Evaluation of energy demand and lifespan of battery-powered ZigBee IEEE 802.15.4 compliant sensor node for Internet of Things-based applications

Namnsowo Edet Akpan[1]
Department of Electrical/Electronic Engineering Technology
Akwa Ibom State Polytechnic, Ikot Osurua , Akwa Ibom State
namnsowoakpan@gmail.com

Ogungbemi Emmanuel Oluropo[2]
Department Of Electrical/Electronic And Computer Engineering,
University of Uyo, Akwa Ibom State Nigeria

Oto-Obong Chijioke Onwunali[3]
Department of Electrical Electronic and Computer Engineering University of Uyo
Akwa Ibom State, Nigeria.

Abstract*— In this paper, evaluation of energy demand and lifespan of battery-powered ZigBee IEEE 802.15.4 compliant sensor node for Internet of Things-based applications is presented. The sensor node energy consumption is modelled with four states, namely; transmit, receive, measure and sleep state. The sensor node runs in each of the four states in each cycle with a given cycle time and duty cycle. Mathematical model for computing the energy consumed in each of the states and the battery lifespan and other relevant parameter are presented. Specifically, the energy consumption parameters of Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node was used for the case study numerical computations. The results show that with duty cycle of 1 %, the data capture (measure) state has the highest energy consumption of 66.96 mJ per cycle followed by the transmit state with per cycle energy consumption of 40.6377 mJ. The energy consumed per day is 27464.2 mJ and the battery lifespan is 22,084 hours and in this lifespan the sensor node would have run 195,581 cycles and transmitted a total of 16,819,925 bits of data if it transmits 86 bits per cycle. Als, the results show that if active states time and current parameter values are maintained while the duty cycle is increased, the battery lifespan decreases but the number of bits transmitted over the battery lifespan increases. This is due to rapid increase in the number of cycles per day with increase in duty cycle is increased. Also, the energy consumption per day increases with increase in the duty cycle. In all, the specific impact of increase in the duty cycle on the energy consumption of the sensor node depends on which parameters are kept constant and which ones are varied.

***Keywords*— Energy Demand, Sensor Node, Battery Lifespan, ZigBee , Internet of Things, IEEE 802.15.4**

1. Introduction

In recent years, smart applications are increasingly being adopted across the globe [1,2, 3,4, 5, 6, 7,8,9]. The growing smart application industry relies on robust wireless sensors [10,11,12,13,14,15,16,17,18,19]. The sensors on their own are basically meant to capture parameters of their immediate environment and possibly store the data or allow the data to be accessed and utilised in other sub-units of the system [20,21,22,23,24,25,26,27,28,29]. In more advanced sensor nodes, additional functionalities are incorporated, such as transceiver and microcontroller that can enhance the capabilities of the sensor nodes.

In addition, the sensors are in many cases battery-powered which limits the lifespan of such sensors unless energy harvesting recharge mechanism is included [30,31,32,33,34]. In such cases without battery recharge, the possible duration of the battery is dependent upon many factors. One, the battery much provide transmitter power which will be adequate to withstand the various propagation losses the wireless signal will subjected to in its propagation environment [35,36, 37,38, 39,40, 41,42, 43,44,45,46,47,48,49,50,51,52,53,54,55]. The longer the transmission path the higher the transmitter power and the more the energy demand on the battery [56,57,58,59,60,61,62,63,64,65]. More so, satellite-sensor communication link is possible but requires much power for the signal to transverse the distance from the earth to the satellite.

Other factors that can affect the energy demand on the battery of sensor nodes are the duty cycle, cycle time, energy demand in the active state and in the sleep state of the node and other parameters associated with the battery and sensor node. Accordingly, in this paper, the evaluation of the energy demand and lifespan of battery-powered ZigBee IEEE 802.15.4 compliant sensor node for Internet of Things-based applications is presented. The energy consumption of the sensor node is modelled using a four-state model and the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node parameters are used for numerical examples [70,71].

2. Methodology

2.1 Determination of the Energy Demand Profile

The low-end IoT device (LeIoT device) considered in this study is a battery-powered sensor node (with block diagram shown in Figure 1) with four distinct energy demand modes or states (Figure 2), namely; the sensing or data capture/processing mode, the transmission mode, the reception mode and the sleep/wake-up mode. In the diagram in Figure 2, the sleep mode consist of the sleep and wake-up sub-modes whereas, the active mode consists of the sensing or data capture/processing sub-mode, the transmission sub-mode, and the reception sub-mode. One transition from the sleep mode to the active mode and back to the sleep mode constitutes a cycle and the LeIoT device goes through the cycle periodically for a number of cycles in a day.

