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Energy Consumption Performance for Difference Battery Model Capacity Deployed on Design Network Topologies

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Battery models, capacity, energy consumption, internet of things, netsim, network topology

Abstract

This research investigates energy consumption in Internet of Things (IoT) networks, focusing on how different battery capacities impact energy performance. The study is motivated by the need to optimize power usage in IoT devices, which often rely on limited battery power and can experience significant energy consumption. The study evaluates the performance of four battery types: 3.7V and 7.4V batteries with capacities of 1500mAh and 3000mAh, respectively using NetSim tools. The simulations were conducted over time periods of 1, 12, and 24 hours, and the number of active nodes varied from 1 to 5. The findings reveal that for a network with 1 active node and a 3.7V 1500mAh battery, the total energy consumption was 1.1117%, 13.3438%, and 26.6879% for the durations of 1, 12, and 24 hours, respectively. In contrast, using a 3.7V 3000mAh battery reduced consumption to 0.5553%, 6.6652%, and 13.3306%. These results provide valuable insights into battery deployment strategies for energy-efficient IoT networks, highlighting the importance of selecting appropriate battery models based on network topology and node activity.

1. Introduction

The Internet of Things (IoT) is a rapidly growing network of interconnected devices, things, and sensors that can gather, share, and analyze data. While the development of IoT has many advantages and opportunities, there are also many difficulties it must overcome, one of which is energy consumption. Thus, investigating energy consumption becomes crucial [1]. The battery lifespan used in IoT devices must be continuously monitored for better maintenance to prevent problems with the deployed device's productivity [2]. If a device battery fails too soon, there may be severe consequences for the end user or device manufacturer in many IoT applications [3]. Power consumption and energy utilization must be monitored closely and continuously predicted for seamless integration of internet-connected devices in the IoT [4]. The battery is the primary source of power for Internet of Things devices. Moreover, Battery-powered devices are becoming more common in use and on the market today [5]. Therefore, the selection of a battery for the IoT device is essential.

Many factors can influence the energy consumption of the IoT devices. This paper focuses on the number of active nodes and time as an essential parameter in the IoT network. It is critical to research how network energy and performance change as a function of node placement, inter-node distance, and active number of nodes on the Internet of Things [6]. NetSim is a tool that simulates and analyzes network scenarios, including the behavior and performance of network protocols, devices, and services. It allows network administrators and researchers to design, test, and evaluate various configurations and scenarios without affecting live networks. It models and assesses how various network components interact, including sensor nodes, gateways, and sinks [7].

Energy consumption has become one of the most difficult challenges due to the increasing number of IoT devices and the already-existing interconnections between cloud data centers, mobile applications, and people's daily activities. Thus, one of the critical concerns in green IoT-enabled devices is regulating energy efficiency and power consumption [8]. To address this, network simulators like NetSim can be employed to observe energy consumption by IoT devices [9]. This research aims to define various battery models and utilize NetSim to simulate and compare their energy consumption. Studying the variation of these characteristics with changing node placement, inter-node distance, and number of active nodes in IoT is vital since network energy and performance are both essential, as stated in [10]. Managing power depletion becomes critical since batteries power most operational end-devices, including sensors and actuators. Monitoring energy consumption is a crucial aspect of designing the network to cater to application needs effectively [11]. The energy consumed by each task involved in sensing, processing, and packet transmission contributes to the overall power consumption [12]. Therefore, it is essential to investigate energy consumption using different battery models, particularly IoT devices.

This research has investigated the energy consumption performance based on a battery model using NetSim. Simulated modeling is creating and analyzing a digital prototype of an accurate model to show and predict how well is the system perform in practical applications [13]. This research investigates how active nodes and time could impact the energy consumption model based on the battery model using NetSim. Then, the performance of energy consumption in IoT devices was analyzed. The research scope of this project is to simulate an energy consumption model of IoT devices powered by several types of batteries using NetSim. The energy consumption of IoT devices, while powered by variable battery types, is observed when the influence of active nodes and time are applied to the simulation. The first section of this essay presents a survey of the relevant literature. The methods is covered in the next section, followed by a discussion of the findings in the results and discussion section. The conclusion and summary of this study are provided at the end of this article.

2. Literature Review

In the context of Internet of Things (IoT) networks, energy consumption is a critical factor, particularly for devices that are battery-powered and often deployed in remote or inaccessible locations. The battery model capacity, network topology, and the number of active nodes significantly influence the energy efficiency and operational longevity of these devices. This literature review explores the relationship between different battery capacities, network topologies, and the number of nodes, focusing on how they collectively affect energy consumption performance in IoT networks.

Battery model capacity, typically measured in milliampere-hours (mAh) or watt-hours (Wh), directly impacts the energy available to IoT devices. Higher-capacity batteries provide more energy, potentially extending the operational life of a device. However, the efficiency of energy usage also depends on the battery's energy density and its compatibility with the device's power requirements [14] .Research has highlighted those batteries with higher energy densities, such as lithium-ion (Li-ion) and lithium-polymer (LiPo) batteries, are often preferred in IoT applications due to their ability to deliver sustained power over extended periods [15]. The choice of battery capacity influences the operational capabilities of IoT devices, including how often and how long they can function before needing recharging or replacement. Devices with larger batteries can support more frequent data transmissions and more power-intensive operations, such as complex computations or continuous sensing. Conversely, smaller-capacity batteries require more stringent energy-saving measures, such as reduced duty cycles, to maximize operational longevity [16].

