Comparative Analysis of Simulation and Real-World Energy Consumption for Battery-Life Estimation of Low-Power IoT (Internet of Things) Deployment in Varying Environmental Conditions Using Zolertia Z1 Motes

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Abstract. Battery life and power consumption have been a challenging real-world problem for the internet of things (IoT). IoT applications in biomedical, agriculture, ecosystem monitoring, wildlife management, etc., need an accurate estimation of average battery life based on the environment and application. In this paper, we opt for an experimental approach and use various types of real-world environmental conditions such as the presence of interferences and high-intensity lights, to determine the actual power consumption of IoT nodes with a new set of off-the-shelf AA batteries for each scenario. We took readings in each of these environments such as an indoor Basketball Court, an Auditorium, and a room (our lab) and to verify results in outdoor conditions we chose parking lot as one of the testing environments. Further analysis and experimentation were performed to get detailed results. Results were obtained using widely used Zolertia Z1 hardware motes arranged in a specific and consistent pattern. We have compared our experimental results with simulated results in the Cooja simulator.

Keywords: Energy consumption · Battery life · Internet of Things

1 Introduction

In modern times, low powered IoT devices have evolved and gained popularity as well as attention amongst various developers and researchers. They form a critical part of many systems due to their high-performance capacities while using limited power. These nodes consist of low-powered microprocessors, sensors, communication chips and so on. All aspects of these systems, from designing the hardware to the protocol depend on the amount of power that is being consumed by such devices. The power consumption cannot be predicted as the amount of energy required varies with respect to various external factors such as the deployed application, the environment device functions in and so on. The current works on power consumption are mostly based on simulations and offer low reliability, and thus affecting the effective use of these devices in physical environments. The simulations run digitally and do not take into consideration the real

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world parameters such as high-intensity lights, temperature, humidity, the wind, etc. These parameters referred to as interferences, can cause a significant variation in the actual outcomes versus the simulations, which is shown in this work. This paper exploits experimental results in an actual environment with interference to present these unpredictable behavior.

The presented research was conducted using Zolertia Z1 hardware motes. These devices are compact and low powered which makes them easy to deploy and cost-effective. Natural or artificial lighting can prove to be a major source of interference towards the functioning of these low powered IoT devices. In an indoor environment, the energy consumption of a device varies with the lighting conditions which results in degradation of battery life of the device. These devices use two 1.5 V AA batteries. It is important to determine the battery-life when these devices are being used for some critical applications with this limited power source. Based on the domain of application, e.g., medical sensors, human life could be put at risk if this prediction or calculation is incorrect. The power consumption of these devices should be known before deployment. In this paper, we are considering experimental as well as simulated results. For this, we created a close-to-silent environment – an ideal environment devoid of any interference. Therefore, we could compare real-world readings with simulated results and gain some insights into better-predicting battery-life based on application and operational environment.

1.1 Related Work

Since the conception of Zolertia Z1, there has been much research on power analysis of Z1 motes because it is primarily a low power device. Power consumption is our priority, but measurement and estimation of power have also been an issue. In the past, researchers have implemented *powertrace*, a system for network level profiling for low power wireless network nodes. Powertrace tracks the estimated power consumption by employing energy capsules to trace the activities of transmission and reception of data packets. It has been experimentally proven that powertrace has an accuracy rating of 94% to the energy consumption of a device [1]. Power trace implements state tracking to estimate the power consumption of the local node and records the energy consumption in energy capsules that represent node-level activities such as packet reception or packet transmission. We have implemented the same system to analyze the power consumption of networks influenced by different environments to compare power consumption.

There are several works regarding energy consumption analysis, but most of them are through simulation. Very few have any real-world experimental data which shows how energy consumption varies according to change in lighting or other environmental conditions. Several researchers have monitored power consumption using powertrace in simulation. Moreover, the works discuss power consumption analysis for different applications using two motes in the simulation for both Z1 and Sky motes. The motive of these works was to provide total power consumption along with detailed results based on various modes such as T_x, R_x, idle power consumption and active power consumption [2–4]. Another work discusses an extensive accounting of network topologies in simulation, detailing the impact of topologies and the density of the network on power consumption. Having implemented both the random network and the grid network of topology in the simulation, this work uses 20, 30, 40, 45 nodes with changing distance of 20 m and 30 m between motes and varying R_x values of 20, 40, 60, 80, 100% for the grid topology [5]. Another simulation-based work calculated power consumption during an ongoing wormhole attack as well as when an IDS was running to prevent the attack [6].