The time spent by the LeIoT device in each of the modes are denoted respectively as ; $T_M, T_T, T_R,$ and T_S where the time is in ms unless otherwise stated. The current drawn by the LeIoT device in each of the modes are denoted respectively as ; I_M, I_T, I_R and I_S , where the current is in mA unless otherwise stated. Similarly, the energy consumed by the LeIoT device in each of the modes are denoted respectively as; E_M, E_T, E_R and E_S, where the energy is in mJ unless otherwise stated.

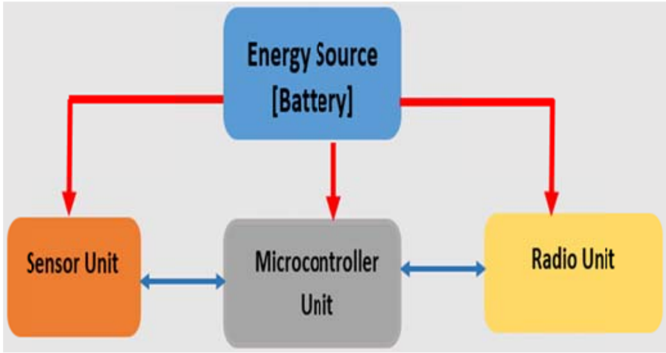

Figure 1 The block diagram of a typical battery-powered sensor node used as the case study low-end IoT device

The operating voltage (in volt) of the LeIoT device and battery is denoted as V_{op}. The LeIoT device is assumed operate in a periodic cycles that consist of data capture/processing operations, transmission of data, and reception of data or acknowledgment and enters the sleep mode for the remaining part of the time in the given cycle.

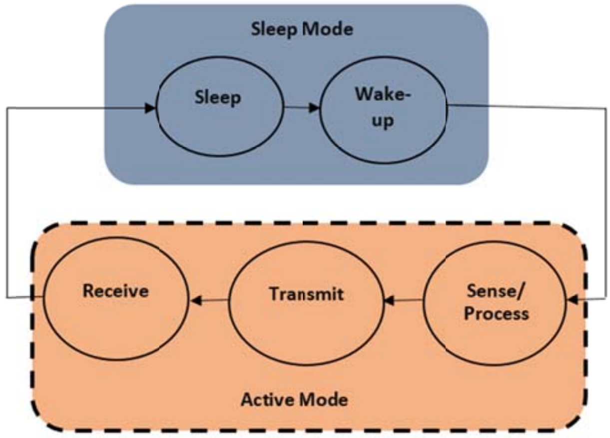

Figure 2 The diagram showing the low-end IoT device modes and state transition

The duration of one cycle is denoted as T_{CY}, and the number of cycles or data capture in a day is denoted as n_{CY} . Then, T_{CY} in ms is given as follows;

$$T_{msHR} = 60 * 60 * 1000 \quad (1)$$

$$T_{CY} = \left(\frac{24\,(T_{msHR})}{n_{CY}}\right) \quad (2)$$

The data capture, transmission and reception modes are collectively referred as the active state of the LeIoT device with time, current and energy denoted as T_A, I_A and E_A respectively. Then, the duty, D_{CY} in % and the energy demand, E_M, E_T, E_R and E_S given as follows;

$$T_A = T_M + T_T + T_R \quad (3)$$

$$T_S = T_{CY} - T_A = \left(\frac{24\,(T_{msHR})}{n_{CY}}\right) - T_A \quad (4)$$

$$D_{CY} = \left(\frac{T_A}{T_{CY}}\right) 100\ \% \quad (5)$$

$$E_M = (I_M)(T_M)\, V_{op} \quad (6)$$

$$E_T = (I_T)(T_T)\, V_{op} \quad (7)$$

$$E_R = (I_R)(T_R)\, V_{op} \quad (8)$$

$$E_S = (I_S)(T_S)\, V_{op} \quad (9)$$

$$E_A = E_M + E_T + E_R \quad (10)$$

2.2 Determination of the battery-powered device lifespan

The LeIoT device is powered by a battery with rated capacity C_{BRC} in mAh and percentage of useful capacity, C_{BUP} , then the effective battery capacity, C_{BEC} in mAh and the LeIoT device lifespan in hours, T_{Lhr} are given as follows;

