increasing density of sensor request for the length of waiting emergency requests. In the lower domain of the parameter the random operation of the RF unit proved less efficient than in Controlled mode.

Fig. 4 shows how orbit fills up when the request generator parameter is increasing. These types of results are useful for fine tuning the orbit size in different cases of low priority requests densities.

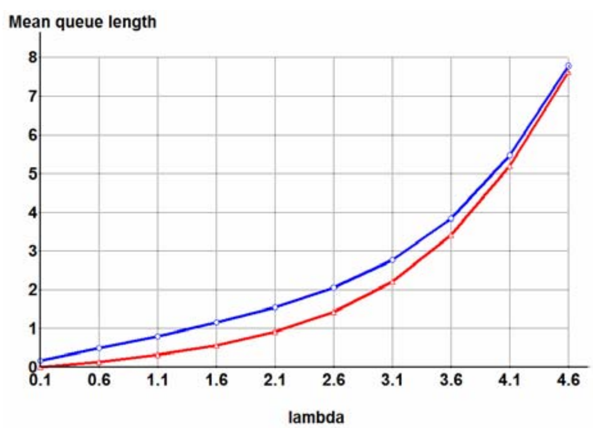

Fig. 3 Mean queue length vs. λ

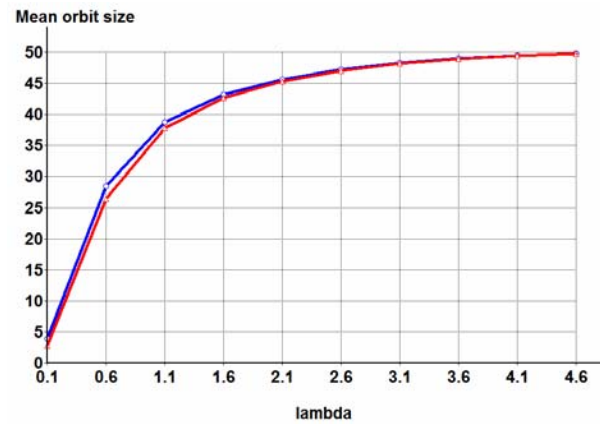

Fig. 4 Mean orbit size vs. λ

Fig. 5 deals with the essential part of the response time of RF unit, since processing a single request of a sensor can be described with a simple service rate. In Controlled case the average waiting time of emergency requests in queue, consequently the response time of processing an emergency signal is much more efficient than the random operation case. In higher request generation domain this difference fades out.

Fig. 5. Mean time spent in queue vs. λ

Fig. 6 displays the effect of different operational modes on the average waiting times of standard requests in the orbit. Since a standard mode requests is not able to wake up the radio unit, no significant difference can be observed.

For the following two figures the overall request generator parameter (lambda) is set at value of 0.5, which can be considered as a low density of request generation. The effect of mean time of the OFF state periods for the system characteristics is investigated.

On Fig. 7 the average number of waiting emergency requests is shown. In the random case (Non Controlled) this number significantly increases with the increasing length of the OFF state period. The longer time the RF unit sleeps, the more emergency requests are waiting. Due to the 'wake up' property, in Controlled case this queue length does not depend on the length of sleeping period of RF unit.

