# Evaluating Autonomous-Energy-Harvesting Device Lifetime for the Internet of Medical Things with a Petri Net Formulation Considering Battery SoH

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### Abstract

During charging-discharging operations, the batteries of the Internet of Things (IoT) devices are subject to a depletion that should be considered when predicting their lifetime. This paper proposes a new modeling for the IoT autonomous devices (AD) using Colored Generalized Stochastic Petri Nets (CGSPN). The ADs we consider are equipped with an energy harvesting system, and use a wireless link to connect with their neighbors. The CGSPN formulation models AD functionalities, and evaluates their impact on the battery lifetime by considering its state of health (SoH). The conducted analysis shows the ability of the proposed model to predict the ADs' lifetime which is very critical for medical applications.

Keywords [1]
IoT, Autonomous devices, Rechargeable battery, Energy harvesting, Battery State of Health, Colored Petri net

## 1. Introduction

Nowadays, the world enjoys a considerable growth of the Internet of Things (IoT) applications. IoT makes it possible to the IoT devices to exchange data via the Internet network. The IoT can connect a large number of objects to the Internet via wired or wireless links [1]. People can use, share and offer services anytime anywhere in the world.

The Internet of Medical Things (IoMT) is an IoT applied in a medical environment [2, 3], where various monitoring medical sensors are connected via a wireless network (see Figure 1). IoMT devices are used to monitor people or medical instruments. When dynamic sensors and actuators are used in the IoMT, the technology will become an integral part of physical electronic systems connected to the Internet [4].

When the IoMT uses autonomous devices (ADs), the impact of the network on enhancing the medical services can be amazing. ADs use artificial intelligence to process their collected information and take their own decisions.

In many cases, the battery is the only source of energy for ADs. Usually, the battery cannot be replaced due to the conditions surrounding the implementation site, or the process of replacing the battery is too expensive. Therefore, researchers used energy conservation mechanisms such as the sleeping mechanism, clustering, and improved the performance of protocols in order to reduce energy consumption [5]. On the other hand, collecting renewable energies from the environment and converting it into electrical energy to feed devices with energy, is considered a viable solution to the power shortage problem [6, 7].

Given that external energy sometimes may not be available, storing the collected energy in batteries will

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resolve this issue, since it allows for continuous feeding of the device components. However, several studies have shown that battery efficiency is affected by recharging operations. That is, after a certain period of time, it becomes unusable. Battery aging involves a drop in battery capacity. Therefore, the capacity of the battery is relative to its use. One Charge/discharge process is called a cycle. As the number of cycles increases, the relative capacity decreases. The battery State of Health (SoH) is defined as an indicator of this capacity decline [8, 9].

By making use of modeling, the behavior of a device can be predicted before its realistic installation. Indeed, we can find many works that used Petri Nets of different kinds to evaluate the performance of sensors [10, 11], drones [12], robots [13], and others [14]. The presented works allowed to improve AD networks applications by studying the feasibility of their implementation, identifying potential problems and anticipating their solutions.

To the best of our knowledge, there is no modeling that uses Petri nets and simultaneously takes into account the following factors :

- monitoring power consumption while interacting with the network,
- energy harvesting capability of the ADs,
- sleeping mechanism to save battery energy, and
- health status of the ADs’ rechargeable batteries.

In order to address these aspects, we present a Colored Petri net model that mimics the functionalities of the ADs so as to predict their lifetime. The model represents all the processes that have a relatively high impact on power consumption, such as monitoring, sending and receiving, listening to the network, and processing data. It also models the process of collecting energy from the ambient. Furthermore, the model considers the batteries' life cycle by monitoring their SoH.

The remainder of this paper is organized as follows. Section 2 gives a background for our work: we present the CGSPN formalism, the internet of medical things, and the SoH feature. Section 3 presents some related works. Next, section 4 illustrates our proposal. In section 5, we present and discuss the obtained results. Finally, we draw our conclusion as well as some directions for further investigations.

# 1. Background

## 1.1. Internet of Medical Things

Prevention, diagnosis, treatment of disease, and injury are the processes of maintaining or improving human health. Most conventional healthcare uses manual management and maintenance of patient demographics, history, diagnoses, medications, billing, medication inventory maintenance, which leads to human error and affects patients.

A wide range of IoT devices and applications have been designed for healthcare needs [15], such as sensors and applications for remote healthcare monitoring [16] which are used to capture, transmit and store health statistics. Real-time monitoring can improve patient outcomes. The IoMT offers new opportunities to improve patient care and manage the complexity inherent in the healthcare industry. On the other hand, IoMT makes it possible to diagnose and monitor patients without human intervention (remote health monitoring) thanks to interconnected medical objects: Smart sensors, smart devices, and advanced lightweight communication protocols have been developed especially for IoMT.