This paper studies the wireless technologies for IoT applications regarding power consumption [17]. It identifies several factors that influence the battery lifetime in sensor nodes, such as the wireless communication protocol, the module used for a particular wireless communication protocol, the coverage range and the distance between sensor nodes, and the nature of the application.

The number of active nodes in an IoT network significantly affects energy consumption. Higher node density can lead to increased communication overhead, as nodes compete for communication channels, potentially leading to more retransmissions and collisions, particularly in dense networks [18]. This can result in higher energy consumption across the network, particularly in topologies like mesh, where nodes are frequently relaying data for one another. In networks with a large number of nodes, load balancing becomes critical to maintaining energy efficiency. Effective load balancing ensures that no single node is overly burdened with data transmission and relaying, which can prevent premature battery depletion in certain nodes [19]. Techniques such as dynamic routing and adaptive duty cycling can help distribute the energy load more evenly across all nodes, thereby extending the overall network lifespan. The scalability of the network's battery management strategy becomes increasingly important as the number of nodes increases[20]. Networks must be designed to handle varying numbers of nodes without significantly impacting the energy consumption of individual devices. Advanced battery management systems that can adapt to changes in node density and communication patterns are crucial for ensuring sustained energy efficiency. In-network performance concerning the number of active nodes and the inter-node distance was examined using ns2.34 simulations [21]. The simulation results demonstrate that a higher number of active nodes facilitates easier multi-hop communication and contributes to an increase in node residual energy. This contributes further to a prolonged network lifetime.

Energy consumption in LoWPAN networks is a critical factor as many IoT devices are deployed in environments where frequent battery replacement is impractical. The protocol's design inherently supports energy efficiency through header compression, reducing the amount of data transmitted and, consequently, the energy required for transmission[22]. In [23], the authors examined the energy consumption patterns in a LoWPAN network with varying numbers of active nodes. Their findings indicate that energy consumption increases exponentially as the network density grows, primarily due to the increased number of data collisions and retransmissions. The study suggests that implementing adaptive sleep schedules and energy-aware routing protocols can mitigate the impact of high node density on energy consumption.

3. Methodology

Identification of the output parameters is important which affected the energy consumption for the first activity in this research. Then, the network diagram of the topology that can be used for the parameters would be designed and simulated. After that, the energy consumed by the battery based on the parameters can be observed. Lastly, make a suitable conclusion based on the result obtained from the simulation.

3.1 Flow Chart

Figure 1 shows the flowchart diagram of the research flow. The process begins with knowledge acquisition and data gathering concerning battery models, network nodes, and energy consumption. Subsequently, the parameters for the battery model are determined, and a network topology is designed based on identified nodes. The alignment of the designed network with specified nodes is then evaluated, prompting adjustments if necessary. The battery model is simulated on the network topology, and any simulation issues are addressed before the model is executed. Data on energy consumption is collected during the battery model's operation, and potential problems with data collection are rectified. Based on the collected data, the system undergoes testing and evaluation, with identified issues being addressed before moving forward. Following successful testing, the energy consumption is analyzed based on network nodes, and the percentage of the remaining battery is evaluated from simulation results. The process concludes with a systematic and comprehensive understanding of energy consumption within the network and the remaining battery percentage, ensuring a thorough analysis of the simulated system.

