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Evaluating the Impact of Environmental Conditions on Wireless Sensor Nodes Using Stochastic Reward Nets

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ABSTRACT: wireless sensor networks (WSNs) are one of the most important distributed computing systems and environmental conditions have a great impact on their functionality. Some sensor nodes in WSNs have a battery as the power source and use renewable energy such as solar energy to charge it. If the batteries are not charged by harvesting energy from the environment, the tasks of the sensor nodes will fail. To prevent it, the sensor nodes can also decide to migrate tasks to neighbor nodes based on their battery status. On the other, the arrival rate of tasks at day hours is more than the arrival rate of tasks at night hours, but the charging rate of batteries is higher during the day than at night. Therefore, decisions of WSNs should be based on information from environmental conditions. The different arrival rates of tasks and charge rates of the batteries at day and night hours as the main environmental conditions have been ignored in the modeling of WSNs. In this paper, we model a WSN node using Stochastic Reward Nets (SRN) and then compute the steady-state probabilities of processing, failure, and migration of tasks and evaluate the impact of different environmental conditions on them in the WSNs. The results prove that changing the charge rate has a greater impact on the WSN functionality than changing the arrival rate.

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1- Introduction

Today, the unified power and performance modeling and evaluation of computing systems is an important research issue. These two measures, power, and performance, are inversely proportional together, which simultaneously evaluate them via a unified model motivates researchers.

Wireless sensor networks (WSNs) are computing systems to monitor the environment and long-distance communications that include nodes with sensing capabilities and wireless communications that collect data and send them to one or more sinks [1] [2]. The Internet of Things (IoT) and WSNs do have some commonalities [3]. Automation and connectivity are the hallmarks of the IoT landscape, made possible through WSNs. However, despite this link, WSNs are also able to exist independently of IoT. Their most important difference is in routing [4]. IoT is a network of devices that are connected to the Internet. The devices have sensors and actuators like WSNs, but there is not much routing involved. Things in IoT are typically designed to join the Internet immediately. However, WSNs may or may not be connected to the Internet. Instead, WSN nodes route their data to and from sink nodes. Therefore, WSNs and IoT can be used interchangeably, ignoring routing and Internet access.

According to Figure 1, sensor nodes and IoT devices can have various power sources [5]. One of the most important challenges is the conservation of battery life in sensor nodes. Energy harvesting is a method of collecting energy from the environment and converting it to energy that can power electronic circuitry [6]. Methods of harvesting energy from the external environment include thermoelectric conversion, solar energy conversion, wind energy conversion, radio frequency (RF) signal, and vibrational excitation.

Some sensor nodes have a battery as the power source and use renewable energy such as solar energy to charge it. Furthermore, the arrival rate of tasks and the charging rate of batteries are various in different environmental conditions. So environmental conditions affect the functionality of these nodes. If the environmental conditions are not suitable (for example, the solar panel of the WSN node does not capture energy from the sun), the battery energy of nodes will be consumed after a while, causing nodes to be disabled and their tasks, especially real-time tasks, to be failed. To prevent tasks from being lost, nodes can migrate their tasks to neighbor nodes. Therefore, analyzing the impact of environmental conditions on the functionality of WSNs and the processing and failure of tasks is more important.

To model the sensor nodes and evaluate the impact of different environmental conditions on their functionality, stochastic reward nets (SRN) [7] are used in this paper. One of the advantages of modeling is to simplify the problem. The SRN is a stochastic extension of Petri nets that provide a powerful way for modeling distributed computing systems