The main idea behind the IoMT is the remote monitoring throw portable patient monitoring unit (PPMU) at the patient’s home or at emergency medical service vehicles, and real-time monitoring with a decision support system at the hospital. Ultra-low power sensor devices, and lightweight communication protocols have been developed for patient well-being. PPMU mainly consists of sensors and electronic circuits capable of acquiring vital parameters (such as heart rate, heart rate variability, pulse rate, respiration rate, systolic blood pressure, diastolic blood pressure, oxygen saturation, body temperature, body mass index, level of consciousness, muscular activation, total lung volume, height, blood glucose level, urine report), a processing unit to process the acquired data, and a device network to upload the data to a server for further analysis [17].

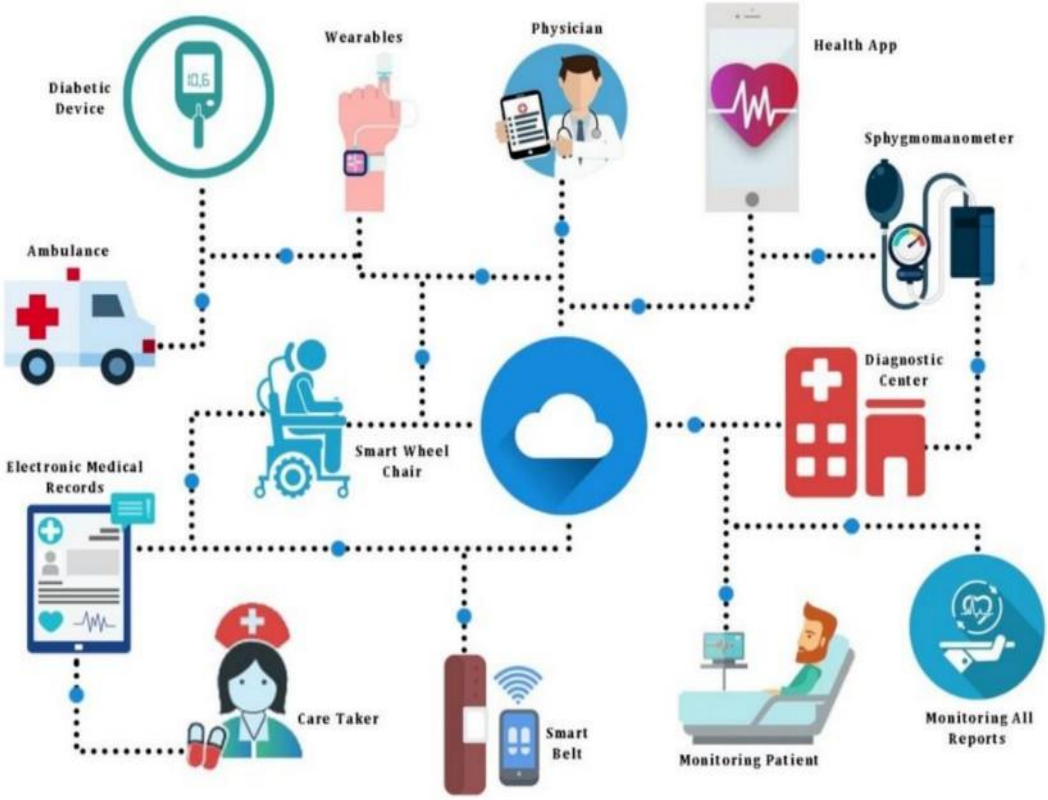

**Figure 1:** Architecture of IoMT [18]

## 1.2. State of health of IoMT autonomous devices

Autonomous devices play a vital role in IoMT. The life of these devices is linked to the performance of their energy resources, which are generally batteries. Therefore, whatever may be the kind of ADs, they all share a major issue, which is the battery life cycle. Indeed, the available battery capacity depends on what is called battery cycle number [19], and as the operating time of ADs increases, the batteries will inevitably age. Battery state of health refers to the ability of the battery in its current state to store electrical energy compared to a new battery, and is usually used as a percentage to quantitatively describe the current battery SoH [20]. The initial condition of ADs is estimated at 100% which decreases with use (see Figure 2). The battery is considered down if the SoH drops below 80% [9].

An accurate estimation of battery SoH is important for the proper functioning and safety of the connected medical devices. Different variables can be used to describe the SoH of the battery, such as capacity, charge, internal resistance, number of cycles, etc. The most widely used definition for calculating SoH is the percentage of battery capacity (see eq. 1) [20].

$$SoH = (C_i / C_0) * 100\% \qquad (1)$$

Where, $C_i$ is the relative capacity after i cycles, and $C_0$ is the initial capacity.

As mentioned earlier, the battery will be considered exhausted when the relative capacity reaches a certain threshold (let us denote it by $T$ ). Generally, $T$ is between 75% and 80% [9, 20, 21].