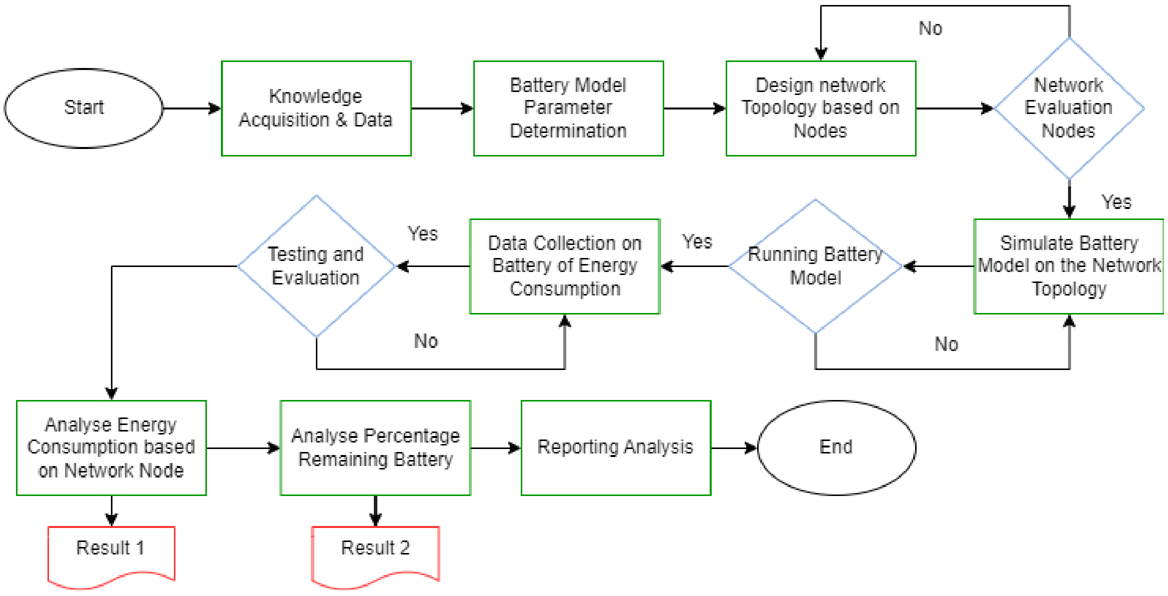
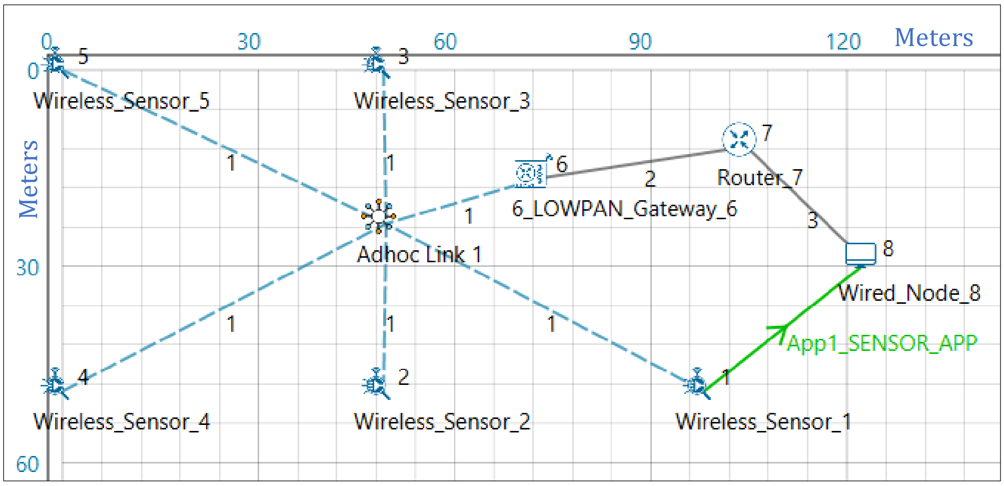


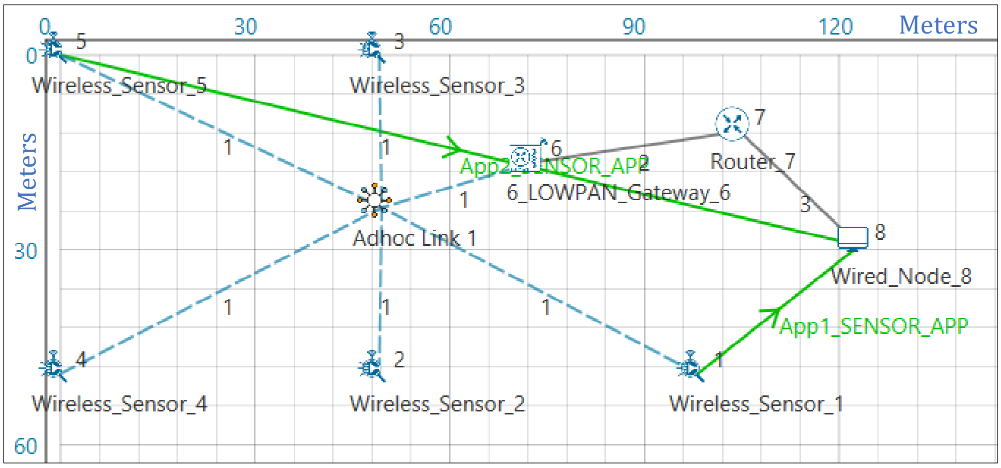
Fig. 1 *Flow chart of the research*

3.2 Network Topology and Parameter Design

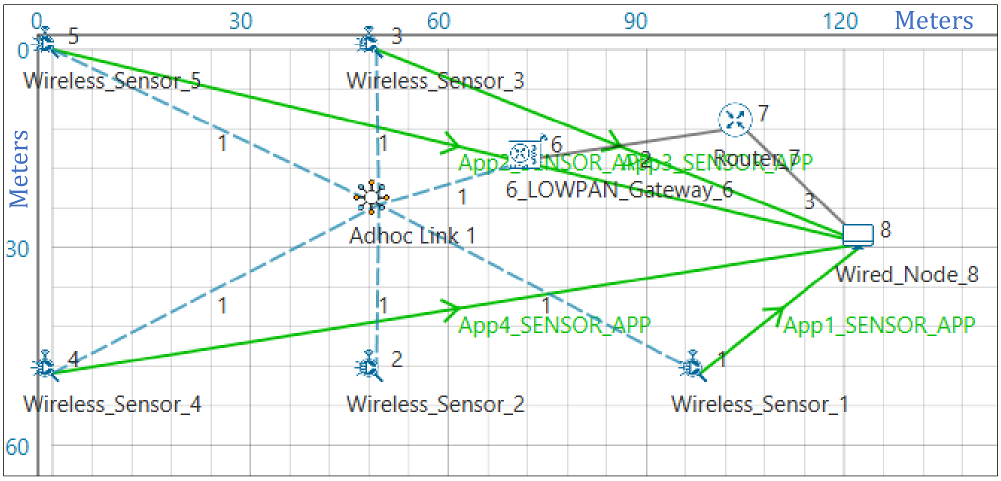
Fig. 2 (a), (b), (c), (d), and (e) shows the network topologies setup for the simulation in NetSim for 1, 2, 3, 4, and 5 active nodes respectively. Both axis X and Y indicates the grid area in meters. It consists of 5 sensor nodes, one ad hoc link, one Low-power Wireless Personal Area Network (LoWPAN) gateway, one router, and one wired node, as stated in Table 2. A LoWPAN gateway is a device that connects sensors to the internetwork, whereas an ad hoc link is a device that connects all the sensor nodes in a network. There is an increasing number of active nodes from 1 to 5 active nodes to send the data to the wired node in the setup. The active nodes were set at the sensor app to establish an application between sensors and wired nodes. The green line indicates the active nodes in the network and the dotted line represents the connection of the nodes in the network.