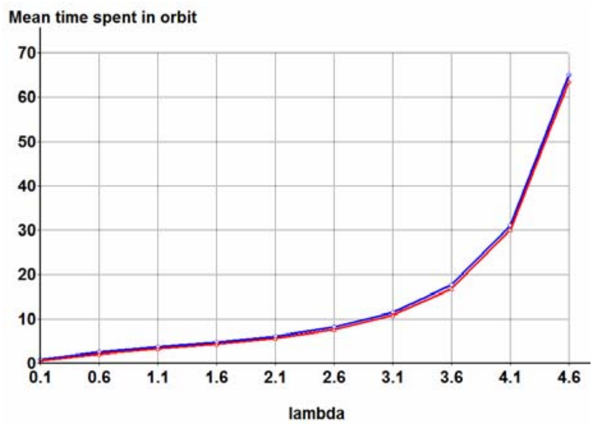

Fig. 6 Mean time spent in Orbit vs. λ

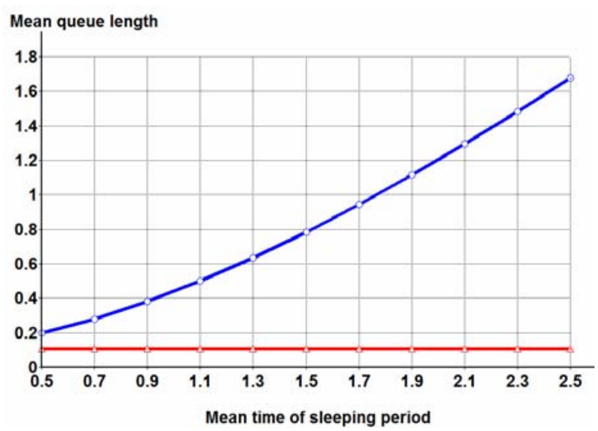

Fig. 7 Mean queue length vs. sleeping period, λ=0.5

Fig. 8 presents the corresponding results for standard requests. Here the length of RF unit OFF state period has a great influence to the number of waiting requests in orbit. The difference between the two cases is growing with the length of sleeping period, since there are a relatively low number of emergency requests, and serving a high priority request will leave the RF unit in idle state thus request can leave the orbit.

Fig. 9 shows that the RF unit is in sleeping state with smaller probability, when the generation rate is increasing. In case of normal working conditions (not too high generation rates), the utilization of RF unit is better in Controlled case, than in Non Controlled case.

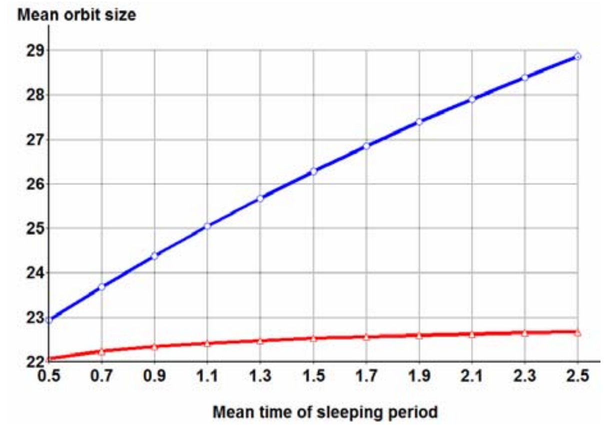

Fig. 8 Mean orbit size vs. sleeping period, λ=0.5

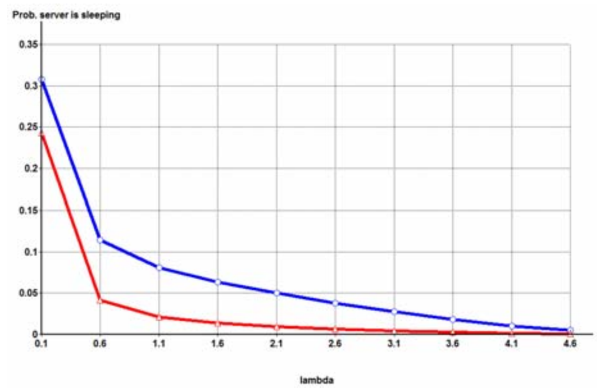

Fig. 9 Prob. server is sleeping vs. λ

The probability of the idle state of the RF unit can be observed in Fig. 10. This probability decreases with the increasing value of generation rate, but the difference between the two working modes is not significant.