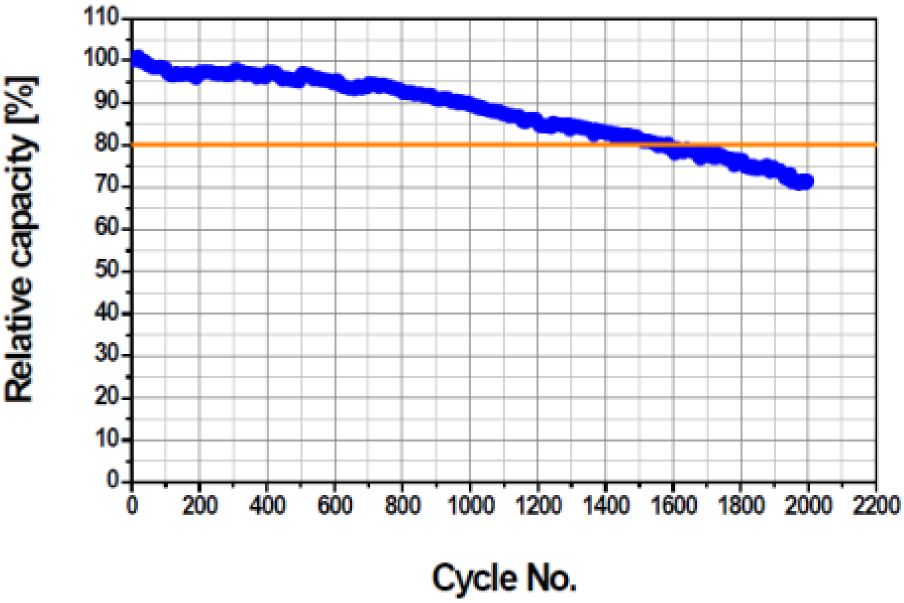

**Figure 2:** Relative battery capacity versus cycles number [19]

## 1.3. Colored Generalized Stochastic Petri Net formalism

CGSPN is a high-level modeling tool that can build models of multi-class systems. Mainly based on GSPN [22, 23], it brings various improvements and options that make modeling more flexible. Like other Petri nets, CGSPN is composed of places and transitions connected by weighted arcs. Hereafter, we mention the most important features of the tool we took advantage of in this work:

- The possibility of defining several types of tokens or marks (also called classes, and the objects derived from them represent the color of the token).
- Capability to specify a maximum capacity for each place.
- Possibility of naming the consumed or produced tokens with temporary variables, which makes it possible to place conditions and limitations on the arcs. See the variables x, y, and q in Figure 4. For example, the transition named *DecreaseSOH* consumes one token (named y) from the place SOH, and ten tokens (named x) from the place Cycles.
- A guard function can be defined for each transition that allows to filter consumed marks from the input places, put conditions on them, or perform arithmetic operations before generating the products. In Figure 4, the guard function of each transition is written in brown color between two brackets. For instance, the transition named Receive has the guard function [#Standby == 0] which means the condition ’firing forbidden if the AD is in standby state.
- Transitions can convert, assemble, or consume marks without producing any of them. They can also create new marks without needing to consume any tokens.

After building the model and defining the performance measures, two types of analysis can be carried out to evaluate the system's performance:

- Stationary analysis (analysis in the steady state): the obtained results represent the average values associated with the defined measures.
- Transient analysis: it is possible to calculate performance measures by simulating the model for a certain period of time determined by the analyst.

For more details, we refer the interested reader to [14, 24].

## 2. Related works

Petri nets are commonly used to model and evaluate the performances of sensors [10], drones [12], autonomous devices in IoT [25], and many other systems.

Wuchner et al. [11] proposed the phenomenon of unreliable orbit. They used Petri nets to evaluate the performance of wireless sensors, and considered the sensor-neighbors relationship. Gharbi and Charabi [26] proposed an algorithmic approach based on GSPN. They modeled with, and analyzed finite-source wireless networks with recall constraint and two receiver classes. In [27], the authors proposed a colored Petri net to model and evaluate the performances of a medium access control protocol in WSNs named S-MAC [28]. S-MAC uses a sleeping mechanism with rendezvous scheduling. Although they studied the energy consumption of the protocol, they neither considered energy harvesting nor breakdowns. In the same context, the authors of [29] presented an analytical modeling method by using Petri nets for energy consumption assessment in WSNs. The proposed model led to the construction of a formal model based on GSPN to evaluate the power consumption of sensors in an S-MAC based WSN. The conducted experiments focused on the number of nodes, duty cycle rate, the upper layer data flow and packet size.

The quantification principle is used to model the sensor node battery [10, 30]. The authors used GSPN to represent the energy stored in the battery in a discrete form (see Figure 3). In [31], the same authors enhanced their formulation by proposing a GSPN that models a sleeping mechanism with channel polling schedule. The authors supposed the battery has a fixed capacity. However, this supposition contrasts with the reality. Indeed, in actual circumstances, the battery capacity decreases gradually according to the number of discharge/recharge cycles.
Aiming to advance the related state of the art by addressing these shortcomings, this paper proposes a new CGSPN formulation to assess the energy of IoMT autonomous devices, and predict their lifetime. In a nutshell, the approach we propose models:

- AD's battery by using the quantification principle [10],
- energy harvesting capability,
- energy-consuming functionalities (transmission, reception, listening, and processing),
- sleeping mechanism, and
- battery SoH.