One of the real-world work has deployed a pair of Zolertia Z1 motes and a pair of OpenMote in the testbed. One of the Z1 motes was connected to monsoon power monitor (which measures the energy consumption of the mote with microsecond precision), and the other mote, working as a proxy, was connected to a PC to collect data located a meter apart. The experiment is conducted for a total of 100 data packets with a packet interval of 1, 2 and 5 s for a total duration of 100, 200 and 500 s respectively [7]. There are some other comparative studies regarding energy consumption with parameters like single hop and multi-hop [8].

2 Experimental Setup

This paper concentrates on the real-world or physical experiments. While the simulation requires only the Contiki-Cooja environment, the physical experiment requires both the hardware and the Contiki OS code to be executed.

2.1 Hardware

The experimental setup is being employed on a low-power Zolertia Z1 mote equipped with an MSP430F2617 microcontroller. Z1 also features 8 Kb RAM and 92 Kb flash memory. In addition to the low-power microcontroller, the mote is equipped with a CC2420 transceiver [9], operating at 2.4 GHz, and IEEE 802.15.4, 6LowPAN and ZigBee protocols compliant. The additional features include a 3-Axis, ±2/4/8/16 g digital accelerometer (ADXL345) and a low-power digital temperature sensor (TMP102) with ±0.5 °C accuracy (in –25 °C–85 °C range). Since this device is designed to work in a range of 0.3 V to 3.6 V, it can be powered by two 1.5 V AA standard batteries. Figure 1(a) and (b) show the low-powered IoT device Zolertia Z1 and its actual board respectively. A new set of batteries was used for each experiment conducted in different environments such as the basketball court, auditorium, and lab. A testbed consisting of nine Zolertia Z1 nodes was used, out of which eight were running the broadcasting (BC) and one-to-one communication (unicasting, UC) applications. A ninth node was running alternatively the powertrace code to measure the energy consumption in joules (J). This was done to trace exactly how much power was consumed during each transmission. During the experiments, we started with eight nodes in 15 ft × 5 ft testbed of Z1 motes. After 15 min, we reduced the number of nodes to 6 and ran the BC and UC applications again. Subsequently, we reduced the number of nodes to 4 and then to 2 and repeated the same procedure. The data obtained from the experiments was recorded and compared. Proper drivers for Zolertia Z1 are available in TinyOS and Contiki as a part of the OS. It consists of MSP430 microprocessor, communication devices, sensors such as an accelerometer, and temperature sensor [10].

(a) (b)

Fig. 1. (a) Zolertia Z1 low powered IoT device used for experiment, (b) Actual Zolertia Z1 board

2.2 Platform

Contiki OS is a very efficient open source OS for low-powered IoT devices because of its multi-tasking abilities despite the fact that most embedded networks and low powered IoT devices carry microcontrollers with small memory design. Due to the constrained size of its memory, Contiki OS is compact in its RAM usage and the size of the code. This can be seen from the fact that an average system with RPL routing based sleepy routers in IPv6 networking uses about 10 KB of RAM and 30 KB of ROM [11]. With major implementation in the field of wireless networks, Contiki OS has the advantage of providing both IPv4 and IPv6 communication [12, 13]. A running Contiki system consists of the kernel, libraries, the program loader, and a set of processes [14]. It can run on a variety of platforms like MSP430 which is employed in Zolertia Z1 and written in the C programming language.

A network with any topology can be created and checked for many different network parameters using Contiki. This can be done by running various example applications defined within Contiki, or by creating a custom library. For our use, we created a network topology of 15 ft × 5 ft grid and ran the same BC and UC applications for both the actual motes in the experimental setup and simulation. The testbed ensures that each set of neighboring nodes are at least 5 ft. apart, as illustrated in Figs. 2 and 3.

