Energy Consumption Analysis of A Sensor Node Working in A Wireless Sensor Network

M. A. Khan*
Department of Electrical and Electronic Engineering, Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj-8100, Bangladesh,
*corresponding author's email: asad.khan@bsmrstu.edu.bd, arzu1013@gmail.com

Abstract – *Energy consumption is an important aspect of a battery driven sensor node used in a wireless sensor network. In the existing literature, there are many energy consumption models available but most of them considered only one layer of energy consumption. Instead of the existing model, this research work proposed a cross layer based energy consumption model in which both the physical layer and mac layer energy consumption are measured. For mac layer energy, energy consumption is analysed with different multiple access techniques such as time-hopping (TH) and direct-sequence (DS) multiple access. In the physical layer, the proposed energy consumption model is to calculate the energy consumption of bit-by-bit data transfer of the sensor module. The ultimate goal of this research work is to develop a close form cross-layer energy consumption model of a sensor module working in a wireless sensor network. Further, to reduce the energy utilization of a sensor module, the sleeping technique by which the sensor node will remain inactive where there is no data for sending to others is introduced. The usefulness of this proposed energy consumption model is verified by assessing the node active time as well as network lifetime for various loads in the network.*

Keywords: *Energy consumption, Sensor module, Sleeping protocol, Wireless sensor network*

Article History
Received 11 March 2022
Received in revised form 7 Jun 2022
Accepted 8 September 2022

I. Introduction

Wireless sensor network (WSN) is a network where the battery driven small sensor nodes are embedded in a network by distributed manner. Nowadays the WSN becomes an attractive network for its several applications of survival monitoring, infrastructure free disaster area monitoring, structural health monitoring, remote medical diagnosis monitoring and so on [1]. In WSN sensor nodes are communicated with each other without any fixed infrastructure. The nodes are gathered information from the environment and send it to neighbors toward the destination [2]. The nodes are placed in various environmental locations and follow many different network topologies of the wireless network. Due to the infrastructure free communication, the WSN has to face many more challenging issues than the conventional wireless network such as it needs different routing topologies for self-configuration networking, needs to concern about network location and even the placement of each sensor node so on [3]. The most challenging issue of the WSN is the energy consumption of each node due to its battery driven attributes [4]. The size of the sensor node is very small like a coin, so the battery size is also small. Due to the small battery size of the sensor nodes the energy consumption analysis is a key issue for the researcher. So enhancing the node lifetime by reducing the energy consumption of a sensor node as well as increasing the network lifetime is a crucial concern of WSN research. All over the world researchers are working on this energy consumption issue in the WSN [5]. For saving the energy utilization of each sensor module many more policies are needed. Among these existing policies, first of all, it needs to know the details of the energy consumption of a sensor node working within a network. Second, it needs to measure energy consumption by an exact formulation. Third, it needs to apply some techniques to reduce the energy consumption of a sensor node. To achieve all these three goals together the existing strategies of energy consumption research is inadequate. To fill up the existing research gap this research paper proposed a mathematical model of energy consumption by introducing sleeping protocols of a sensor module working in a wireless sensor network. The rest of the paper is followed up as; in section II, the existing literatures are reviewed and justified in this proposed work. In section III, the detail energy consumption model is discussed. The usefulness of the proposed energy consumption model is analyzed and visualized by simulation results presented in section IV. Finally, Section V concludes the proposed research work.