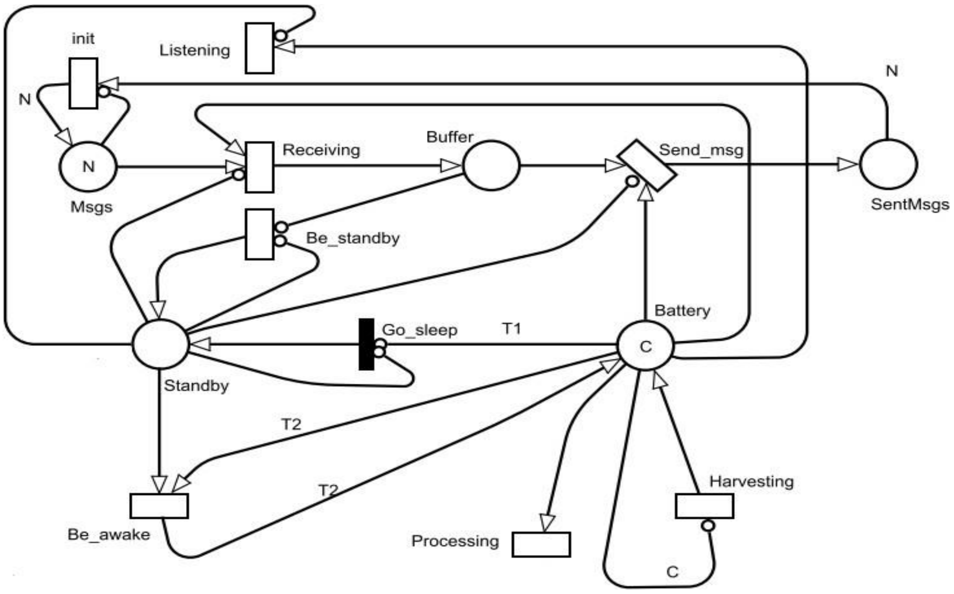

**Figure 3:** GSPN model for a sensor node [10]

## 3. Proposed Approach

Figure 4 represents a CGSPN model for an AD. We use different kinds of tokens to model energy, conditions, and messages. The place *Msgs* plays the role of a container for daily messages. A message is received by the AD by firing the transition Receive. As a consequence, a message is added to the place *Buffer*. Firing the transition Transmit models a successful sending of the message. Both *Receive* and *Transmit* transitions consume one quantum from the battery. AD listening to the channel is achieved by triggering the transition *Listening*. The processing unit consumes energy by firing the transition *Processing*. Sent messages are accumulated in the place *MsgsSent*. Every twenty four hours, transition *Init* moves the sent messages to the place *Msgs* for a new working day.

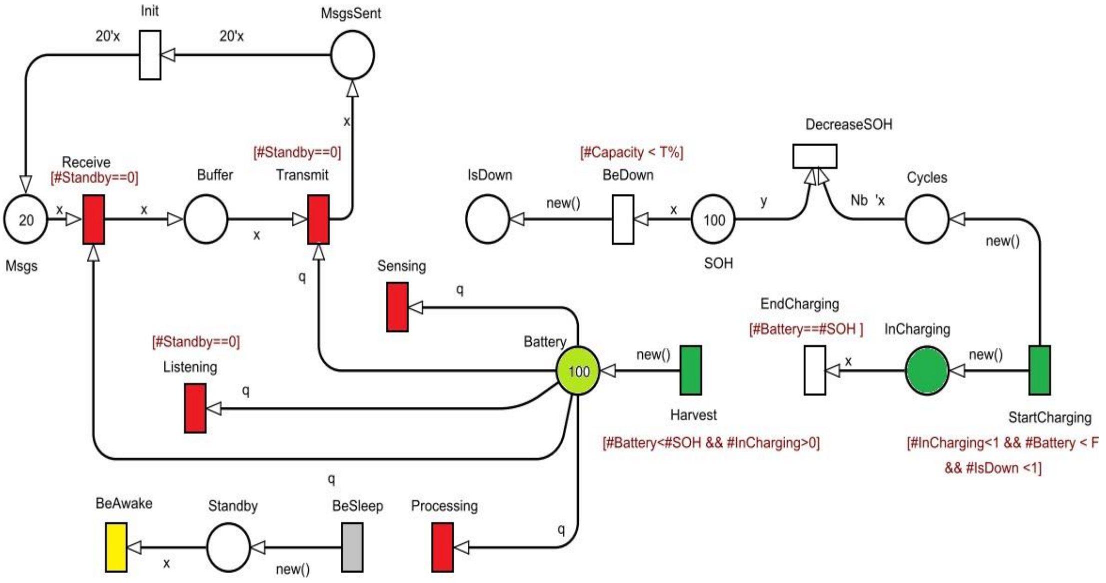

**Figure 4:** Proposed model

On the other hand, neither Receive nor Transmit nor Listening transitions can fire if the place Standby contains any token (i.e. the AD is in sleeping mode). The device joins the sleeping state (see BeSleep transition) from time to time in order to save energy. It awakes when the transition BeAwake fires. The place Standby cannot contain more than one token (its capacity equals one).