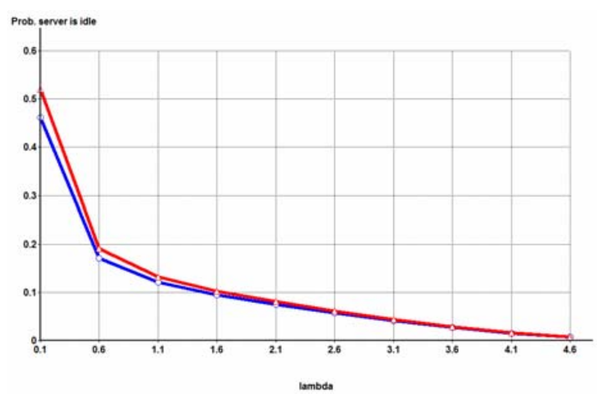

Fig. 10 Prob. server is idle vs. λ

In Fig. 11 a similar probability is displayed for the busy state of the RF unit. Beside the natural result (increasing probability with increasing generation rate) it can be observed, that in cases of medium values of λ this probability is higher for Controlled case.

For the last two figures the overall request generator parameter (lambda) is set again at value of *0.5*. The effect of mean time of the listening periods is investigated for the system characteristics.

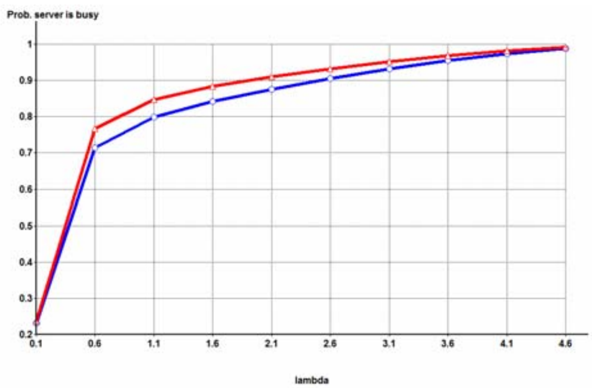

Fig. 11 Prob. server is busy vs. λ

Fig. 12 displays the correspondence between the average number of standard requests and the listening period with a given value of generation rate. A small value of this period implies a large number of requests waiting in orbit. As the listening period increases, the standard requests have greater chance to reach the RF unit, thus the size of the orbit is decreasing.

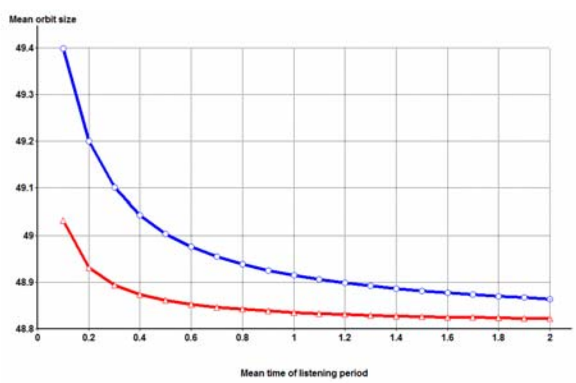

Fig. 12 Mean orbit size vs. listening period, λ=0.5

The impact of the length of listening period to the emergency requests can be seen in Fig. 13. A similar effect can be observed for this type of requests, as well. In case of a large listening period there is almost no need to initialize the RF unit. In addition, the Controlled case is more efficient for both groups of requests. For emergency requests this average queue length is almost constant, incoming jobs find the RF unit in ON state.

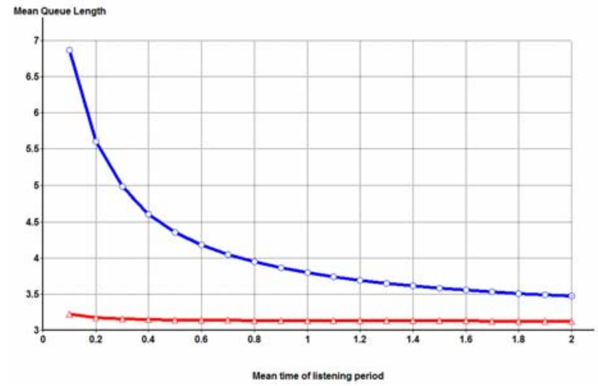

Fig. 13 Mean queue length vs. listening period, λ=0.5

IV. CONCLUSION

A sensor network with two priority request classes was investigated. Two operation modes were considered. The emergency (high priority) cases were able to wake up the RF unit while the standard (low priority) cases not.