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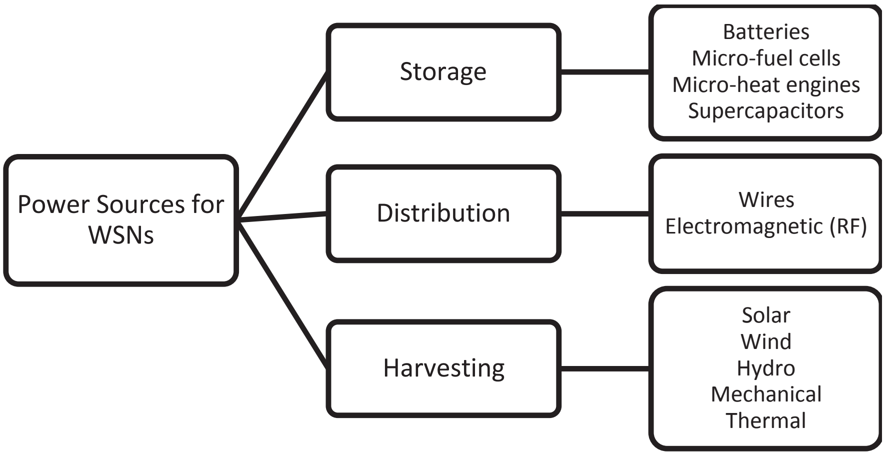


Fig. 1. The various power sources for sensor nodes [5]

and it is supported by the SPNP tool [8] [9]. The places, transitions, and tokens are three basic elements of SRN formalism. Places, represented by circles, can contain tokens. Transitions, represented by rectangles, are used to change the number of tokens of the places. If the guard function of a transition is true, the transition can be done according to the exponential distribution function. The main contribution of this paper can be summarized:

- The SRN is used to model a WSN node.
- The proposed model can evaluate the impact of different environmental conditions on the charge and discharge of the battery of the sensor nodes.
- The proposed model can evaluate the impact of different arrival rates of tasks on the functionality of the WSN node.
- The proposed model is used to compute the steady-state probability of processing, failure, and migration of tasks.

The rest of this paper is organized as follows. Section 2 presents the related work of WSN modeling and the unified power and performance modeling and evaluation. Section 3 introduces the proposed SRN model and the measures that can be computed by it. In Section 4, the results obtained from different environmental conditions are compared by analytically solving the proposed SRN model. Furthermore, the results obtained from the proposed model are compared with the results obtained from the OMNeT++ simulator. Finally, Section 5 concludes the paper and gives ideas for future work.

2- Related work

A guide has been provided in [10] for researchers and IoT node/application developers in selecting the best technique for an IoT use-case, presenting a review of processor power and energy consumption estimation techniques starting from the lowest level of abstraction to the highest level of abstraction.

There are many papers on modeling different aspects of WSNs, but they usually ignore the impact of the battery and the environmental conditions. Table 1 compares related works with our work. For example, a probabilistic algorithm has been proposed in [11] to analyze the network connectivity in mobile WSNs by considering network probability, detection area, radius of the individual nodes, and whole detection area.

Energy consumption for sensors and systems on chips has been calculated in [12] concerning the duty cycle to optimize power consumption by using an artificial neural network. In [13], a sensor node with energy harvesting capability has been modeled to determine performance parameters and to extract some experimental results to predict energy consumption. An automatic solution based on the integration of formal models, a set of power consumption and reliability models, and a sensitivity analysis strategy to select WSN configurations have been proposed in [14] to design power consumption-aware WSN applications and communication protocols. A mixed integer linear programming model has been presented in [15] to determine the multicast sink optimal route of the source sensor nodes to mobile sinks in WSNs which determines the time and location of sinks to collect maximum coded data and reduce the delay in sinks movement and energy consumption. In [16], a two-phase lifetime-enhancing method has been proposed to increase the network lifetime in energy-harvesting WSNs while satisfying the full target coverage which comprises both static non-rechargeable sensor nodes and mobile rechargeable ones. In [17], an SRN model has been proposed to evaluate the functionality of mobile WSNs in different environmental, communication, and movement conditions but its assumptions are different from this paper and it ignores different arrival rates of tasks to nodes in different environmental conditions and also the probability of failure of tasks. In [18], a computing system with a three-layer architecture (IoT-Fog-Cloud) has been

Table 1. Comparing related works with our work

Ref	WSN	Battery	Different Arrival Rate	Environmental Conditions	Migration	Power & Performance	Stochastic Model
[11]	✓	✓	x	x	x	✓	x
[12]	✓	x	x	x	x	✓	x
[13]	✓	✓	x	✓	x	✓	✓
[14]	✓	x	x	x	x	x	✓
[15]	✓	x	x	x	x	✓	x
[16]	✓	x	x	x	x	✓	✓
[17]	✓	✓	x	✓	✓	✓	✓
[18]	x	x	✓	✓	✓	✓	✓
[19]	x	x	✓	x	x	✓	✓
[20]	x	x	✓	x	x	✓	✓
[21]	x	x	✓	x	✓	✓	✓
[22]	x	x	x	x	x	✓	✓
Ours	✓	✓	✓	✓	✓	✓	✓

modeled to propose an optimized power-performance manner of task offloading.