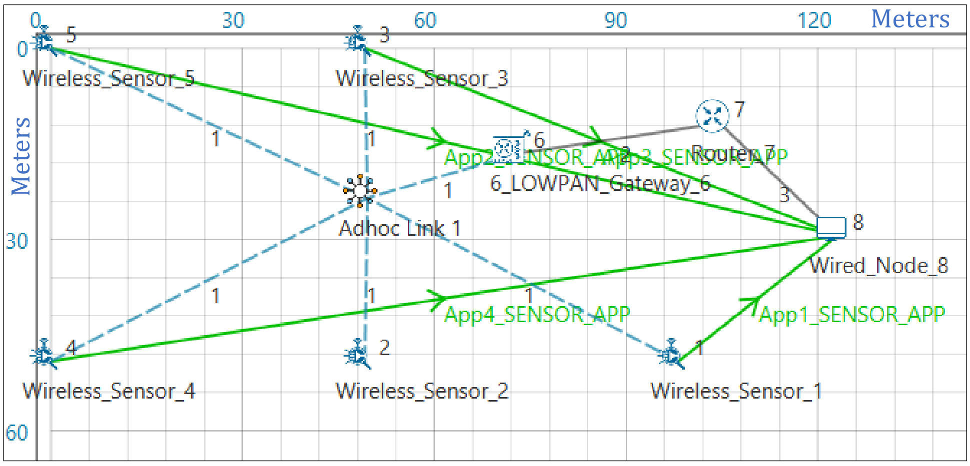
(a) 1 Active nodes



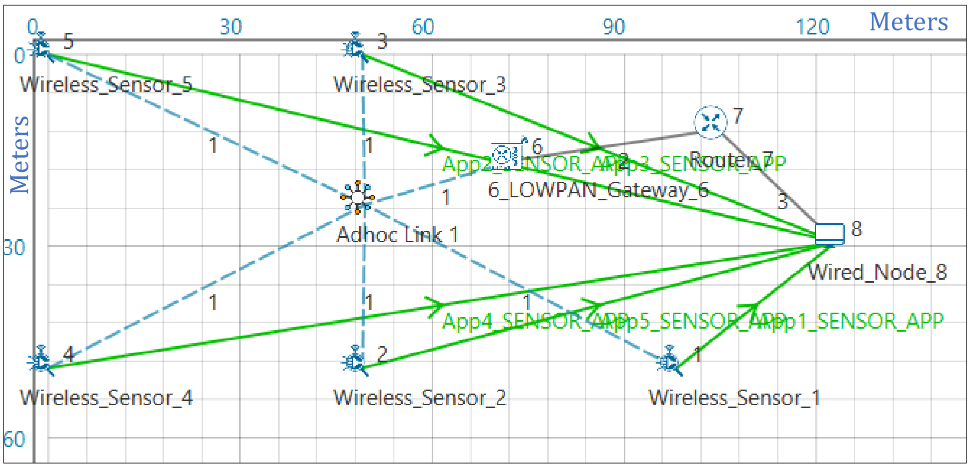
(b) 2 Active nodes



(c) 3 Active nodes



(d) 4 Active nodes



(e) 5 Active nodes

Fig. 2 *Network diagrams of the topologies for (a) 1 active node; (b) 2 active nodes (c) 3 active nodes; (d) 4 active nodes; and (e) 5 active nodes*

Table 1 presents the parameters used which were obtained from lithium-ion batteries (18650) with four types of designs. Fixed parameters include transmitting current, receiving current, idle mode current, sleep mode current, along with variables such as initial energy and nominal voltage. Simulation times were set at 1 hour, 12 hours, and 24 hours. Table 2 displays the parameter used for simulations, and the active nodes participating during the simulation are stated in Table 3.