When the dependence on the request generation rate was under consideration, the Controlled RF unit functionality has better system characteristics (e.g. response time). The Non Controlled cases show lower performance.

Similarly, when we investigate the effect of sleeping period of the RF unit, the main system parameters (response time, waiting times in orbit and queue, and queue length) prove the efficiency of the Controlled mode.

Since this Controlled operation corresponds to the power safe working of RF units, these results have some technical and economical advantages, as well. Further task could be to study the cases when the sensors have different request generation rates.

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REFERENCES

[1] I. F. Akyildiz and M. C. Vuran, *Wireless Sensor Networks*. John Wiley & Sons, July 2010.

[2] B. Almási, J., Roszik, and J. Sztrik, "Homogeneous finite-source retrial queues with server subject to breakdowns and repairs," *Mathematical and Computer Modelling*, vol. 42, no. 5-6, pp. 673–682, 2005.

[3] J. R. Artalejo, "Accessible bibliography on retrial queues: Progress in 2000-2009," *Mathematical and Computer Modelling*, vol. 51, no. 9-10, pp. 1071–1081, 2010.

[4] J. R. Artalejo and M. J. Lopez-Herrero, "The single server retrial queue with finite population: a BSDE approach," *Operational Research*, vol. 12, no. 2, pp. 09–131, 2012.

[5] P. Baronti, "Wireless sensor networks: A survey on the state of the art and the 802.15.4 and zigbee standards," *Computer Communications*, vol. 30, pp. 1655–1695, 2007.

[6] T. Bérczes, J. Sztrik, P. Orosz, P. Moyal, N. Limnios, and S. Georgiadis, "Tool supported modeling of sensor communication networks by using finite-source priority retrial queues," *Carpathian Journal of Electronic and Computer Engineering*, vol. 5, pp. 13–18, 2012.

[7] G. Bolch, S. Greiner, H. de Meer, and K. Trivedi, *Queueing Networks and Markov Chains, 2nd ed*. New York: John Wiley & Sons, 2006.

[8] A. Buchman, "An overview of hardware platforms used in wireless sensor nodes," *Carpathian Journal of Electronic and Computer Engineering*, vol. 4, pp. 19–22, 2011.

[9] M. W. Chiang, "Architectures of increased availability wireless sensor network nodes," in *Proceedings of ITC International Test Conference*, 2004.

[10] Z. Gál, T. Balla, and G. Terdik, "Statistical analysis of heating system with spatially distributed sensor network," in Plenary Lecture, *Embedded Systems and Wireless Sensors Networks Design and Applications ESWSNDA 2012*, 2012.

[11] V. T. Do, "An efficient solution to a retrial queue for the performability evaluation of DHCP," *Computers & OR*, vol. 37, no. 7, pp. 1191–1198, 2010.

[12] F. Dressler, *Self-Organization in Sensor and Actor Networks*. John Wiley & Sons, 2007.

[13] N. Gharbi and L. Charabi, "Wireless networks with retrials and heterogeneous servers: Comparing random server and fastest free server discipline," *International Journal on Advances in Networks and Services*, vol. 5, no. 1-2, pp. 102–115, 2012.

[14] C. Lung, S. Oniga, A. Buchman, and A. Tisan, "Wireless data acquisition system for IoT applications," *Carpathian Journal of Electronic and Computer Engineering*, vol. 6, pp. 64–67, 2013.

[15] P. Wüchner, J. Sztrik, and H. de Meer, "Modeling wireless sensor networks using finite-source retrial queues with unreliable orbit," *Lecture Notes in Computer Science*, vol. 6821, Springer-Verlag, pp. 275–285, 2011.

[16] F. Zhang and J. Wang, Stochastic analysis of a finite source retrial queue with spares and orbit search," in J. B. Schmitt, ed., MMB/DFT, *Lecture Notes in Computer Science*, vol. 7201, Springer-Verlag, pp. 16–30, 2012.

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