$$C_{BEC} = \frac{(C_{Bat})(C_{BUP})}{100} \quad (11)$$

$$I_{AV} = \frac{\{(T_T * I_T) + (T_R * I_R) + (T_M * I_M) + (T_S * I_S)\}}{T_M + T_T + T_R + T_S} \quad (12)$$

$$T_{Lhr} = \frac{C_{BEC}}{I_{AV}} \quad (13)$$

Furthermore, the LeIoT device lifespan in days, T_{Ld} and in years, T_{Ly} are given as follows;

$$T_{Ld} = \frac{24(C_{BEC})}{I_{AV}} \quad (14)$$

$$T_{Ly} = \frac{8760(C_{BEC})}{I_{AV}} \quad (15)$$

The energy consumption parameters of Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node (as presented in Table 1) is used in this study for the numerical examples.

Table 1 The energy consumption parameters of ZigBee IEEE 802.15.4 compliant sensor nodes used in this study [70,71]

S/N	Parameter	Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node
1	Data rate	250 kb
2	Sleep mode	15 µA
3	Processor consumption	8 mA
4	Transmission	17.4 mA
5	Reception	19.7
6	Supply voltage	2.7

3 Results and discussion

The requisite impute parameters for the case study sensor node were used to compute the energy consumption, lifespan and other relevant parameters and the results are presented and discussed. The results for the power profile, as well as the energy consumed per cycle and per day in each of the four states of the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node are shown in Table 2. The results in Table 2 show that the data capture (measure) state has the highest energy consumption of 66.96 mJ per cycle followed by the transmit state with per cycle energy consumption of 40.6377 mJ , as shown in Figure 3.

Table 2 The results for the power profile, as well as the energy consumed per cycle and per day in each of the four states of the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node

Sensor Node Mode	Current , I (mA)	Time, t (mS)	Power (W)	Energy (mJ) consumed per cycle	Energy (mJ) consumed per day
Transmit	17.4	865	0.04698	40.6377	8637.39
Receive	19.7	100	0.05319	5.319	1130.53
Measure	8	3100	0.0216	66.96	14232.09
Sleep	0.015	402435	0.0000405	16.2986	3464.21
Total				129.22	27464.21508

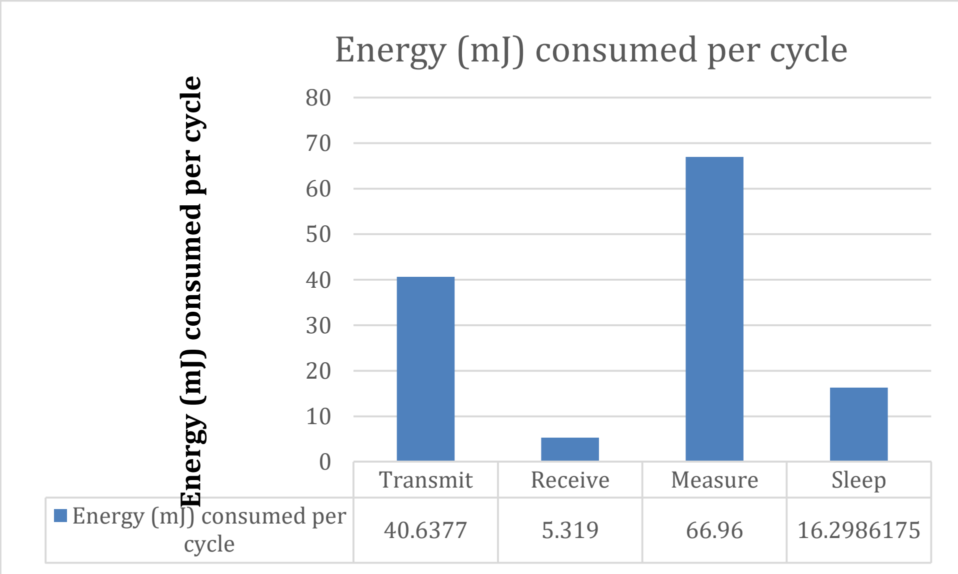

Figure 3. Per cycle energy consumption in each of the four states of the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node

The active states time and current parameter values are maintained while the duty cycle is varied from 1 % to 30 %. The results on the impact of duty cycle on the cycle time and number of data capture for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node are shown in Table 3 and Figure 4. The results in Table 3 and Figure 4 show that increasing the duty cycle while maintaining the active state time duration amounts to reduction in the cycle time and increase in the number of cycles (or number of data capture) per day.