II. Literature Review

In the existing literature, there are several energy consumption models are available. Energy consumption analysis of a sensor node and sleeping protocols is introduced in [6] but the authors have not considered the node energy consumption for the amplification part. In [7] the energy consumption model is extended by introducing the time-hopping multiple access and discrete-sequence multiple access but the authors ignored the transmitting power amplifier energy consumption part. In [8] a linear model-based energy estimation technique of a sensor node is described but it is not a details energy consumption model because the energy consumption for synchronization is not considered. A physical layer and mac layer based energy consumption analysis is conferred in [9] but which is for specific applications of ultra-wide band communication systems. Again, time-hopping based energy consumption model is described in [5] and [10] for the wireless body area network and the impulse radio ultra-wide band network respectively where a detail mathematical form of energy consumption is inattentive. In [4] the author has described the energy consumption model for time-hopping and direct-sequence multiple access only for the low data rate ultra-wide band network. Node energy consumption analysis is described in [11] but closed form mathematical expression is absent. An energy consumption model is described in [12]. But the sleeping protocol technique for energy saving policy is not considered. Energy consumption models are described in [13]–[15] but they have not considered the sleeping protocol in detail. A number of research have been done for calculating the energy consumption of a sensor node [1], [3], [16]-[17] but most of the existing analyses have failed to explain the energy consumption properly by taking advantage of cross-layer design facilities such as physical layer and mac layer based energy consumption. Also sleeping protocol technique to save energy for the sensor node is ignored. In [2] the authors aim to develop an energy-efficient WSN model implemented for perimeter surveillance but detail energy consumption model is ignored. Energy saving sleeping protocol is introduced in [18] where the energy consumption model is proposed but detail classification of slotted and unslotted sleeping protocols are not considered. The authors in [19] point out the energy consumption analysis of a WSN but mathematical models are absent. In [20] a prototype model with a simulation model is presented and this work may lower the amount of power used by each sensor node, while also increasing the life of sensors by shutting down certain of their components in order to achieve higher energy savings and longer life whereas the detail design model is ignored. On the other hand, a design based energy consumption analysis is discussed in [21] where the mathematical based calculation is lacking. According to the above existing work a cross-layer based energy consumption technique is needed to enhance the node lifetime. The main focus of this research work is to elucidate detail mathematical models of cross-layer based energy consumption with considering the sleeping protocol of a sensor node working in a wireless network.

III. Energy Consumption Model

In this part, the energy utilization model of a sensor module is examined exhaustively and insightful models of energy utilization are proposed for DS-SS and TH-SS individually. A sleeping protocol is one of the most efficient methods for preserving the energy of sensor module in WSN. This sleeping protocol needs a scheme that permits the sensor module to take a rest when no data to send in the network. The sleeping protocol can be classified as slotted-time and unslotted-time. In the slotted-time situation, time is partitioned into small parts of time and the information transmission happens during these time slots. In the unslotted-time event, the information transmission happens afterward the sensor node wakes up in listening window time as in Fig. 1.

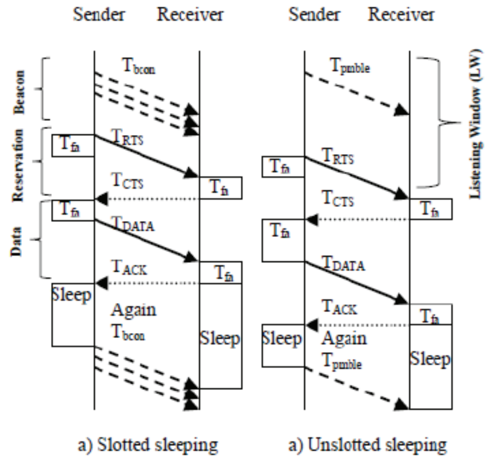

Fig. 1. Slotted and unslotted sleeping protocols

In slotted-time protocol, the synchronization is done by a periodic beacon T_{bcon} which also denotes the beginning of a data-frame. Each data-frame beginning needs a booking policy with receiver. The booking policy is done by sending a request file as RTS and completed by receiving clear for sending file as CTS. Where the receiver sent number of slots information for communication of data to the transmitter. According to the receiver's defined slots, the transmitter able to send data during that given slots and at other times the receiver goes to sleep mode.

Whereas in the unslotted-time policy, the receiver has its self-sleeping and wake-up timetable. So according to each node's wake-up time, the node able to reply the senders' request for data-frame transmission. Therefore, each sender must know the roster of each receiver and then send the preamble T_{pmble} for synchronization. But the duration of this preamble needs to be sufficiently long by which it able to wait before wake-up the receiver sensor module. After receiving this preamble, the receiver will send a request file to the transmitter to send the data-frame for receiving.

