A Comprehensive Model for Energy Consumption in Wireless Sensor Networks Using the Markov Model

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Abstract:
Due to the availability of energy-efficient sensors, microprocessors, and radio frequency circuits for data transfer, wireless sensor networks developed rapidly and spread. Wireless sensor networks that include thousands of low-cost sensor nodes are used in various applications such as health surveillance, battlefield surveillance, and environmental monitoring. The sensor node non-rechargeable, non-replaceable and limited power supply is considered as the main challenges of these type of networks. With the completion of the node's power supply, the node actually remains unused. Sleep-wake scheduling is used to reduce energy consumption and extend the life of nodes. In this paper we try to investigate sleep-wake scheduling in sensor nodes with the Markov model. In probability theory, a Markov model is a stochastic model used to model randomly changing systems where it is assumed that future states depend only on the current state not on the events that occurred before it (that is, it assumes the Markov property). Generally, this assumption enables reasoning and computation with the model that would otherwise be intractable. For this reason, in the fields of predictive modeling and probabilistic forecasting, it is desirable for a given model to exhibit the Markov property. It is expected that the proposed Markov model covers all aspects of sleep/wake scheduling in wireless sensor networks.

Keywords:
Wireless Sensor Network, Markov Model, Scheduling, Sleep/Awake

1. Introduction

Recent advances in the design of the electrical circuits have expanded the use of wireless sensor networks. Wireless sensor networks consist of many small devices called sensor nodes that have the restricted ability to sense and process communication [1]. Sensor nodes sense environmental data, and if necessary, carry out partial processing on the data. Then sensor nodes send the sensed information using a specific method to a base station, which is connected to AC power and has no hardware limitation, for overall processing and a status evaluation of the entire network.

However, sensor nodes in terms of hardware are weak due to economic factors. These nodes have a memory with low capacity, a poor processor, relatively short-range antennas and most importantly have a restricted, non-rechargeable and irreplaceable power supply [2]. With the completion of the power supply node, the node is practically useless and so-called dies. To avoid quick extinction nodes, two main strategies to reduce energy consumption have been suggested: optimal routing and sleep/wake scheduling. The nodes exposure to long-term sleep situations, in which at least possible circuit-switched and other circuits switched off, play an important role in reducing energy consumption and extend the lifetime of wireless sensor networks [3].

A model requires checking the nodes sleep-wake process and its impact on energy consumption. It is necessary to study all existing aspects of the sleep-awake process and propose a perfect model for this process. Among modeling tools, Markov model [4] due to its robust mathematical basis, can be selected as the sleep-wake process modeling tool. We, in this paper, propose a comprehensive model using the Markov model for the node sleep-wake process in a wireless sensor network (WSN) with respect to all available aspects. It is expected that the proposed model will make the evaluation of sleep-awake process easier and be regarded as a reference in the field. The proposed model can be applied to other wireless networks to improve the performance of 5G networks [5,6].

The rest of the paper is organized as follows. Section II describes the related work. The Markov model, in order to model the sleep-awake process, is presented in Section III. Section IV presents the results of the performance evaluation of the proposed scheme including the comparison with the existing schemes, followed by the conclusion in Section V.

2. Related Works

There are few papers on sleep-awake modeling using Markov model. The previous papers listed are about Markov model and sleep-awake scheduling separately or mainstream.

In [7] the proposed scheme is improved by controlling the node operation based on the sleep-and-wake up mechanism for energy efficiency. In that paper, an event detection scheme with WSN is introduced, which adopts a hierarchical structure to efficiently integrate the spatial and temporal correlation of sensor data. Here a fusion algorithm considering both the weight of the sensors and spatial information is applied to the Markov random field to properly fuse the decisions of the neighboring nodes. A Markov chain is also adopted to effectively extract the temporal correlation after the spatial correlation is decided.

The contribution of [8] is three-fold. First, a new attack decision criterion is proposed which exploits the spatial–temporal characteristics hiding in the generation mechanism of wake-up packets. Second, a Hidden semi-Markov model (HsMM) is presented that captures the spatial–temporal characteristic of a control server's signaling behavior. Third, an advanced LTE signaling attack detector is proposed and proves its superiority in various simulations. It is shown that the proposed detector results in much less frequent false alarms.