The results on the impact of duty cycle on the energy consumed per cycle for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node are shown in Table 4 and Figure 5. The results in Table 4 and Figure 5 show that increasing the duty cycle while maintaining the active state time and current parameter values amounts to reduction in the sleep state time and cycle time and hence decrease in the energy consumed in the sleep time and energy consumed per cycle. In this case, the energy consumed in the active state is constant.

The results on the impact of duty cycle on energy consumed per day for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node are shown in Table 5 and Figure 6. The results show that the resultant effect of the increase in the duty cycle is increase in the daily energy consumption. This seems to contradict the decrease in the per cycle energy consumption with increase in duty cycle. The increase in per day energy consumption is due to the rapid increase in the number of cycles per day.

The results on the impact of duty cycle on the battery lifespan and number of bits transmitted for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node are shown in Table 6, Figure 7 and Figure 8. The results in Figure 7 and Figure 8 show that while the battery lifespan decreases with increase in duty cycle the total number of bits transmitted over the battery lifespan increases with the duty cycle. This is due to the rapid increase in the number of cycles per day as the duty cycle increases.

Table 3 The results on the impact of duty cycle on the cycle time and number of data capture for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node

Duty Cycle (%)	Cycle Time (s)	Number of cycles per day	Duty Cycle (%)	Cycle Time (s)	Number of cycles per day
1	406.5	212.5461	16	25.40625	3400.738
2	203.25	425.0923	18	22.58333	3825.83
4	101.625	850.1845	20	20.325	4250.923
6	67.75	1275.277	22	18.47727	4676.015

8	50.8125	1700.369	24	16.9375	5101.107
10	40.65	2125.461	26	15.63462	5526.199
12	33.875	2550.554	28	14.51786	5951.292
14	29.03571	2975.646	30	13.55	6376.384

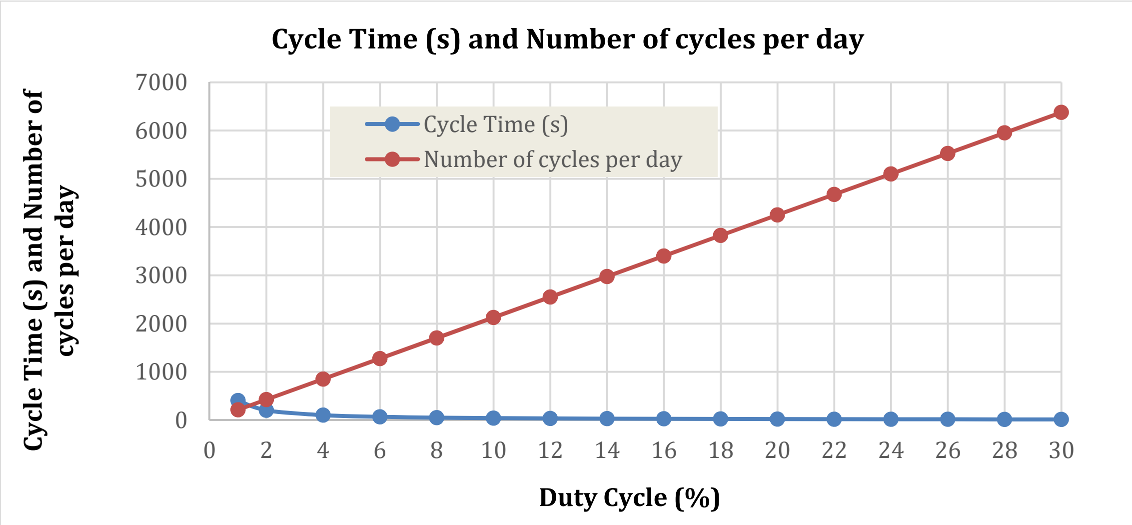

Figure 4 **The graph of cycle time and number of data capture versus duty cycle for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node**

Table 4 The results on the impact of duty cycle on the energy consumed per cycle for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node