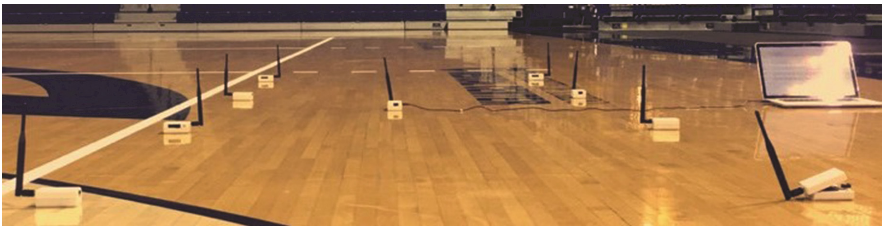


Fig. 2. Experimental setup in the indoor basketball court

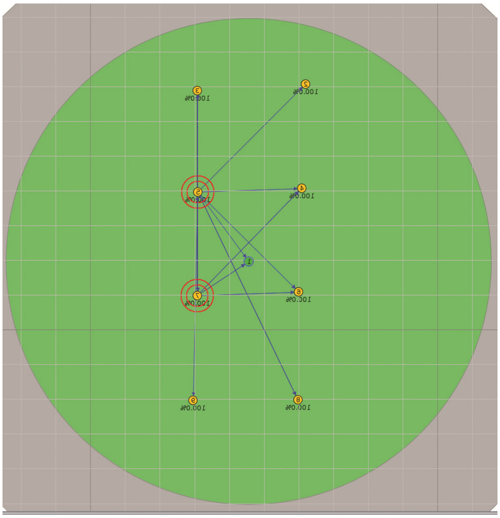


Fig. 3. Topology used in simulation

2.3 Operating Environment

Power consumption varies according to interference and change in environment. Changing this environment can allow observation of significant changes in power consumption. For analysis purpose, we chose a four different environments – (i) an indoor basketball court, (ii) an auditorium, (iii) our lab space, and (iv) an outdoor parking lot. For the basketball court and auditorium, we took readings with zolertia Z1 motes and observed power consumption with lights on and lights off. Moreover, for parking lot, we conducted an experiment with the same set of devices in varied temperature. To achieve this variation we have conducted the experiments at parking lot during day and night timings. Moreover, temperature ranges from 10 c to 20 c. For its justification, we made test bed of 15 ft × 5 ft. We observed significant changes in power consumption in a different environment as discussed in the results section of this paper. Figure 2 shows the setup used in the basketball court. For comparison, we used the same network topology in the Cooja simulation environment, as shown in Fig. 3.

2.4 Simulation

During this experiment, we used Cooja simulator for Contiki which is widely used for simulating network topology with many predefined libraries. This can be used to simulate networks with different examples such as broadcast and one to one communication. The Cooja simulator shows the physical layout of the network motes placed in accordance with the topology of the network [15–17]. Cooja simulator has the advantage of supporting the visualization of power consumption in the form of graphs for the entire network making it easier to understand the behavior of low powered IoT devices [1, 18]. Figure 3 shows the topology used in a simulation which is the same topology as used during real-world experiments.

3 Results

We measured energy consumption for the nodes in varying environmental conditions. We use Contiki powertrace to measure the energy consumption. The output from the powertrace application is the total time in a number of ticks the system spent transmitting, receiving and being idle. Ticks per second for a system is typically defined as the operating clock speed of it processor. The energy consumption is calculated using the typical operating voltage and current values of the Zolertia Z1 mote, as indicated by Table 1. When the radio was off, the MCU was idle; state is referred to as low power mode or low power mode (LPM). The time the MCU is on, and the radio is off, is being referred to as CPU time. The time the radio is receiving and transmitting with the MCU on is referred to as listen and transmit respectively. We ran some examples to see how energy consumption will change in different scenarios. We calculated energy with the help of the following equation [6]

$$Energy\ (\mathrm{mJ}) = \frac{(CPU * 0.5 + LPM * 0.0005 + Tx * 17.4 + Rx * 18.8) * 3}{32768} \tag{1}$$

Where,

CPU = Time for which mote was active
LPM = Total time for which the mote was in low power mode
T_x = Total transmission time
R_x = Total listening time