Some researchers model the computing systems to evaluate the power and performance measures using different stochastic extensions of Petri nets, but they do not model WSNs. The impact of resource heterogeneity and failures on the power and performance of the infrastructure of cloud computing systems has been investigated in [19] by presenting a stochastic activity network (SAN) model. The impact of the temperature and network traffic on the power and performance of cloud computing systems has been studied in [20] by proposing an SRN model. The impact of the resource allocation algorithms and process migration methods on the power and performance of virtualized systems has been evaluated in [21] by presenting an SRN model. The impact of the network routing algorithms and protocols on the power and performance of communication networks has been studied in [22] by proposing an SRN model.

3- Proposed model and measures

In this section, we model a WSN node using the SRN and then introduce the measures that can be computed by the proposed model.

3- 1- Modeling the WSN node

Figure 2 represents the proposed SRN model for a WSN node. The number of tokens inside the place *Battery* which can be equal to zero, one, and two represents the low, medium, and high statuses of the battery of the WSN node, respectively. The timed transitions *Charge* and *Consume* model how to charge and consume the battery of the WSN node, respectively. They follow an exponential distribution with rates α and β, respectively. Two guard functions G5 and G6, listed in Table 2, are assigned to transitions *Charge* and *Consume*, respectively. The guard function G5 checks the battery of the WSN node is not high. If this condition is true, function G5 returns true to enable the timed transition *Charge*; otherwise, it returns false to prevent the transition from firing. When the timed transition *Charge* fires, a token is added to place the *Battery*. On the other hand, if the node does not have any task, it does not consume power. The guard function G6 checks the situation that the battery is not low and the node has a task. If this condition is true, timed transition *Consume* is enabled; otherwise, it cannot fire. When timed transition *Consume* fires, a token is removed from the place *Battery*.

The number of tokens inside place *NeighborNode* which can be equal to zero and one represents the non-existence and existence of neighbor nodes for this node to migrate its tasks to them, respectively. The timed transitions *Available* and *NoAvailable* model the availability or non-availability of neighbor nodes for this node. Two guard functions G7 and G8, listed in Table 2, are assigned to transitions *Available* and *NoAvailable*, respectively. According to the guard function G7, if the neighbor nodes are not available for this node, the timed transition *Available* can provide them at an exponential distribution with rate δ. Similarly, according to the guard function G8, if the neighbor nodes are available for this node,