Duty Cycle (%)	Eactv (mJ) per cycle	Eslp (mJ) per cycle	Eperiod (mJ) per cycle	Duty Cycle (%)	Eactv (mJ) per cycle	Eslp (mJ) per cycle	Eperiod (mJ) per cycle
1	112.9	16.3	129.2	16.0	112.9	0.9	113.8
2	112.9	8.1	121.0	18.0	112.9	0.7	113.7
4	112.9	4.0	116.9	20.0	112.9	0.7	113.6
6	112.9	2.6	115.5	22.0	112.9	0.6	113.5
8	112.9	1.9	114.8	24.0	112.9	0.5	113.4
10	112.9	1.5	114.4	26.0	112.9	0.5	113.4
12	112.9	1.2	114.1	28.0	112.9	0.4	113.3
14	112.9	1.0	113.9	30.0	112.9	0.4	113.3

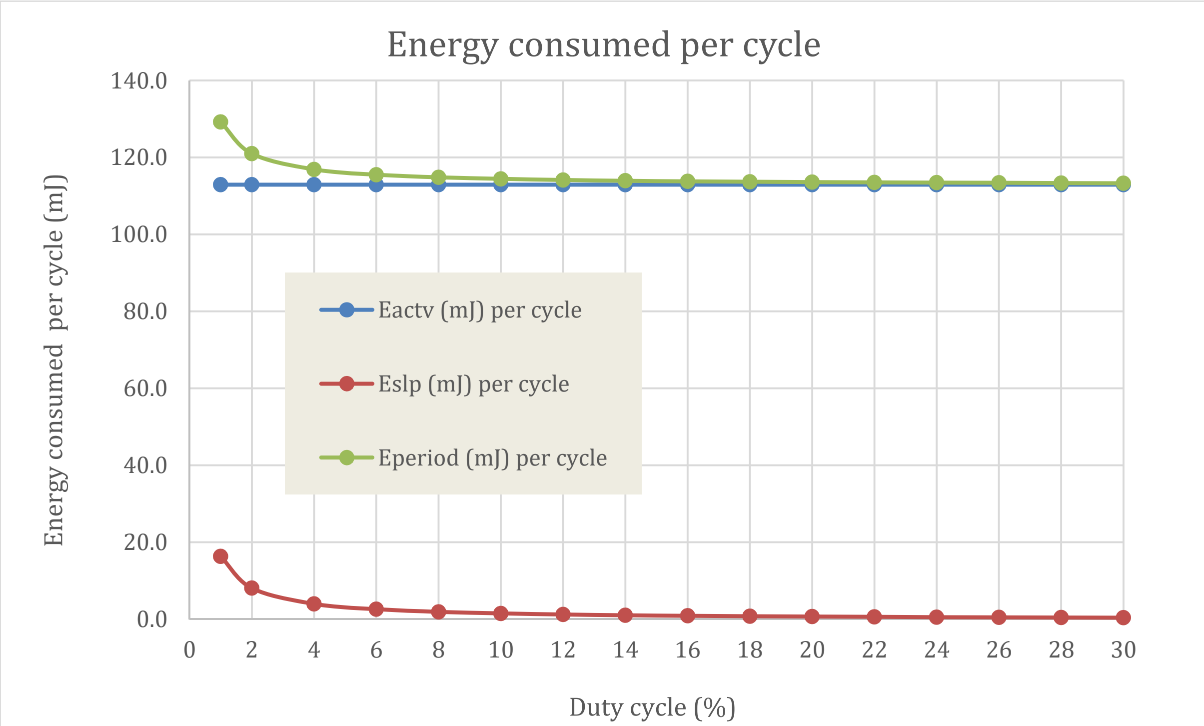

Figure 5 **The graph of energy consumed per cycle versus duty cycle for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node**

Table 5 The results on the impact of duty cycle on energy consumed per day for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node

Duty Cycle (%)	Energy (mJ) consumed per day	Duty Cycle (%)	Energy (mJ) consumed per day
1	27464.2	16	386939.4
2	51429.2	18	434869.5
4	99359.3	20	482799.5
6	147289.3	22	530729.5
8	195219.3	24	578659.6
10	243149.4	26	626589.6
12	291079.4	28	674519.6
14	339009.4	30	722449.7