A. TH-SS Energy Consumption

In TH-SS, the time is divided into a frame which consists of N_{chip}, number of chips and the duration of each chip is T_{chip}. In this case, each pulse carries one data bit. During a chip time, the physical layer can transmit data, receive data, do a signal acquisition, keep active-off, and go to sleep. According to the above activities of a sensor node in a network the total energy consumption model for a data frame to transmit or receive is expressed as follows:

$$E_{Total\_CF\_TH} = E_{trx} + E_{revx} + E_{aoff} + E_{sleep} \quad (1)$$

In (1) $E_{Total\_CF\_TH}$ is the total energy consumption of a sensor node for a frame of data exchange within a network. Here the energy consumption of a sensor node during transmission including active-off state is expressed as

$$\overbrace{P_{St}T_{St} + \left[L_{pmble} + L_{Syn} + \frac{L_{Total} - L_{syn}}{R_{code}}\right] \times \left[\left(P_{pulse} + P_o d^{\gamma}\right) \times T_{chip} + \left(N_{chip} - 1\right) E_{aoff}\right]}^{E_{trx} + E_{aoff}} \quad (2)$$

where,

$$P_o = \frac{(S/N)(NF_{revx})(N_o)(BW)\left(4\frac{\pi}{\lambda}\right)^{\gamma}(10)^{\gamma}}{(G_{ant})(\eta_{amp})} \quad (3)$$

In (2), P_{st} and T_{st} are the consumed power and time to transit from sleep mode to active mode respectively. L_{pmble}, L_{syn}, and L_{Total} are preamble, synchronization, and total length of the packet in bit, respectively. P_{pulse} is the power of a single pulse, P_o, d, γ, are the amplifier power, the distance between transmitter and receiver, and the path loss exponent, respectively. In (3), P_o is the amplified power that is needed to achieve the required signal to ratio (S/N) at the receiver for decoding the information properly. Besides that, NF_{revx} is the receiver noise figure, the bandwidth BW in hertz, wavelength λ in meter, thermal noise N_o, antenna gain G_{ant}, and transmitter efficiency η_{amp}.

The energy consumption for receiving the data including the active-off state is expressed as

$$\overbrace{P_{sr}T_{sr} + L_{syn}N_{chip}E_{acq} + \left[L_{pmble} + \frac{L_{Total} - L_{syn}}{R_{code}}\right] \times \left[E_{revx} + \left(N_{chip} - 1\right)E_{aoff}\right] + \left(L_{Total} - L_{syn}\right)E_{decb}}^{E_{revx} + E_{aoff}} \quad (4)$$

where, P_{sr} and T_{sr} are the consumed power and time to transit from sleep mode to active mode in receiver respectively. The energy for decoding E_{decb} a bit in the receiver section is expressed as in [5].

$$E_{decb} = C_0 \alpha_c^{k_c} V^2_{DD} + \left(T_0 \alpha_t^{k_c}\right) \frac{f_{\max}}{f} V_{DD} I_0 e^{\frac{V_{DD}}{nV_T}} \quad (5)$$

While the energy consumption for different sleeping protocols is expressed as

$$\overbrace{\left(P_{bcon}T_{bcon}\right)}^{E_{sleep(slotted)}} \; or \; \overbrace{\left(P_{pmble}T_{pmble}\right)}^{E_{sleep(unslotted)}} \quad (6)$$

In the above equation (6), P_{bcon} and P_{pmble} are the power of beacon and preamble pulse respectively.

B. DS-SS Energy Consumption

In DS-SS, the time is divided into a frame which consists of N_{chip} number chips and the duration of a chip is T_{chip}. In this case, each pulse carries one data bit. During a chip time, the physical layer can transmit data, receive data, do signal acquisition, and go to sleep.

The active-off state is not available in DS-SS strategy because each chip contains a data bit. According to the above activities of a sensor node in a network the total energy consumption model for a data frame to transmit or receive is expressed as follows:

$$E_{Total\_CF\_DS} = E_{trx} + E_{revx} + E_{sleep} \qquad (7)$$

In (7), $E_{Total\_CF\_DS}$ is the total energy consumption of a sensor node for a frame of data exchange within a network. The energy consumption for transmitting section is expressed as

$$\overbrace{P_{St}T_{St} + \left[L_{pmble} + L_{Syn} + \frac{L_{Total} - L_{syn}}{R \times R_{code}} \right] \times \left[\left(P_{pulse} + P_{o}d^{\gamma} \right) \times T_{chip} + \left(L_{Total} E_{txDS} \right) \right] \times N_{chip}}^{E_{trx}} \qquad (8)$$

where R is the bit rate, R_{code} is the coding rate and P_o is same as in (3). The energy consumption for receiving section is expressed as

$$\overbrace{P_{sr}T_{sr} + L_{syn}N_{chip}E_{acq} + \left\{ \begin{matrix} \left[L_{pmble} + \frac{L_{Total} - L_{syn}}{R \times R_{code}} \right] + \\ \left[\left(L_{Total} - L_{syn} \right) E_{rxDS} \right] \end{matrix} \right\} \times N_{chip} + \left(L_{Total} - L_{syn} \right) E_{decb}}^{E_{revx}} \qquad (9)$$

where, E_{decb} is same as in (5).