In order to improve power efficiency and meet users of cognitive wireless sensor networks (UCWSNs) in a distributed cognitive wireless sensor network, a game-theoretic power control mechanism based on Hidden /Markov model (HMM) is proposed in [9]. By the HMM model, UCWSNs can infer the set of competitors accurately and choose an optimal policy of transmission power. Simulation results indicate that the game-theoretic power control mechanism based on HMM can incur better power efficiency on the premise of QoS requirements compared to others, which is at the expense of implementation cost.

A MAC protocol is presented for WSN in [10] that is based on the ON/OFF Markov model. The key idea is to adapt the radio activation time based on the network traffic. The passage from passive to active mode is set according to the transition probability from the OFF to ON state. Based on this probability, the period that the transceiver can stay in sleep mode is given.

By developing a stochastic Markov model of the sensor node of WSNs and applying the stochastic method, the explicit expression of the distribution of the number of data packets in a sensor node is derived in [11]. A numerical analysis was provided to validate the proposed model and the results obtained. The proposed model and analysis method are expected to be applied to the design and analysis of various WSNs, taking the times spent in active and sleep modes into consideration.

In [12], a new general analytical Markov model for a thinning scheme in wireless cellular networks is presented, where channel holding times for new calls and handoff calls are distinctly distributed with different average values. For the proposed model, the closed matrix product-form solutions for the stationary probability were derived.

3. Proposed Method

In this section, the proposed method has been discussed. The main structure of this paper is based on [11], where a sleep/awake scheduling was introduced. Let a WSN in which each sensor node may stay in three major modes, i.e., active, semi-active and sleep modes. The active mode, which is called the full-active phase denoted by phase R, and the other phase is called the semi-active phase, which is denoted by phase N. The sleep mode is mentioned as phase S. Figure 1 provides a brief description the transition relationship between these phases.

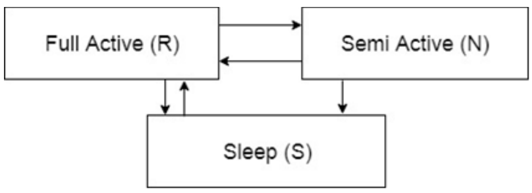

Figure 1. *The sensor node status change diagram.*

The Figure 1 illustrates that the sensor node can switch from the full-active mode to the semi-active mode, and vice versa. It can also change its mode from the full-active to the sleep mode, and vice-versa. Finally, the semi-active mode can only switch to sleep mode in one direction. The proposed method is described in following assumptions:

(a) The duration of a sensor in sleep mode is distributed exponentially with a mean of $1/\beta$. The sensor node which is in sleep mode, consumes minimum energy and almost all its components are off. After the sleep duration, the sensor node turns on its components and changes to full-active mode.

(b) The duration that a sensor spends in the full-active phase is a random time that has an exponential distribution with a mean of 1/α. When a sensor node is in active mode, it may beget packets pursuant to a Poisson process at a rate of λ; or relay packets receiving from other sensor nodes with regards to a Poisson process at a rate of λE; or process (transmit or relay) data packets with random exponential time with a mean of 1/μ.

(c) After the period spent in the full-active phase, the sensor node's mode is changed to either the semi-active phase or the sleep after full active mode. The node is changed to semi-active mode if there is at least one data packet. The sensor node can only transmit data packets with random exponential time with a mean of 1/μ in the semi-active phase, and it cannot beget or receive any data packets. In our proposed model, in each step in semi-active mode, it is possible that the semi-active is changed to full-active in accordance to a Poisson process at a rate of γ.

(d) Each node has sufficient space, or a buffer with infinite size, to store the data it generated or forwarded from other nodes for relaying purposes.

In [11]'s model which is shown in Figure 2, it is assumed that sensor nodes have sufficient space or a buffer with infinite size to store data. It is obvious that this assumption is not correct. We modified the [11] model by considering a fixed size for the buffer which is illustrated in Figure 3.