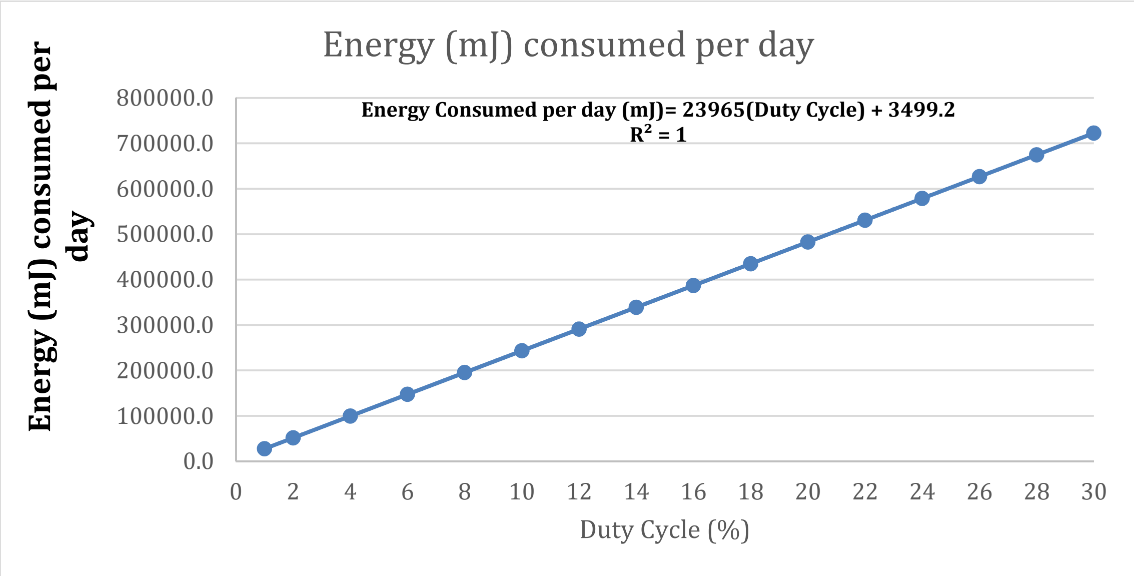

Figure 6 **The graph of energy consumed per day versus duty cycle for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node**

Table 6 The results on the impact of duty cycle on the battery lifespan, number of bits transmitted and energy consumed for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node

Duty Cycle (%)	Battery Lifespan (hour)	Number of cycles in battery lifespan	Number of bits transmitted in battery lifespan (bits)	Energy (mJ) consumed in battery lifespan	Duty Cycle (%)	Battery Lifespan (hour)	Number of cycles in battery lifespan	Number of bits transmitted in battery lifespan (bits)	Energy (mJ) consumed in battery lifespan
1	22,084	195,581	16,819,925	25,272,000	16	1,568	222,111	19,101,534	25,272,000
2	11,793	208,888	17,964,338	25,272,000	18	1,395	222,334	19,120,746	25,272,000
4	6,104	216,244	18,597,000	25,272,000	20	1,256	222,513	19,136,144	25,272,000
6	4,118	218,813	18,817,908	25,272,000	22	1,143	222,660	19,148,761	25,272,000
8	3,107	220,120	18,930,341	25,272,000	24	1,048	222,782	19,159,288	25,272,000
10	2,494	220,912	18,998,449	25,272,000	26	968	222,886	19,168,204	25,272,000
12	2,084	221,443	19,044,127	25,272,000	28	899	222,975	19,175,853	25,272,000
14	1,789	221,824	19,076,888	25,272,000	30	840	223,052	19,182,488	25,272,000