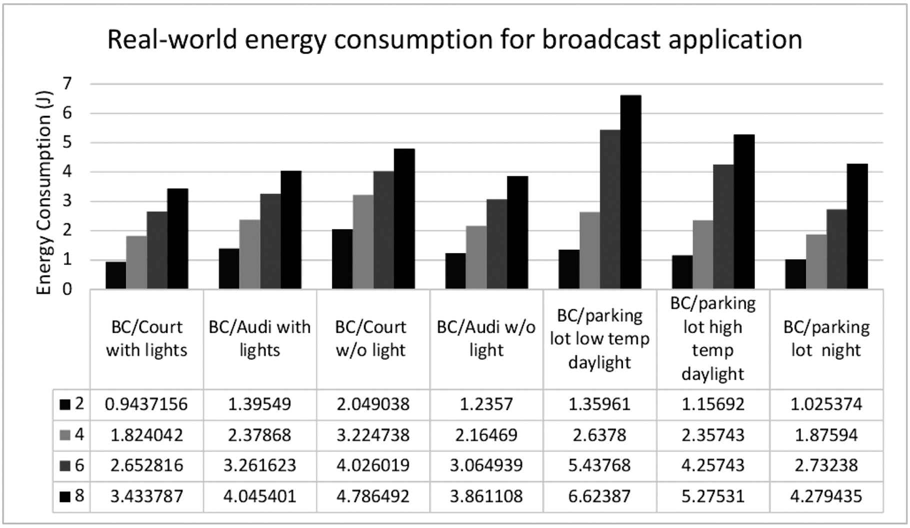
Table 1. Zolertia Z1 mote operating conditions [10]

Typical conditions	Operating	Rating	Unit
MCU on	Radio Rx	18.8	mA
MCU on	Radio Tx	17.4	mA
MCU idle	Radio off	0.1	µA
MCU standby		0.5	µA
Voltage		3.6	V

Equation (1) is multiplied by three because we use a 3 V power supply. In this equation, all the parameters are according to the Zolertia Z1 specification and the denominator indicates the ticks per second value for Z1, i.e., 32768.

3.1 Broadcast

As we discussed earlier, we use 9 zolertia Z1 motes. A broadcast program of the eight-byte data packet was implemented on eight of these nine motes. In the ninth mote, we ran power trace program along with the original broadcast application, to record the actual energy consumption. Figure 4 shows the variation of energy consumption with respect to change in a number of nodes in the basketball court, auditorium and parking lot. We can compare energy consumption during a broadcast in the auditorium with and without lights also in the parking lot to verify experiment in an uncontrolled environment. If we observe this figure, we can see the significant variation in energy consumption during broadcasting with two nodes to eight nodes. With eight communicating in the network we can observe that energy consumption is almost 3.5 times more than two nodes communicating in a network.

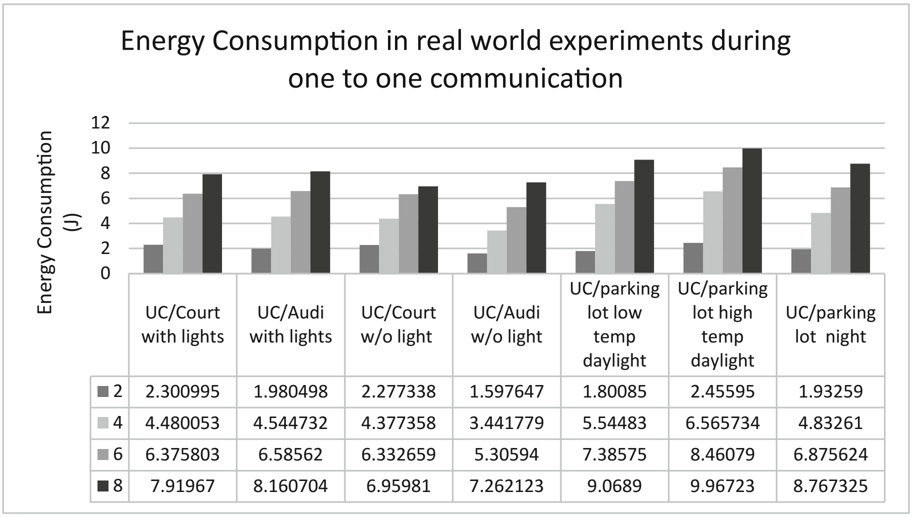


	BC/Court with lights	BC/Audi with lights	BC/Court w/o light	BC/Audi w/o light	BC/parking lot low temp daylight	BC/parking lot high temp daylight	BC/parking lot night
■ 2	0.9437156	1.39549	2.049038	1.2357	1.35961	1.15692	1.025374
■ 4	1.824042	2.37868	3.224738	2.16469	2.6378	2.35743	1.87594
■ 6	2.652816	3.261623	4.026019	3.064939	5.43768	4.25743	2.73238
■ 8	3.433787	4.045401	4.786492	3.861108	6.62387	5.27531	4.279435