Table 1 *Parameter for batteries*

Parameters	Design 1	Design 2	Design 3	Design 4
Initial Energy (mAh)	1500	3000	1500	3000
Transmitting current (mA)	8.8	8.8	8.8	8.8
Receiving Current (mA)	9.6	9.6	9.6	9.6
IdleMode Current (mA)	3.3	33	3.3	3.3
SleepMode Current (mA)	0.273	0.273	0.273	0.273
Nominal voltage (V)	3.7	3.7	7.4	7.4

Table 2 *Parameter for simulations*

Parameters	Values
No. of Sensor Nodes	5
LoWPAN Gateway	1
Router	1
Wired Node	1
Times	1 hour, 12 hours, and 24 hours

Table 3 *Parameter for applications*

Number of Active Modes	Sensors Active During the Simulations
1 node	Sensor 1
2 nodes	Sensors 1 and 5
3 nodes	Sensors 1, 3 and 5
4 nodes	Sensors 1, 3, 4 and 5
5 nodes	Sensors 1, 2, 3, 4 and 5

3.3 Formulation of Power Consumption

This section shows the formula which has been used for the power consumption calculation of the sensor nodes deployed in the network topologies and formulation is referred for power consumption [17] as listed.

$$Initial\ Energy\ = Voltage\ \times Initial\ Energy\ of\ Battery\ \times 3600 \qquad (1)$$

$$Transmit\ Energy\ = Transmit\ Current\ \times Voltage\ \times Time\ for\ which\ Mode\ Transmit\ Packets \qquad (2)$$

$$Receiver\ Energy\ = Recieve\ Current\ \times Voltage\ \times Time\ for\ which\ Mode\ Receives\ Packets \qquad (3)$$

$$Idle\ Mode\ Energy\ = Idle\ Mode\ Current\ \times Voltage\ \times Time\ in\ Idle\ Mode \qquad (4)$$

$$Sleep\ Mode\ Energy\ = Sleep\ Mode\ Current\ \times Voltage\ \times Time\ in\ Sleep\ Mode \qquad (5)$$

$$\begin{aligned} &Consume\ Energy \\ &\quad = Transmit\ Energy + Receive\ Energy + Idle\ Mode\ Energy + Sleep\ Mode\ Energy \end{aligned} \qquad (6)$$

$$\begin{aligned} &Total\ Consume\ Energy \\ &\quad = Energy\ Consumed\ by\ Device\ 1 + \cdots \\ &\quad + Energy\ Consumed\ byDevice\ n\ where\ n\ is\ the\ number\ of\ nodes \end{aligned} \qquad (7)$$

$$Remaining\ Energy\ = Initial\ Energy - Total\ Consumed\ Energy \qquad (8)$$

$$Remaining\ Battery\ Percentage\ = \frac{Remaining\ Energy}{Initial\ Energy} \times 100\% \qquad (9)$$

$$Consumed\ Energy\ Percentage = \frac{Tota\ Consumed\ Energy}{Initial\ Energy} \times 100\% \quad (10)$$

4. Result and Discussion

Table 4 shows the simulation results depicting the overall energy consumption in the network using four types of lithium-ion battery protocols on different numbers of active nodes. The data analysis presented the total energy consumed by the 3.7V battery and 7.4V battery with 1500mAh and 3000mAh, increases as the simulation duration extends for each number of active nodes. This escalation is attributed to the prolonged activation of sensors with the increasing duration, consequently raising energy consumption. Moreover, in terms of total energy consumed by the 3.7V battery and 7.4V battery with 1500mAh and 3000mAh, as the number of active nodes rises, the results exhibit variations. This discrepancy is a consequence of the allocation of processing tasks in a network modelling environment like NetSim among multiple nodes. The adoption of parallel processing diminishes burden on individual nodes and their associated batteries by distributing the workload across the active nodes. The augmentation in the number of active nodes facilitates more efficient resources management through distributed processing, thereby significantly reducing overall energy consumption.

Table 4 *Total energy consumed for active nodes*

Battery level (V)	Initial energy (mAh)	Time (hour)	Total Energy Consumed (kJ)				
			1 active node	*2 active nodes*	*3 active nodes*	*4 active nodes*	*5 active nodes*
3.7	1500 (19.98kJ)	1	0.2219	0.2221	0.2227	0.2232	0.2231
		12	2.6634	2.6660	2.6728	2.6792	2.6775
		24	5.3269	5.3321	5.3457	5.3585	5.3550
	3000 (39.96kJ)	1	0.2219	0.2221	0.2227	0.2232	0.2231
		12	2.6634	2.6660	2.6728	2.6792	2.6775
		24	5.3269	5.3321	5.3457	5.3585	5.3550
7.4	1500 (39.96kJ)	1	0.4438	0.4442	0.4454	0.4465	0.4462
		12	5.3268	5.3321	5.3457	5.3585	5.3550
		24	10.6538	10.6641	10.6915	10.7170	10.7099
	3000 (79.92kJ)	1	0.4438	0.4442	0.4454	0.4465	0.4462
		12	5.3268	5.3321	5.3457	5.3585	5.3550
		24	10.6538	10.6641	10.6915	10.7170	10.7099