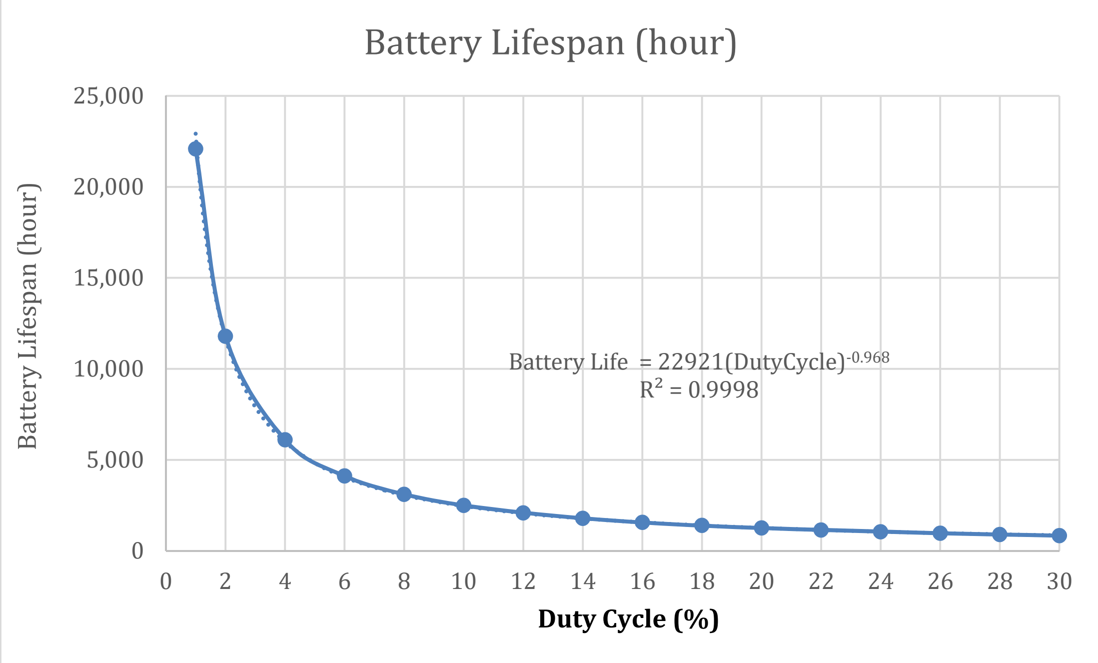

Figure 7 **The graph of battery lifespan versus duty cycle for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node**

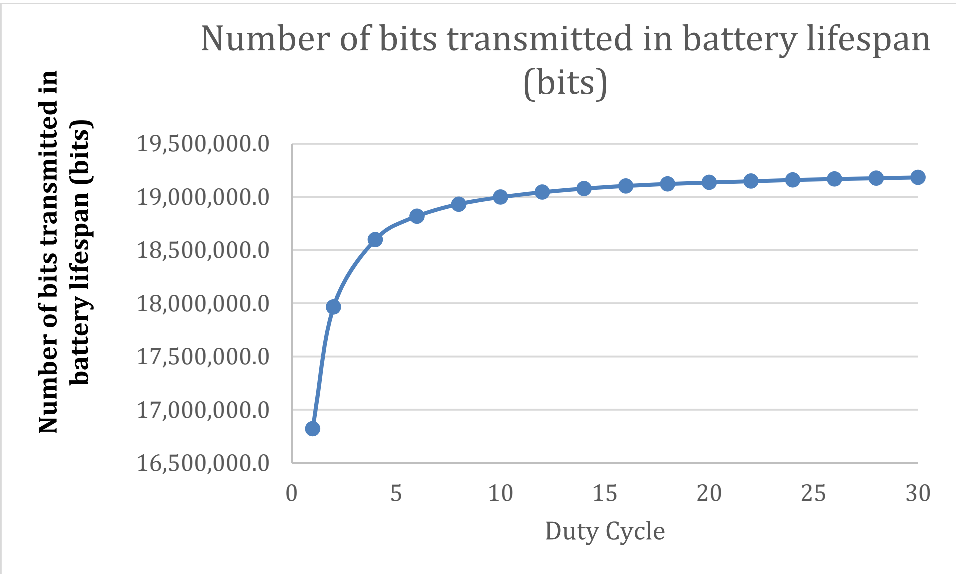

Figure 8 The graph of number of bits transmitted in battery lifespan versus duty cycle for the Crossbow MICAz ZigBee IEEE 802.15.4 compliant sensor node

4. Conclusion

The energy consumption and battery lifespan, as well as the impact of duty cycle on the energy consumption and data communication capability of a ZigBee IEEE802.15.4 compliant sensor node is presented. The sensor node energy consumption is modelled with four states and which it runs in each cycle with a given cycle time and duty cycle. The results show that if active states time and current parameter values are maintained while the duty cycle is increased, the battery lifespan decreases but the number of bits transmitted over the battery lifespan increases. This is due to rapid increase in the number of cycles per day with increase in duty cycle is increased. Also, the energy consumption per day increases with increase in the duty cycle. In all, the specific impact of increase in the duty cycle on the energy consumption of the sensor node depends on which parameters are kept constant and which ones are varied.

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