**Table 1:** Transitions descriptions

| Index | Transition | Signification | Guard function |
|---|---|---|---|
| 1 | *Receive* | AD receives a packet | [#Standby == 0] |
| 2 | *Transmit* | AD sends a packet | [#Standby == 0] |
| 3 | *Listening* | AD listens to the channel | [#Standby == 0] |
| 4 | *Processing* | AD works | / |
| 5 | *Sensing* | AD monitors the ambient | / |
| 6 | *Init* | Initializes the model every 24 h | / |
| 7 | *BeSleep* | AD sleeps | / |
| 8 | *BeAwake* | AD awakes | / |
| 9 | *Harvest* | Energy harvesting | [#Battery < #SOH && #InCharging > 0] |
| 10 | *StartCharging* | Battery charging | [#InCharging <1 && #Battery < 50 && #IsDown < 1] |
| 11 | *EndCharging* | Stop charging when full | [#Battery == #SOH ] |
| 12 | *DecreaseSOH* | Decreasing SoH | / |
| 13 | *BeDown* | Battery downs | [#Capacity < 80%] |

Our model considers the energy aspect as follows: the place Battery models the amount of power in the AD’s rechargeable battery. Energy is acquired or delivered by discrete levels. Each level corresponds to a quantum of energy. The transition Harvest recharges the battery when its energy becomes under a certain threshold (30%, for example). The satisfaction of this condition is represented by a token in the place *InCharging*. The *StartCharging* and *EndCharging* transitions monitor the beginning and the end of charging, respectively, by adding or consuming a token in the place *InCharging*. The battery has an initial capacity denoted by C.

The decaying nature of the battery is modeled as follows: the model calculates the number of recharge/ discharge cycles. Every K cycle, the battery capacity decreases by one level. So, the place Cycles plays the role of a counter for the transition *StartCharging* firings. If the relative capacity becomes under the T threshold (80%, for example), the battery is down, and the process of recharging will no longer be possible. The dead battery situation is identified by the presence of a token in the place Down.

Most of the transitions of the proposed model have guard functions to control their firings. Table 1 gives an overview of these transitions with their corresponding guard functions; whereas Table 2 summarizes the places with some related information.

Another perspective is given by the activity diagram depicted in Figure 5, which illustrates the functionalities of the AD system as they are formulated by the proposed model.