The energy consumption of a sensor node in sleeping mode is calculated depend on the time duration T_{bcon} of a beacon pulse and the power P_{bcon} need to transmit this beacon signal for the slotted sleeping technique. The energy consumption for sleeping part of unslotted sleeping technique depends on the preamble P_{pmble} pulse power and its time duration T_{pmble}. The expression of the energy consumption for different sleeping protocols is as

$$\overbrace{\left(P_{bcon} T_{bcon} \right)}^{E_{sleep(slotted)}} \text{ or } \overbrace{\left(P_{pmble} T_{pmble} \right)}^{E_{sleep(unslotted)}}. \qquad (10)$$

The details operation of a sensor node either in working mode or in sleeping state is described by a flow chart given in Fig. 2. The flow chart elucidates the energy consumption analysis of data transmission between the transmitter and the receiver part of a sensor node working in a network.

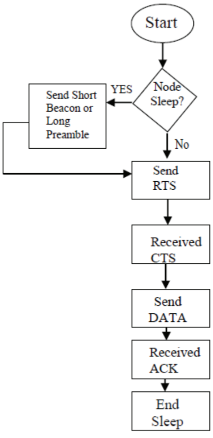

Fig. 2. Slotted and unslotted sleeping protocols

IV. Results and Discussion

To show the usefulness of the proposed energy consumption model, the numerical solutions are simulated and the results are discussed in this section. The 30 nodes are embedded in a 30 x 30-meter square area. For simulation, the Matlab tool is used and the simulation parameters are as followings:

$T_{chip} = 1\,ns$, $N_{chip} = 1000$, $P_{bcon} = 50\,\mu s$, $P_{pulse} = 0.2818\,mW$, $P_{st} = 0.12\,mW$, $T_{st} = 0.9\,ns$, $R_{code} = 1, 1/2$, $E_{decb} = 4.18\,mJ$,

and other numerical values are taken from [7] and [10].

Firstly, the multiple access techniques are investigated by varying the traffic load as shown in Fig. 3, where it is observed that when the network data load is minimum, the energy consumption is almost the same for TH-SS and DS-SS multiple access. When the data load increases however, the energy consumption by DS-SS multiple access increases more than the TH-SS. This is because in DS-SS all chips in a frame carry a message bit and the active-off state is absent, make it to consume more energy than the TH-SS.

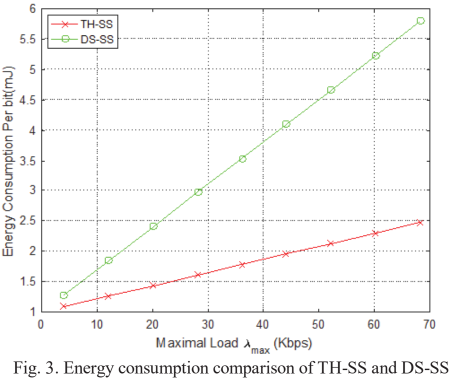

Fig. 3. Energy consumption comparison of TH-SS and DS-SS

Secondly, Fig. 4 shows the energy consumption comparisons of different sleeping protocols in view of sensor node active time (duration of active on the node) with respect to load variation in the network. When the network load is minimum then the node active time is almost same both for slotted-time sleeping and unslotted-time sleeping protocol. But when the load of the network increases the node activated time increases. But the unslotted-time sleeping protocol circumstance this increasing is more rapid then the slotted-time sleeping protocols. The reason behind the above phenomenon of Fig. 4 is for slotted-time policy the small beacon frame is needed before the data frame begin but this beacon frame does not carry any useful data which is wastage of energy. Furthermore, in this slotted-time case this beacon needs after finishing the transmission of each frame through the given slots by the receiver which consume more energy. Whereas in the unslotted-time case initially the preamble needs for beginning of data-frame and sensor module goes to sleep after finishing this data-frame. Therefore, the unslotted-time sleeping protocol increases the lifetime of the sensor node by consuming less energy than the slotted sleeping protocol for higher traffic load in the network.