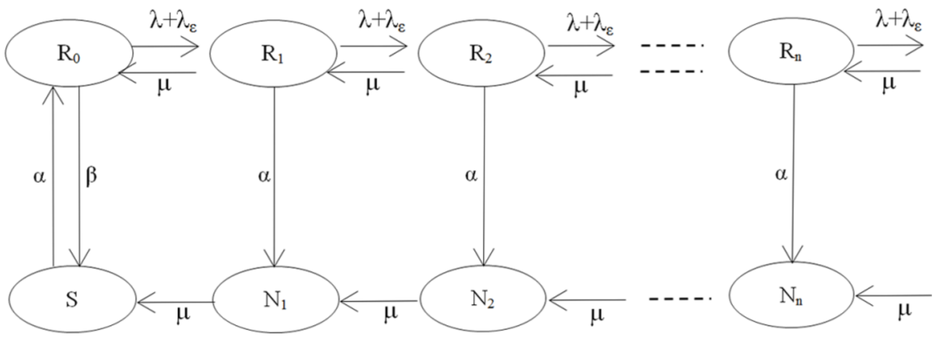

Figure 2. *Imperfect Markov model presented in [9].*

In [11]'s model which is shown in Figure 2, after processing all data packets in the semi-active phase, the sensor node will move to the sleep mode automatically. The model proposed in [11] does not consider supervised active commands which emerge from the base station or any other sensor node.

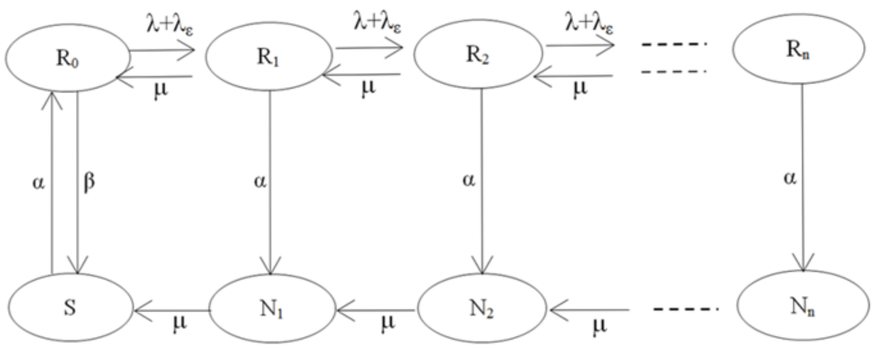

Figure 3. *Markov model with finite buffer size.*

Ignoring supervised commands in order to change modes in active phase is another drawback of [11]'s model. Considering these weaknesses, we propose a complete

Markov model in order to describe sleep/awake situations of a sensor node. Figure 4 shows our proposed Markov chain.

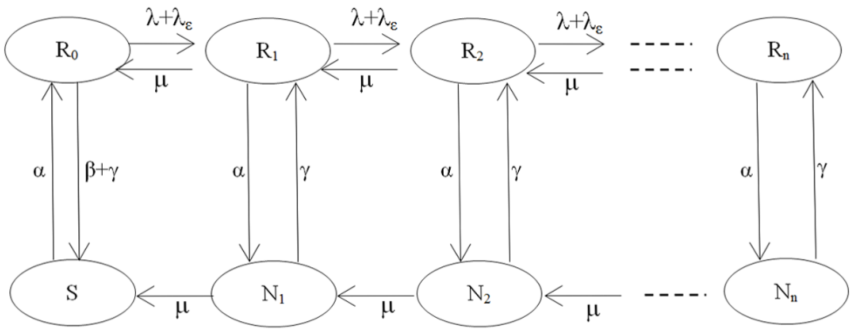

Figure 4. *The complete Markov chain.*

In wireless sensor networks due to restricted, non-rechargeable and non-replacement power supply, the nodes' energy consumption is a critical issue that needs to be investigated. Energy consumption occurs in the sending and receiving of data packets and the context of switching between modes. The following notations show all energy consumption states.

etfa: the transmitter power consumption per data packet in the full-active mode;

etsa: the transmitter power consumption per data packet in the semi-active mode;

eofa: the operation power consumption per unit time in the full-active mode;

eosa: the operation power consumption per unit time in the semi-active mode;

eos: the operation power consumption per unit time in the sleep mode;

efasa: the power consumption when the sensor switches from the full-active mode to the semi-active mode;

efas: the power consumption when the sensor switches from the full-active mode to the sleep mode;

esas: the power consumption when the sensor switches from the semi-active mode to the sleep mode;

esafa: the power consumption when the sensor switches from the semi-active mode to the full-active mode;

esfa: the power consumption when the sensor switches from the sleep mode to the full-active mode.