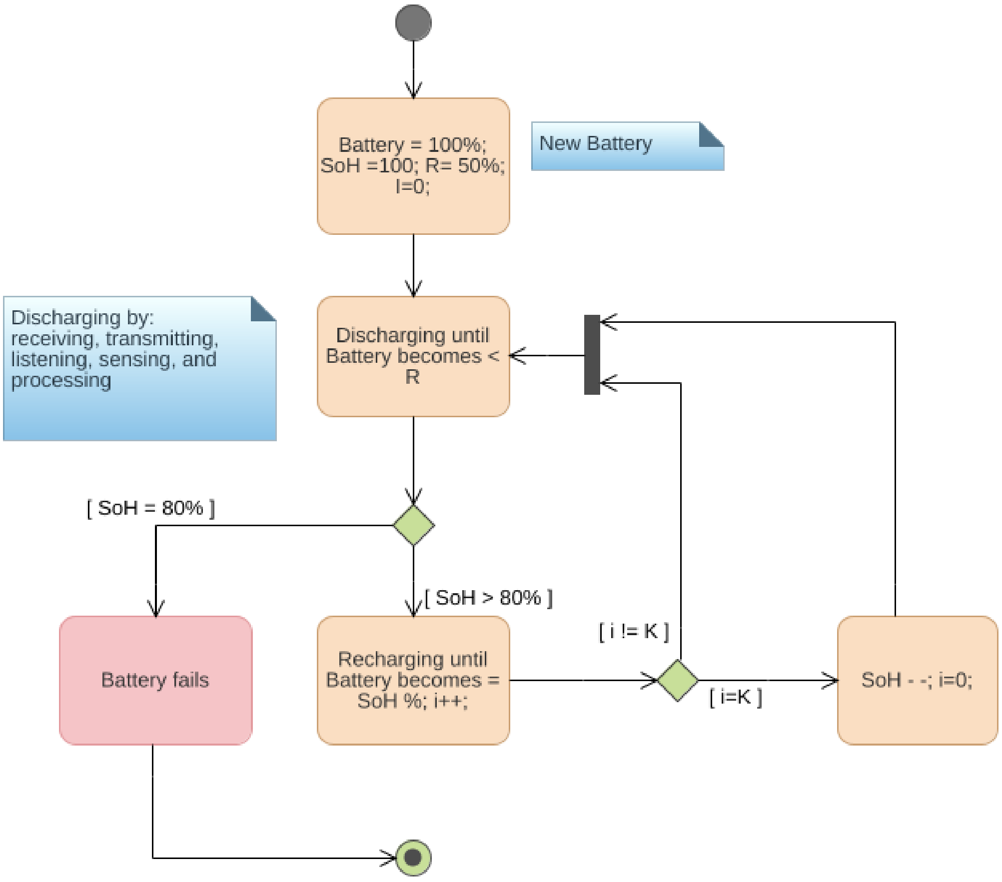

**Figure 5:** Activity diagram for the proposed approach

**Table 2:** Places descriptions

| Index | Place | Description | Capacity | Initial marking |
|---|---|---|---|---|
| 1 | *Msgs* | Daily packet number | N | N |
| 2 | *Buffer* | AD Buffer | B | 0 |
| 3 | *MsgsSent* | Sent packets | N | 0 |
| 4 | *Standby* | Sleeping flag | 1 | 0 |
| 5 | *Battery* | AD battery | C | C |
| 6 | *InCharging* | Charging flag | 1 | 0 |
| 7 | *Cycles* | Counter of cycles | K | 0 |
| 8 | *SoH* | Relative battery capacity | C | C |
| 9 | *IsDown* | Battery failure | 1 | 0 |

## 4. Results

Table 3 presents the input values we used for the experimental analysis. After configuring the model with these inputs, we obtained the following results:

**Table 3:** Input values

| Parameter | Value |
|---|---|
| Initial battery capacity | *100 quanta* |
| SoH | 80% |
| Mean daily message number | *20* |
| Harvesting rate | 50 quanta/hour |
| Processing rate | 2 quanta/hour |
| Sensing rate | 3 quanta/hour |
| Listening rate | 25 quanta/hour |
| Sleeping delay | one minute |
| Awakening delay | one minute |
| Recharging threshold | 30% |
| K (cycle number for 1% decrease in capacity) | 10 |