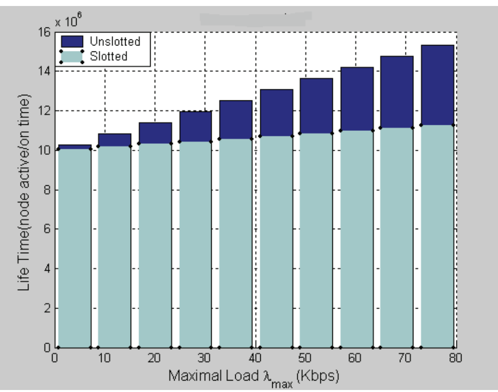

Fig. 4. Comparison of energy consumption of sleeping protocols

Further in Fig. 5, the access delay is defined as the delay time for the reservation before sending the data to the destination. The figure shows that in the unslotted-time sleeping protocol circumstance the sensor node active time is less than the slotted-time sleeping protocol. This is because in the unslotted-time sleeping the sensor node only wave up (active/on) during its own listening window for example one time for a data frame. But in slotted-time sleeping need to keep active on during reservation where each node receives RTS throughout a number of slots.

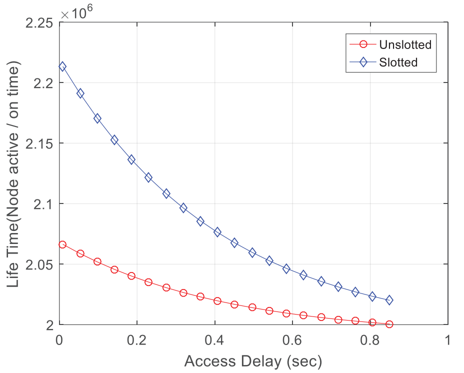

Fig. 5. Comparison of energy consumption of sleeping protocols considering the load access delay

V. Conclusion

In this research work, a cross-layer based energy consumption model of a sensor node working in a wireless sensor network is developed. Considering the physical layer and mac layer activities a detail mathematical expression of the energy consumption model is presented. The given results show the usefulness of the proposed model and it is found that with the maximum load in the network the TH-SS outperforms than the DS-SS by consuming less energy. Further, in the condition of the maximum traffic load in the network, it is observed that the unslotted time sleeping protocol provides longer node active time than the slotted time sleeping protocol. Whereas for the access delay load circumstance the unslotted sleeping protocol consumes less energy than the slotted sleeping protocol by keeping less active on time of the sensor node in the network.

References

[1] P. Joshi, S. Gavel, and A. S. Raghuvanshi, "Estimating Energy Consumption for Various Sensor Node Distributions in Wireless Sensor Networks," *Nanoelectronics, Circuits and Communication Systems*, *Springer*, pp. 289-299, 2021.

[2] A. L. Imoize, O. A. Ajibola, T. R. Oyedare, J. O. Ogbebor, and S. O. Ajose, "Development of an Energy-Efficient Wireless Sensor Network Model for Perimeter Surveillance," *International Journal of Electrical Engineering and Applied Sciences (IJEEAS)*, vol. 4, no. 1, pp. 1-16 2021.

[3] R. Shanmugavalli and P. Subashini, "Energy Consumption Analysis in WSN Based on Node Placement Strategies," International Journal of Engineering & Technology, vol. 7, no. 3, pp. 531-535, 2018.

[4] M. Usman, "Analysis of the Impact of Different Parameter Settings on Wireless Sensor Network Lifetime," *International Journal of Advanced Computer Science and Applications*, vol. 9, no. 3, pp. 16-21, 2018.

[5] D. Xuebing, Y. Zhang, and C. Wang. "An Reliable Transmission Scheme Based on Opportunistic Cooperation for Wireless Body Sensor Networks," *Journal of Networks*, vol. 9, no. 7, pp. 1927-1934, 2014.