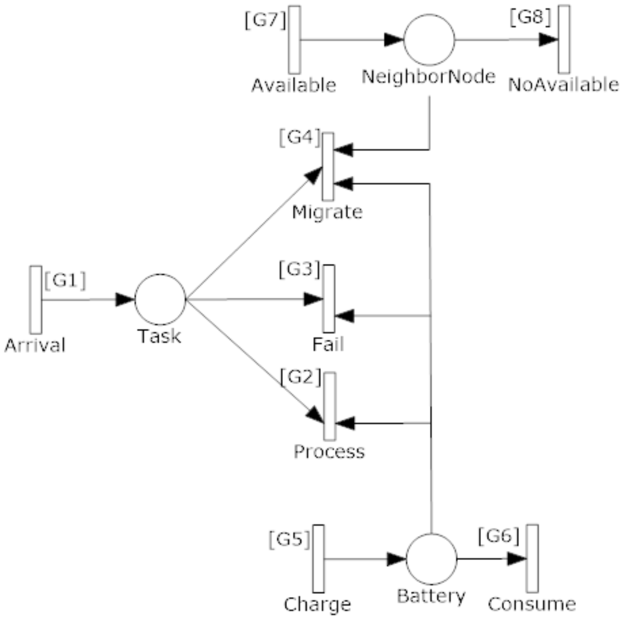


Fig. 2. The proposed SRN model for a WSN node

Table 2. Guard functions associated with transitions

Guard	Function
G1	$Mark(Task) == 0$
G2	$Mark(Task) == 1\ \&\&\ Mark(Battery) > 0$
G3	$Mark(Task) == 1\ \&\&\ Mark(Battery) == 0\ \&\&\ Mark(NeighborNode) == 0$
G4	$Mark(Task) == 1\ \&\&\ Mark(Battery) == 0\ \&\&\ Mark(NeighborNode) == 1$
G5	$Mark(Battery) < 2$
G6	$Mark(Battery) > 0\ \&\&\ Mark(Task) == 1$
G7	$Mark(NeighborNode) == 0$
G8	$Mark(NeighborNode) == 1$

the timed transition *NoAvailable* can eliminate them at an exponential distribution with rate δ.

The number of tokens inside place *Task* which can be equal to zero and one represents the non-existence and existence of tasks in this node, respectively. The timed transition *Arrival* model how to arrive tasks to this node. According to the guard function G1, assigned to transition *Arrival*, if the WSN node does not have any task, the timed transition *Arrival* can arrive at a task at an exponential distribution with rate λ. According to the guard function G2, assigned to the transition *Process*, if the WSN node has a task and its battery is not low, the timed transition *Process* can process its task at an exponential distribution with rate μ. According to the guard function G3, assigned to transition *Fail*, if the WSN node has a task and its battery is low and there are no neighbor nodes for it, the time transition *Fail* can process its task at an exponential distribution with rate ρ. According to the guard function G4, assigned to transition *Migrate*, if the WSN node has a task and its battery is low and there are neighbor nodes for it, the timed transition *Migrate* can migrate its task at an exponential distribution with rate θ.

3- 2- Measures

The proposed SRN model can compute the functionality-related measures of the sensor nodes defined by the reward functions. The interesting measures in the proposed SRN model are as follows.

- **Probability of existence of tasks (P).** This measure computes the probability that the WSN node has a task. Since the number of tokens inside place *Task* represents the non-existence and existence of tasks in the WSN node, we compute this measure by defining the reward function (1). This measure is equal to the sum of the probabilities of processing, failure, and migration of tasks.

$$P = \pi(Mark(Task) == 1) \tag{1}$$

- **Probability of task processing (P_p).** This measure computes the probability that tasks are processed in the WSN node. If the battery of the WSN node is not low, its tasks can be processed. Since the number of tokens inside the place *Battery* represents the status of the battery of the WSN node, we compute this measure by defining the reward function (2).

$$P_p = \pi(Mark(Task) == 1 \ \&\& \ Mark(Battery) > 0) \tag{2}$$

- **Probability of task failure (P_f).** This measure computes the probability that tasks are failed in the WSN node. If the battery of the WSN node is low and there are no neighbor nodes for it, its tasks can fail. Since the number of tokens inside the place *NeighborNode* represents the non-existence and existence of neighbor nodes for the WSN node, we compute this measure by defining the reward function (3).

$$P_f = \pi(Mark(Task) == 1 \ \&\& \ Mark(Battery) = 0 \ \&\& \ Mark(NeighborDevice) == 0) \tag{3}$$

- **Probability of task migration (P_m).** This measure computes the probability that tasks are migrated from the WSN node to neighbor nodes. If the battery of the WSN node is low and there are neighbor nodes for it, its tasks can be migrated. we compute this measure by defining the reward function (4).

$$P_m = \pi(Mark(Task) == 1 \ \&\& \ Mark(Battery) = 0 \ \&\& \ Mark(NeighborDevice) == 1) \tag{4}$$

4- Evaluate and performance comparison

4- 1- Evaluate the result

In this section, we evaluate the steady-state results obtained by numerically solving the proposed SRN model using the SPNP tool [8] [9]. Under our assumptions, if neighbor nodes are never available for the WSN node, no task will migrate and it will fail. But if neighbor nodes are always available, no task will be failed. In the proposed model, we assumed that the probability of the existence of neighbor nodes is equal to 0.5. Furthermore, if the battery of the WSN node always has enough power, no task will fail, so we consider the low, medium, and high statuses for the battery of the WSN node. We define three environmental conditions and compare their impact on interesting measures. These conditions are listed below.