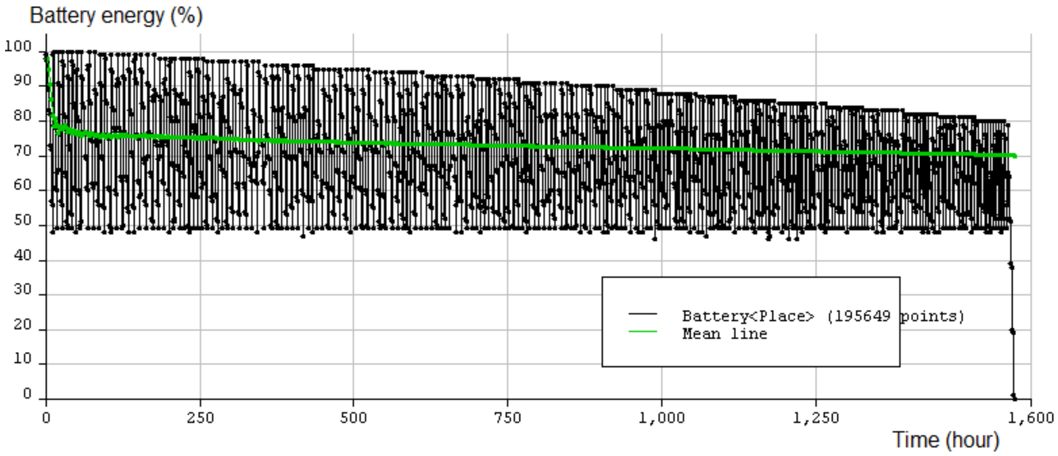

**Figure 6:** Battery level versus time

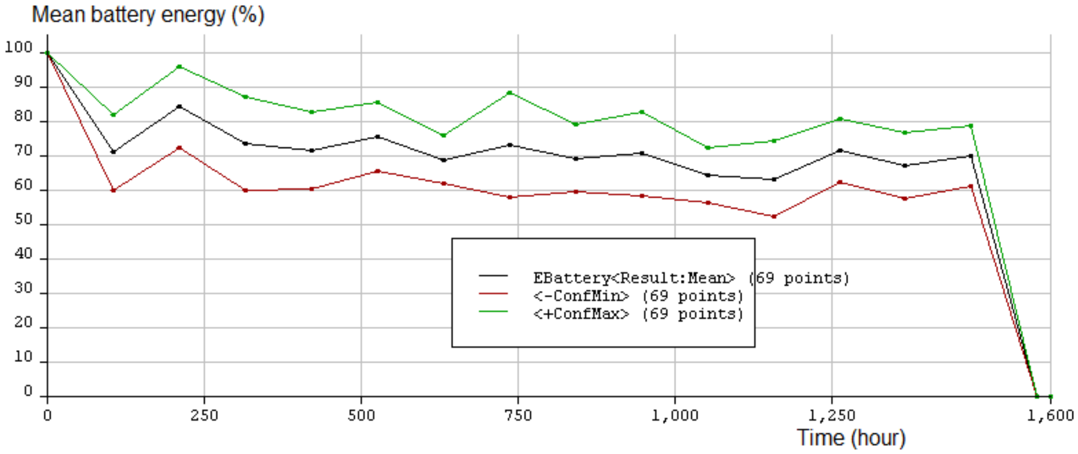

**Figure 7:** Mean battery energy versus time

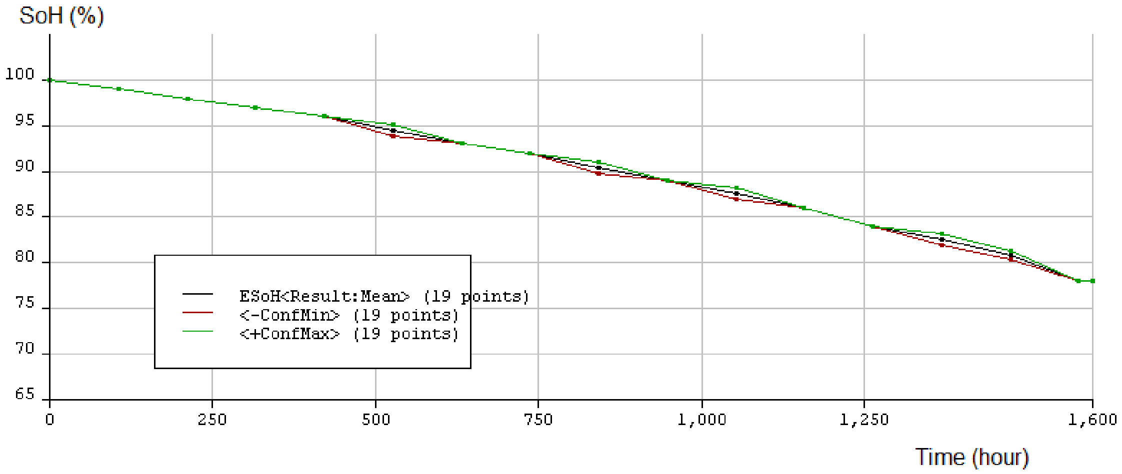

**Figure 8:** SoH versus time

Figure 6 illustrates the battery level versus time. We notice that the battery energy level is sandwiched between the charging threshold and the SoH. It is clear that the battery is not fully charged because the maximum capacity is controlled by the relative capacity. Given that the number of discharging/ charging cycles decreases the SoH, the longer the life of the device, the less the battery capacity. The power storage depletion continues until it no longer recharges, which means the battery is dead. In Figure 6, by considering the input values shown in Table 3, the battery is estimated to last for 1572 hours, which is equivalent to about 66 days.

Figure 7 shows the mean battery energy versus time by considering the average values of the energy level. We notice that the energy level is approximately equal to 75 percent of the initial battery capacity. This means that the selected settings and the conditions under consideration give the device an appropriate behavior, so that the battery level is above the middle.

Figure 8 shows the relative battery capacity versus the time. The battery continues living and remains rechargeable until the relative capacity reaches the specified threshold (in this simulation, the threshold was set to 80%, see Table 3). If the threshold is reached, the battery is considered dead and cannot be recharged again. For this reason, in Figure 7, the battery level becomes equal to zero after reaching the value 80%.

Figure 9 depicts the number of messages in the place Msgs versus the time. The figure shows the activity of the device in terms of receiving, listening, and sending packets.