efafa: the power consumption when the sensor switches from the full-active mode to the full-active mode; and

esasa: the power consumption when the sensor switches from the semi-active mode to the semi-active mode;

In addition to energy consumption, the number of packets sent is another measure in order to evaluate sensor nodes. Where a sensor node is in Rc situation in which c is the buffer size, by a rate of λE, packets may be lost. The evaluation of proposed method in terms of energy consumption and packet transmission is discussed in next section.

4. Simulation Results

We used MATLAB 2015b in order to simulate the Markov chain. Before running simulation, the numerical parameters were set. Table 1 lists the Markov chain parameters along with their values.

Table 1. *Value of parameters used in numerical analysis.*

Parameter	Value
Etfa	31 µw
Etsa	11 µw
Efafa	31 µw
Eofa	25 µw
Eosa	23 µw
Eos	0.3 µw
Efas	0.01 µw
Esfa	0.5 µw
λE	0.2
M	0.5
B	0.05
A	0.1

First, we evaluated buffer size. The generation rate λ and initial energy of sensor node were set to 0.05 and 0.5 joules respectively. The sensor node continued its activities until it had energy. Figure 5 and 6 illustrate the number of drop and sending packets respectively by increasing the buffer size from 5 to 20. It is obvious that whatever buffer becomes larger, the number of drop packets becomes lower and the number of drop packets becomes greater.

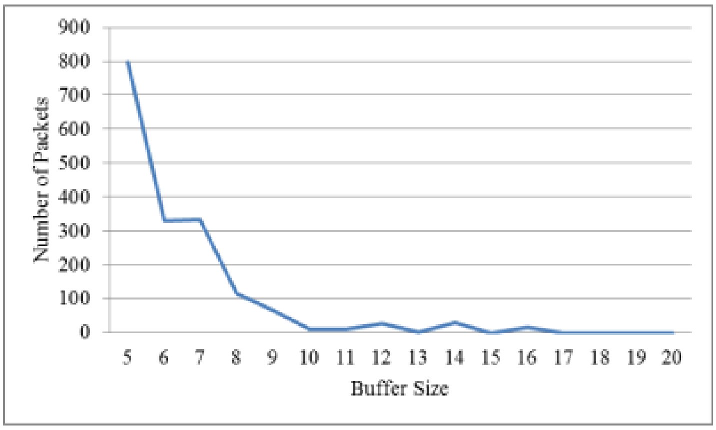

Figure 5. *Number of drop packets.*

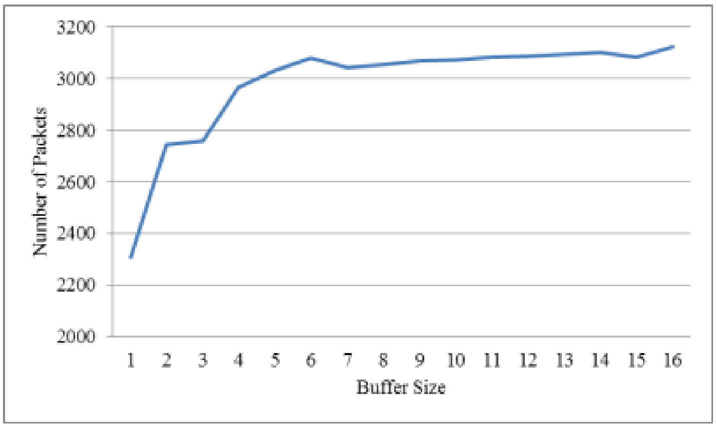

Figure 6. *Number of sending packets.*

According to simulation results, the buffer size was set to 15. The energy consumption of the sensor node in sleep, active and semi-active modes are respectively illustrated in Figure 7, Figure 8, and Figure 9. The sensor data generating rate (λ) changed from 0.05 to 0.5 by 0.05 steps.