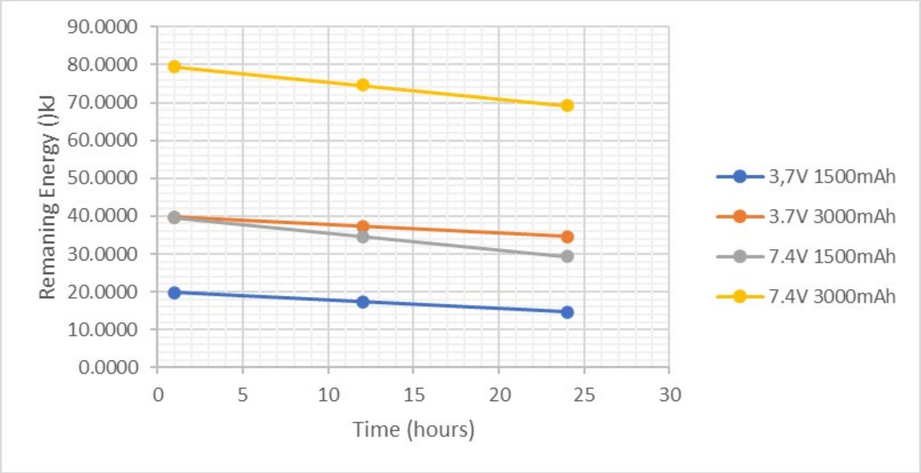
Table 5 presents a data analysis based on simulation result that shows the remaining energy in percentage by 3.7V battery and 7.4V battery, each with 1500mAh and 3000mAh, across different numbers of active nodes during simulations. Batteries with a higher initial energy (eg., 3000mAh vs. 1500mAh) show slower depletion rates over time. This is because a larger capacity battery can supply the same amount of power with a smaller relative drop in its remaining energy. This explains why the remaining energy percentage is consistently higher for the 3000mAh batteries compared to the 1500mAh ones at any given time point. The 7.4V batteries have a higher initial energy (in joules) compared to the 3.7V batteries, even when the capacity in mAh is the same. For instance, the energy content of a 1500mAh, 7.4V battery is double that of a 1500mAh, 3.7V battery. This higher energy reserve translates into a slower percentage drop in remaining energy, especially as the number of active nodes increases. The voltage essentially scales the available energy, allowing the battery to sustain the network's demands for a longer time before the remaining energy decreases significantly.

The data shows a clear trend of decreasing remaining energy percentages as time progresses from 1 hour to 24 hours. This is expected because the battery is continuously supplying energy to the active nodes. The rate of energy consumption leads to a proportional decrease in the remaining energy. the remaining energy percentage decreases more rapidly, as the number of active nodes increases. Each additional active node increases the total energy consumption rate. For example, after 24 hours, the remaining energy in the battery with 5 active nodes is consistently lower than with just 1 active node. This difference is more pronounced in lower capacity batteries (1500mAh), where the energy drain from additional nodes has a more significant impact on the remaining percentage.

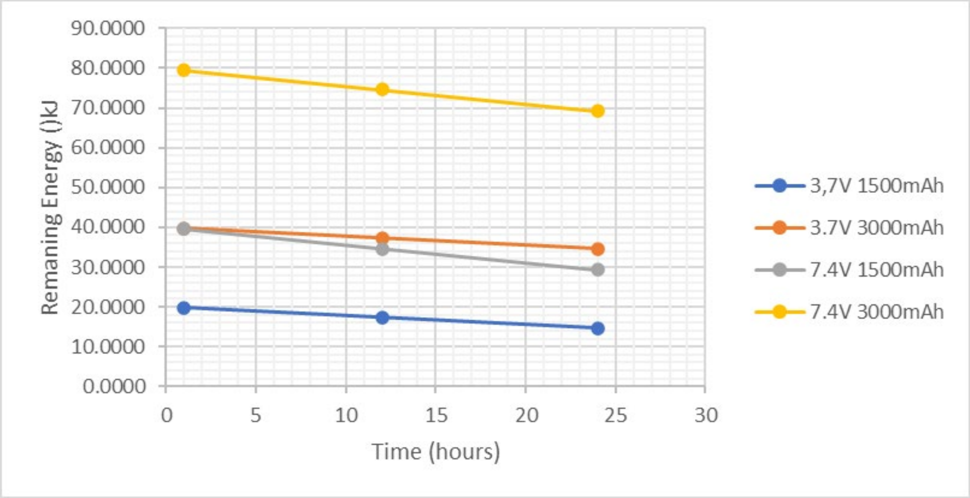
Table 5 *Remaining energy in percentage*

Battery level (V)	Initial energy (mAh)	Time (hour)	Remaining Energy (%)				
			1 active node	*2 active nodes*	*3 active nodes*	*4 active nodes*	*5 active nodes*
3.7	1500 (19.98kJ)	1	98.8883	98.8872	98.8843	98.8816	98.8823
		12	86.6562	86.6431	86.6090	86.5770	86.5857
		24	73.3121	73.2862	73.2177	73.1538	73.1715
	3000 (39.96kJ)	1	99.4447	99.4441	99.4427	99.4414	99.4417
		12	93.3348	93.3283	93.3112	93.2952	93.2996
		24	86.6694	86.6565	86.6223	86.5903	86.5992
7.4	1500 (39.96kJ)	1	98.8894	98.8883	98.8854	98.8827	98.8834
		12	86.6696	86.6565	86.6224	86.5904	86.5992
		24	73.3389	73.3130	73.2445	73.1806	73.1983
	3000 (79.92kJ)	1	99.4447	99.4441	99.4427	99.4414	99.4417
		12	93.3348	93.3283	93.3112	93.2952	93.2996
		24	86.6694	86.6565	86.6223	86.5903	86.5992