[6] M. A. Khan, A. A. Parvez, M. E. Hoque, X. An, and K. S. Kwak, "Impact of Sleep on PHY-MAC in UWB Networks," *2006 International Symposium on Communications and Information Technologies*, pp. 615-618, 2006.

[7] M. A. Khan, A. Al Parvez, M. E. Hoque, X. An, and K. S. Kwak, "Analysis of Energy Consumption and Sleeping Protocols in PHY-MAC for UWB Networks," *The 9th International Conference on Advanced Communication Technology,* pp. 858-863, 2007.

[8] A. Sivagami, K. Pavai, D. Sridharan, and S. S. Murty, "Estimating the energy consumption of wireless sensor node," *Iris:* International Journal of Recent trends in Engineering and Technology, Vol. 3, no., 4, pp. 141-143, 2010.

[9] R. Merz, J. Widmer, J.-Y. Le Boudec, and B. Radunovic, "A joint PHY/MAC architecture for low-radiated power TH-UWB wireless adhoc networks," *Wireless Communications and Mobile Computing Journal, Special Issue on Ultrawideband (UWB) Communications*, vol. 5, no. 5 pp. 567–580, 2005.

[10] Hoque, M. E., M. A. Khan, Al Parvez, Xizhi An, and Kyung Sup Kwak. "An Energy Consumption Model for Time Hopping IR-UWB Wireless Body Sensor Networks," In *ITC-CSCC: International Technical Conference on Circuits Systems, Computers and Communications*, pp. 749-750. 2007.

[11] F. Luo, C. Jiang, H. Zhang, X. Wang, L. Zhang, and Y. Ren, "Node Energy Consumption Analysis in Wireless Sensor Networks," *2014 IEEE 80th Vehicular Technology Conference,* pp. 1-5, 2014.

[12] D.Anouar, "Ultra low power consumption, short transmission time and efficient data coding wireless communication technology for MWSNs," In *2016 5th International Conference on Multimedia Computing and Systems (ICMCS*), pp. 304-309, 2016.

[13] R. Shanmugavalli and P. Subashini, "Energy Consumption Analysis in WSN Based on Node Placement Strategies," *International Journal of Engineering & Technology*, vol. 7, no. 3.12, pp. 531-535, 2018.

[14] S. Khriji, R. Cheour, M. Goetz, D. El Houssaini, I. Kammoun, and O. Kanoun, "Measuring Energy Consumption of a Wireless Sensor Node During Transmission: panStamp," *IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA)*, pp. 274-280, 2018.

[15] R. Yan, H. Sun, and Y. Qian, "Energy-Aware Sensor Node Design With Its Application in Wireless Sensor Networks," In *IEEE Transactions on Instrumentation and Measurement*, vol. 62, no. 5, pp. 1183-1191, 2013.

[16] T. Bouguera, J. F. Diouris, J. J. Chaillout, R. Jaouadi, and G. Andrieux, "Energy Consumption Model for Sensor Nodes Based on LoRa and LoRaWAN," *Sensors 18*, no. 7, pp. 1-23, 2018.

[17] I. Das, R.N. Shaw, and S. Das, "Analysis of energy consumption of energy models in wireless sensor networks," *Innovations in Electrical and Electronic Engineering, Springer, Singapore,* pp. 755-764, 2021.

[18] X. Yan, C. Huang, J. Gan, and X. Wu, "Game Theory-Based Energy-Efficient Clustering Algorithm for Wireless Sensor Networks," *Sensors,* 22, 478, 2022.

[19] Z. Zlatev, T. Georgieva, A. Todorov, and V. Stoykova, "Energy Efficiency of IoT Networks for Environmental Parameters of Bulgarian Cities," *Computers,* 11, 81, 2022.

[20] M. J. Therese, A. Devi, B. Balaji, B. Senthilnayaki, and P. Dharanyadevi, "Rotation Scheme Based Power Consumption Analysis for Wireless Sensor Network," *International Conference on Smart Technologies and Systems for Next Generation Computing (ICSTSN)*, pp. 1-5, 2022.

[21] K. Prasad, S. Manjunatha, S. Soumya, and N. Bappalige, "Energy Consumption Analysis and Evaluation of Communication Technologies in Wireless Sensor Networks," *Design Engineering (Toronto),*pp-12420-12431,2022.