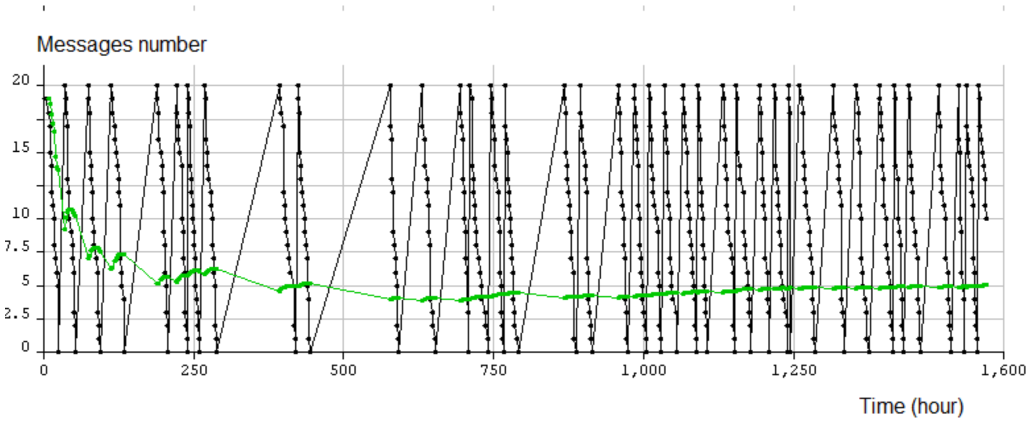

**Figure 9:** Messages number in the place *Msgs* versus time

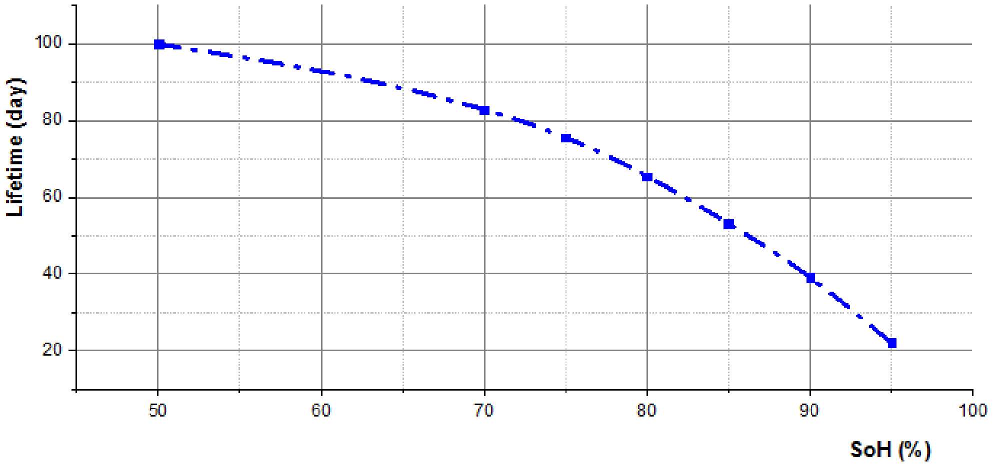

**Figure 10:** Battery lifetime versus SoH

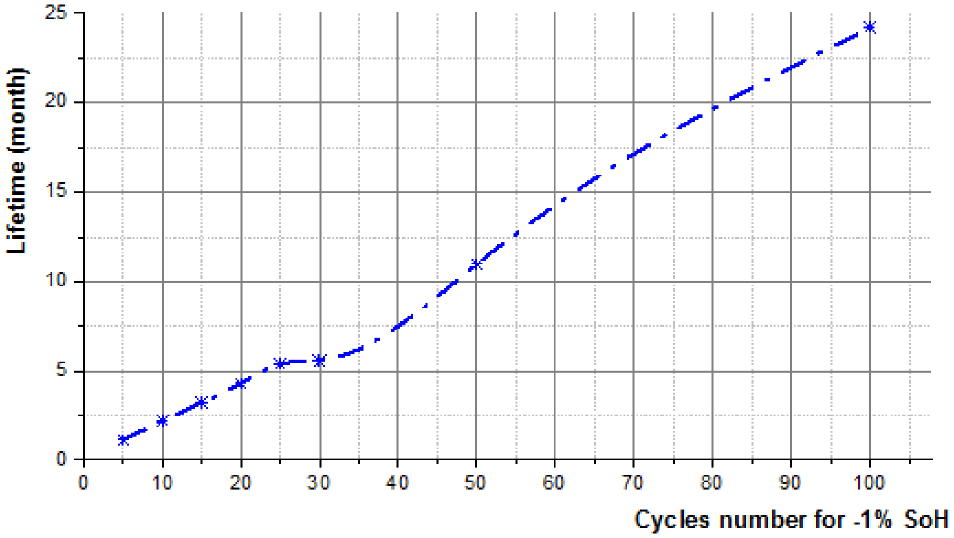

**Figure 11:** Battery lifetime versus cycles number for -1% SoH decreasing

One of the most important analyses that can be done by using the proposed model is to predict the device lifetime through multiple SoH threshold values. This variation resort to testing AD duration of service with different battery types, since each one has its own SoH threshold.

Figure 10 presents the device lifetime versus SoH threshold. We change the value of the SoH threshold, and then measure the lifetime of the device under the conditions and settings shown in Table 3. It is clear that the lifetime of the device is negatively affected by the value of the SoH threshold. The higher the SoH threshold value, the shorter the life of the device. Thus, the battery type should be selected according to the desired period of service.

Figure 11 shows the device lifetime versus the number of cycles for 1% decay in battery capacity (denoted by K). A high value for K means the maximum number of cycles to a dead battery increases (SoH of the death equals 80%). To make explanation more clear, we give the following illustrations:

- Case 1: for K = 100, the total number of cycles to the battery's death equals $100 * 20 = 2000$. From the curve, the battery will last almost 25 months.
- Case 2: for K = 50, the total number of cycles to the battery's death equals $50 * 20 = 1000$. From the curve, the battery will last almost 11 months.

In the first case, the battery stays operational until 2000 cycles. But in the second, it stays operational for only 1000 cycles. It is clear that in both cases, the aging of the battery converges to death. The difference between the two cases is the threshold associated with the death state. Therefore, K affects positively the device's lifetime. That is, if K is high, the AD retains its battery health for a longer period before it dies.

## 5. Conclusion and Future Directions

This paper proposes a new CGSPN model to evaluate energy in the autonomous devices of the Internet of Medical Things. The proposed model represents all the energy-consumption related functionalities of the devices, as well as the recharging process based on an energy harvesting system. In addition, the proposed modeling considers the SoH feature of batteries. The presented CGSPN makes it possible to predict the daily average of energy level in the battery. Also, It allows for predicting the device's lifetime.

The novelty of this investigation is to show through a Colored-Petri-Net-based formulation how to predict the lifetime because equipping them with an energy recovery system to recharge their batteries does not guarantee an eternal life. It also shows how the high number of discharge/recharge cycles negatively affects the battery's health.

As a future direction, we want to improve the model by considering other deployment constraints like the length of messages. We are also working on an improved architecture for these devices to keep their batteries healthy by reducing recharge cycles. The device exploits renewable energy, and uses it directly to feed its various units. In the absence of renewable energy outside, the device uses the battery.

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