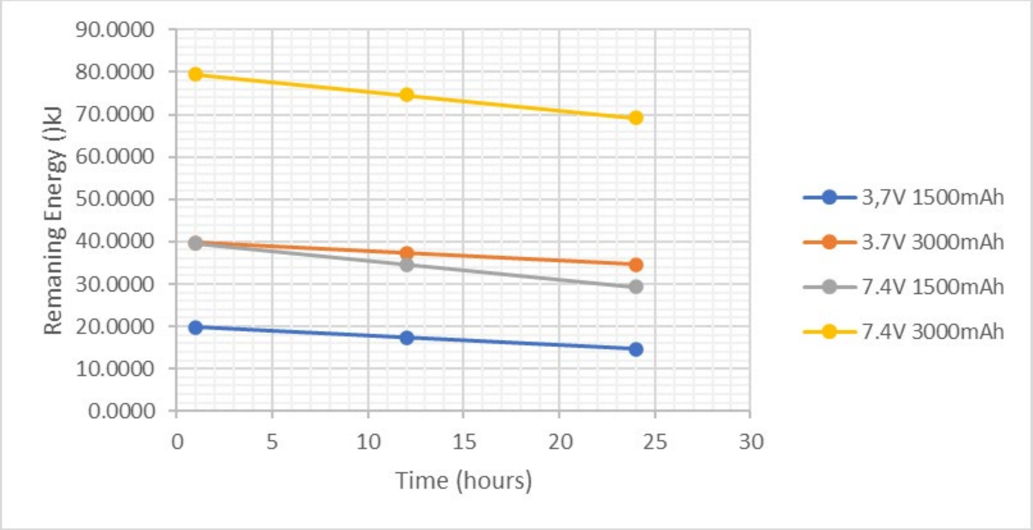
Figure 3 (a), (b), (c), (d) and (e) shows the analysis for the remaining energy in the battery vs time for the 3.7V and 7.4V battery with 1500mAh and 3000mAh each and different numbers of active nodes during simulation. The result shows the battery's remaining energy decreases as the time increases for each number of active nodes during the simulation. Each active node in the network consumes power continuously over time to perform its function such as data processing, communication and possibly sensing. This indicates that the energy consumption is higher when more nodes are active. This ongoing power consumption gradually depletes the energy stored in the battery. The scenarios with a higher energy level, such as the 3000mAh configuration exhibit higher remaining energy compared to lower initial energy, represented by the 1500mAh configuration. The 7.4V battery generally starts with more energy compared to the 3.7V. This leads to having more energy left in the 7.4V battery in different situations. This shows that the voltage level is important for how much energy a battery can store. Simply put, higher voltage means the battery can hold more energy.