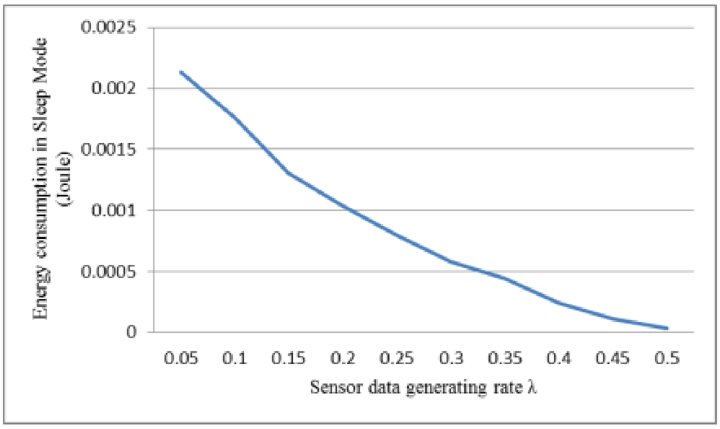

Figure 7. *Energy consumption in sleep mode.*

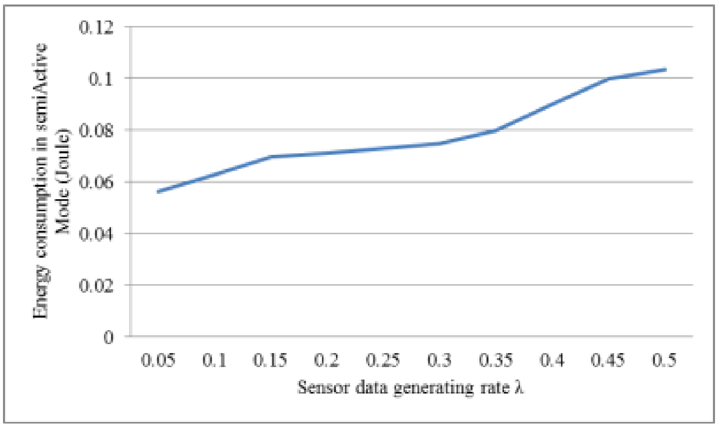

Figure 8. *Energy consumption in semi-active mode.*

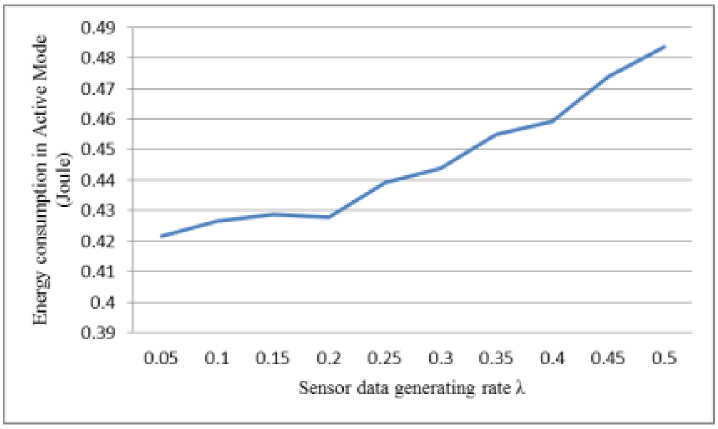

Figure 9. *Energy consumption in full-active mode.*

It is evident that sensor data generating rate has significant effects on energy consumption in various phases. According to Figure 7, Figure 8, Figure 9, by increasing the sensor data generating rate, the sleep mode energy reduced and the sleep mode energy rose. These fluctuations are due to the change in packet generation speed.

5. Conclusions

Our aim of doing this research was to report the results of our study of the energy consumption in WSN. By developing a stochastic model of the sensor node of WSNs and applying the stochastic method, we derived the explicit expression of the distribution of the number of data packets in a sensor node. Then, we determined several important performance matrices related to the sensor node's energy consumption. Numerical analysis was provided to validate the proposed model and the results obtained. The results show that the energy consumption for switching between the active mode and sleep mode does not depend significantly on the number of data packets. However, the energy consumption for transmitting the data packets depends on the rate at which data packets are generated, which means that transmitting high-density data requires the expenditure of more energy. The proposed model and analysis method are expected to be applied to the design and analysis of various WSNs, taking the times spent in active and sleep modes into consideration.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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