- **Suitable ($\alpha = 2\times\beta$).** The rate of charge of the battery is twice that of the consumption of the battery.
- **Moderate ($\alpha = \beta$).** The rates of charge and consumption of the battery are equal.
- **Unsuitable ($\alpha = \frac{1}{2}\times\beta$).** The rate of charge of the battery is half that of the consumption of the battery.

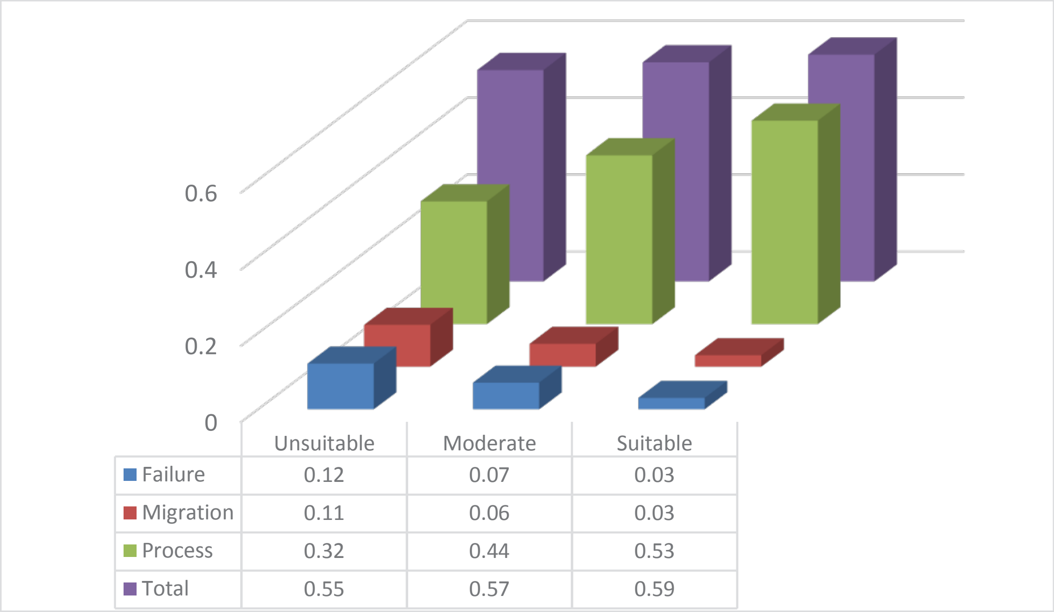
Figure 3 presents the results obtained from the proposed SRN model in different environmental conditions. These results are computed based on the value of rates provided by Table 3.

As can be seen in Fig 3, the environmental conditions can affect the probabilities of processing, failure, and migration of tasks. In suitable environmental conditions, the battery of the WSN node is more, so the probability of the existence of tasks in the WSN node and their processing will improve and the probabilities of failure and migration of tasks will decrease compared with moderate environmental conditions. The values of these probabilities in moderate environmental conditions are also better compared to unsuitable environmental conditions. In unsuitable environmental conditions, the battery of the WSN node is lower, so the probability of task processing will decrease and the probability of failure and migration of tasks will increase.