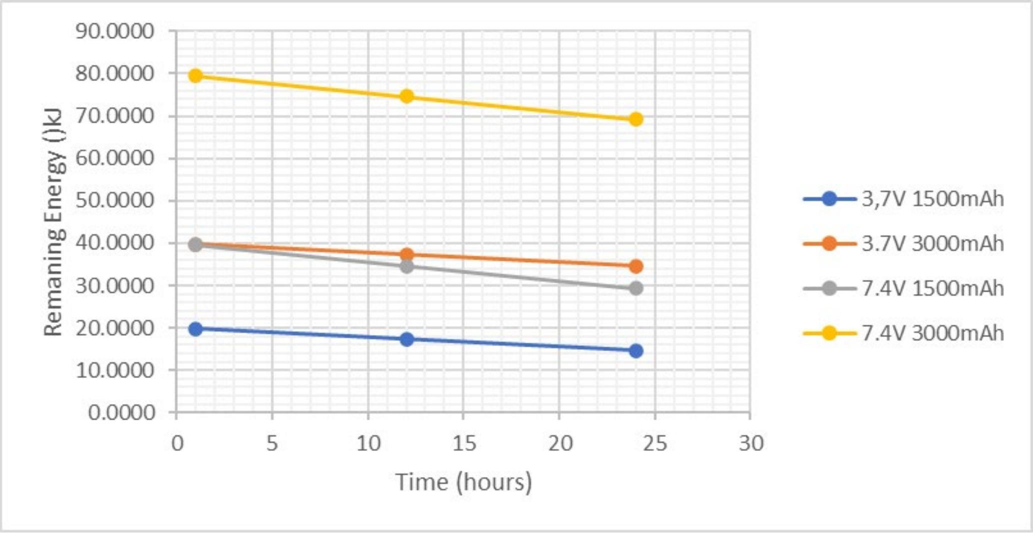
(a) 1 Active nodes



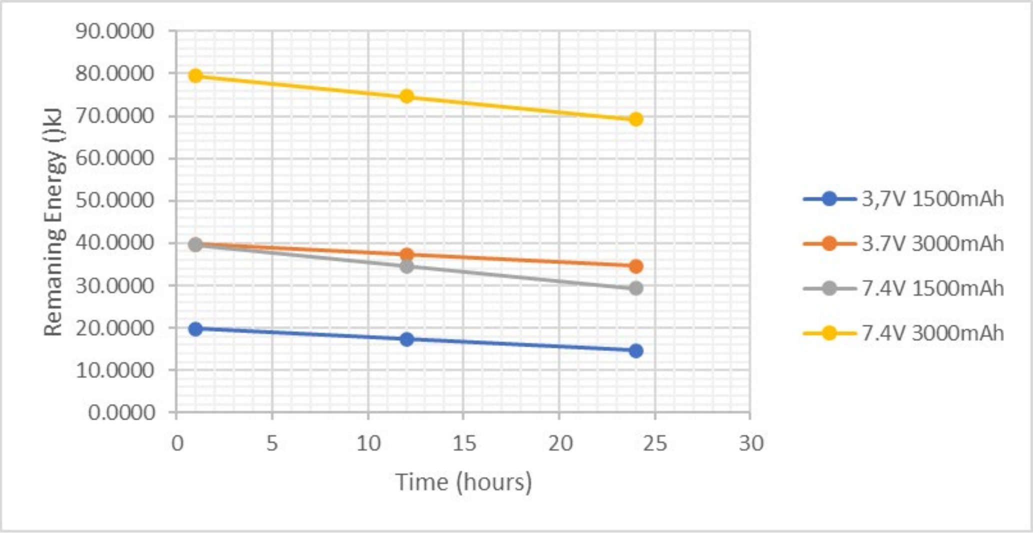
(b) 2 Active nodes



(c) 3 Active nodes



(d) 4 Active nodes



(e) 5 Active nodes

Fig. 3 *Remaining energy vs time with (a) 1 active node; (b) 2 active nodes; (c) 3 active nodes; (d) 4 active nodes; and (e) 5 active nodes*

Figure 4 illustrates the individual energy consumption percentage vs time in milliseconds of sensor 1 for 1 active node, 3.7V with 1500 battery model. The result shows a gradual decrease in percentage of energy as time progress. Over the observed time, there is a consistent downward trend in the energy percentage indicating a continuous consumption or depletion of the available energy. The initial energy level of 100% suggests a fully charged state and the diminishing trend implies a reduction in stored energy over the specified duration. The trend in the graph also enables the proactive measures to be taken such as recharging or optimizing energy usage to extend the operational lifespan of the system.

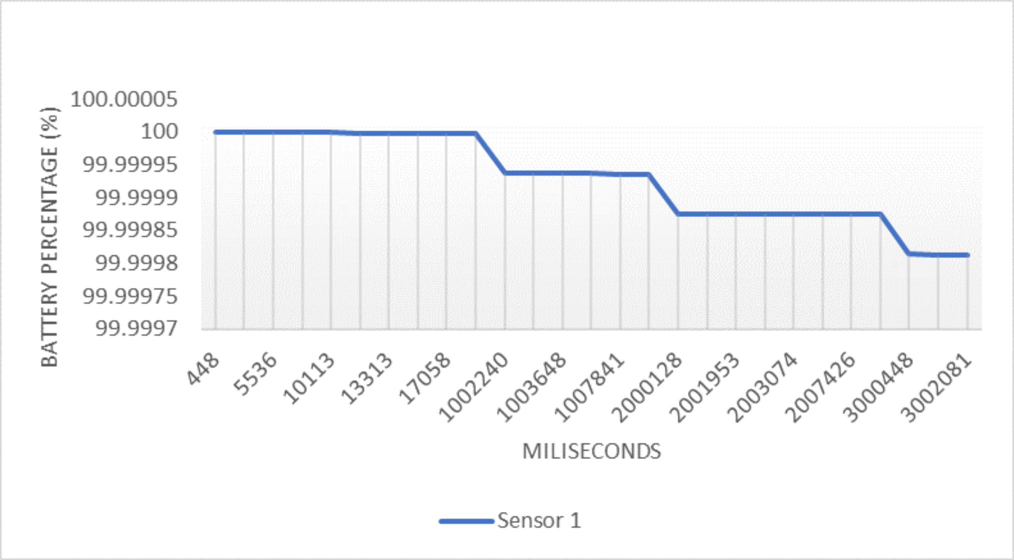


Fig. 4 *Remaining energy vs time (millisecond)*

5. Conclusion

The paper concludes the energy consumption performance based on battery models. The simulation results illustrate the energy consumption for different battery capacities over various durations using a single active node. For the 3.7V battery with a capacity of 1500mAh, the total energy consumed was 1.11% for a 1-hour simulation, 13.34% for a 12-hour simulation, and 26.69% for a 24-hour simulation. In contrast, the design utilizing a 3.7V battery with a 3000mAh capacity consumed significantly less energy, with values of 0.56%, 6.67%, and 13.33% for the same respective durations. The key observation is that the 3000mAh battery consistently demonstrated lower energy consumption compared to the 1500mAh battery across all time intervals. This is attributed to the larger capacity of the 3000mAh battery, which can store more energy and therefore depletes a smaller percentage of its total energy over the same duration. Additionally, for both battery capacities, energy consumption increased with longer simulation durations, as expected, since the active node operates longer and consumes more energy over time. These findings highlight the impact of battery capacity on energy efficiency, demonstrating that higher-capacity batteries enable more efficient energy use over extended periods.

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Conflict of Interest

The authors declare no conflict of interest regarding the paper's publication.

Author Contribution

Mohamad Yusof Y.W. and Tukimin M. N have contributed to the ***simulation design, implementation of the research and analysis of the results****. Mohamad Yusof Y.W and Kassim. M is involved in the details of the* ***concept and data acquisition and validation****. Ismail M.N contributed to the* ***simulation tools testing****. Ismail M.N and Sulaiman N.A do the* ***proofreading of the manuscript****. Kassim, M.* ***finalize the approved result and manuscript for publication****.*

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