Fig. 4. Real-world energy consumption for broadcast application

3.2 One to One Communication

In one to one or unicast communication, the same set of Zolertia Z1 motes were used with a brand new set of 1.5 V AA batteries. Powertrace was used in one of the nine motes and readings for the energy consumption were recorded. Figure 5 illustrates the comparison between one to one communications in the auditorium, basketball court, and parking lot. An exponential trend can be clearly observed with the increase in the number of nodes in a different environment from this figure. For both the auditorium and the court, the energy consumption with lights was less at the beginning, however, as the experiment progresses with time, significant changes could be noted with increased number of nodes. Also, a significant increase in energy consumption in the auditorium was noted compared to the indoor basketball court. This change could be attributed to greater interference due to high-intensity halogen lights in the court. Similarly, it can be observed with a change in the temperature energy consumption is also changes. That means during low-temperature energy consumption is more as compared to normal temperature as in dry atmosphere motes requires more energy to communicate with another node.



	UC/Court with lights	UC/Audi with lights	UC/Court w/o light	UC/Audi w/o light	UC/parking lot low temp daylight	UC/parking lot high temp daylight	UC/parking lot night
■ 2	2.300995	1.980498	2.277338	1.597647	1.80085	2.45595	1.93259
■ 4	4.480053	4.544732	4.377358	3.441779	5.54483	6.565734	4.83261
■ 6	6.375803	6.58562	6.332659	5.30594	7.38575	8.46079	6.875624
■ 8	7.91967	8.160704	6.95981	7.262123	9.0689	9.96723	8.767325

Fig. 5. Real-world energy consumption for one-to-one communication

If broadcasting and one to one communication are compared, the results indicate that one to one communication requires more energy than broadcasting. This is likely because one to one communication node has to establish communication with every single node individually and wait for a response while the broadcasting node sends packets just once without any wait.

Figure 6 shows the drastic differences in the trend obtained from simulation and the real-world experiments. An upward trend for broadcasting is observed but not as significant as one to one (unicast) communication. It should be noted that unicast trend indicates a rather decreasing trend for power consumption in the simulation while it was even worse than broadcasting application in the real-world. This clearly indicates that simulation-based results are highly unreliable due to the inaccurate or absence of model of the channel, path-loss, interference and other important parameters.

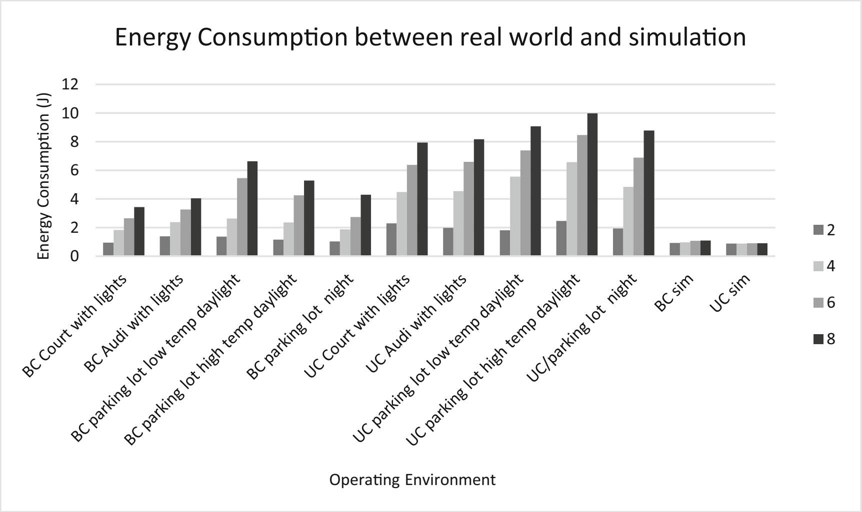


Fig. 6. Energy consumption comparison between various real-world scenarios and simulation results