Now, if we assume that the environmental conditions

Table 3. Input rates of the proposed SRN model

Rate	Value
Charge rate of the battery (α)	Conditional
The consumption rate of the battery (β)	5 event/m
Change rate of access to the neighbor nodes (δ)	10 event/m
Arrival rate of tasks (λ)	3 task/m
Process rate of tasks (μ)	2 task/m
Failure rate of tasks (ρ)	2 task/m
Migration rate of tasks (θ)	4 task/m



	Unsuitable	Moderate	Suitable
🟦 Failure	0.12	0.07	0.03
🟥 Migration	0.11	0.06	0.03
🟩 Process	0.32	0.44	0.53
🟪 Total	0.55	0.57	0.59

Fig. 3. Results obtained from different environmental conditions

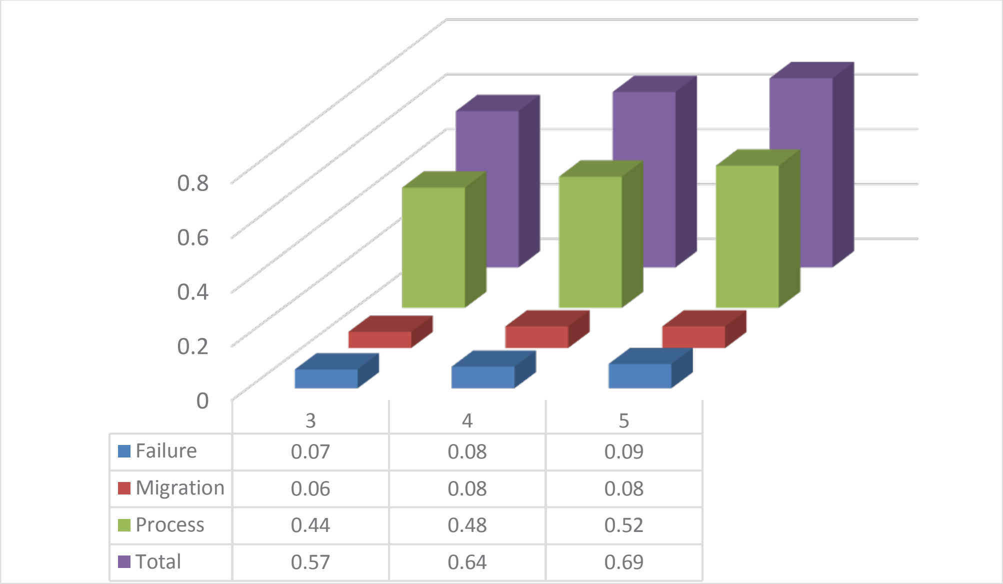


Fig. 4. Results obtained from different arrival rates

Table 4. Comparison of the results obtained from the proposed SRN model and OMNeT++ simulator

Measures	SRN Model	OMNeT++
Failure	0.07	0.069±0.005
Migration	0.06	0.059±0.006
Process	0.44	0.443±0.004
Total	0.57	0.571±0.005

are always moderate ($\alpha = \beta$), the results obtained from the proposed SRN model in different arrival rates ($\lambda = 3,4,5$) will be as shown in Fig 4. As can be seen in Fig 4, increasing the arrival rate of tasks increases all probabilities at the same rate. However, the impact of changing the charge rate is greater than changing the arrival rate on the obtained results.

4- 2- Performance comparison

In this section, we compare our results with the results obtained from the OMNeT++ simulator. This simulator is an extensible, modular, component-based simulation library and framework, primarily designed for building communication network simulators [23]. To summarize, we only simulate the condition of Fig. 4 with the arrival rate ($\lambda = 3$) in the OMNeT++ simulator. Table 4 shows the simulation results obtained from the average of 30 independent runs with the analytical results obtained from the proposed SRN model. Since the difference between them is small, it can be concluded that the proposed SRN model performs as well as it is expected.

5- Conclusion

We proposed an analytical SRN model to evaluate the impact of environmental conditions on the functionality of a WSN node. In the proposed model, the WSN node has a battery and uses renewable energy to charge it. If the battery of the WSN node is not charged, its tasks will fail. To prevent this, the WSN node can migrate tasks to neighbor nodes based on its battery status. The results obtained from numerically solving the proposed SRN model presented that the environmental conditions have a greater impact on the probability of the existence of tasks in the WSN node and their processing, failure, and migration. Furthermore, it was proved that changing the charge rate has a greater impact than changing the arrival rate on the WSN functionality.

As a future work, the impact of other factors, such as communication and movement conditions on the functionality of the sensor nodes can be modeled and evaluated. Furthermore, the impact of heterogeneity of nodes can be analyzed using the SRN models.

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