3.3 Battery Life Estimation

After running the broadcast code for 30 min. in a network of 2/4/6/8 nodes while recording the power consumption of each node, we have formulated a graph as seen in Fig. 7 for the broadcast nodes in the physical environment. This figure illustrates a battery life estimate for all the experiments. The overall battery life (T) was calculated using the following equation:

$$E = I * T * V \tag{2}$$

E = Energy in Joules; I = Current drawn; T = Time; V = Voltage required

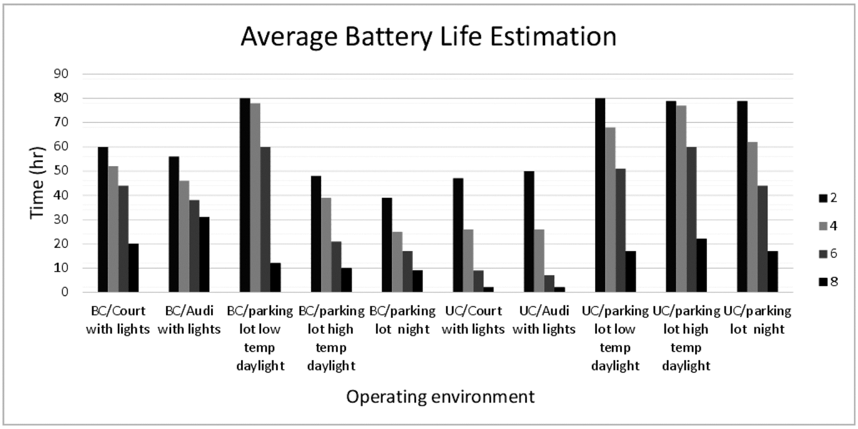


Fig. 7. Average battery life comparison in real-world environments.

In Fig. 7, we can clearly see average battery life during broadcasting. It can be observed that battery life is more when a lesser number of nodes are used in the network. As we keep on increasing the nodes, the energy consumption is more and results in a reduction of battery life. It is also observed that battery life is more during broadcasting compared to one to one communication.

4 Discussion

We captured many energy consumption results under different lighting conditions so that actual power consumption of the devices used can be observed. Through these calculations, the actual power usage can be determined, and we can predict the life of the battery. With the help of these calculations, we can predict exactly how much time the deployed low powered IoT devices will last in certain environments before they stop working at their full potential. These devices have many applications such as medical, military, and environmental monitoring. In all of these environments, energy consumption will be different and might affect the reliability of these devices as they might stop working after a certain time due to battery power exhaustion. For example, if these devices are used for healthcare monitoring, then the devices should have full functionality while the monitoring is underway. Similarly, for an agricultural farm, environmental factors such as humidity and temperature, play a major role in the quality of produce and timely detection of changes in these parameters will have a huge impact on crop production. The experiments in the open parking lot were aimed at specifically evaluating mote battery performance for such conditions/applications.

If an intruder attacks such an IoT network, its energy consumption would also increase, resulting in greater energy consumption and the potential for the device to run out of power. The power consumption of these IoT nodes has been observed in widely varied environments for optimum accuracy in results, thus generating data that is relevant to real world application designers. Any change in the environment affects battery life negatively, which results in unpredictable shutdowns due to loss of power. Based on observed results, it can also be concluded that accurate prediction of important parameters such as battery life is not possible due to unreliable results obtained through simulation. Our experiments show how wildly contrasting the energy consumption results were for simulation compared to the real-world. The simulation results claim that the one to one communication system should be much more energy efficient than the broadcast system while real-world experiments in diversified environments show that the one to one communication uses the significantly large amount of power to run while the broadcast system is comparatively power efficient. The amount of energy used increases with the increase in the number of nodes, but even in this case, the broadcast communication system reflects more efficiency. If these devices are used for healthcare purposes, then complete reliability while functioning is expected when used with the broadcasting application.

5 Conclusion

Considering the popularity of low powered IoT devices, it is important to understand the energy consumption of different applications in different environment. From the results, a significant change in energy consumption was observed, resulting in increased battery power consumption. These devices are popular for many applications, and such an analysis is important for them. These devices use limited power, so energy management is necessary and should be accurately predicted. In this paper, we conducted an analysis on energy consumption in different environments and observed that consumption varies continuously in various environment depending on the operating environment. To employ these low powered IoT devices for critical applications such as health monitoring and defense, a real-time energy consumption monitoring system should be in place which could alert a technician to take appropriate in case energy consumption levels are high. This would allow users to take appropriate action before system malfunction or critical damage.

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