A Study on Effect of Duty Cycle in Energy Consumption for Wireless Sensor Networks

Jyoti Saraswat
Department of Electronics and Communication Engineering
Faculty of Engineering and Technology
Mody Institute of Technology & Science
(Deemed University)
Lakshmangarh, Dist. Sikar, Rajasthan, Pin-332311,India

Partha Pratim Bhattacharya
Department of Electronics and Communication Engineering
Faculty af Engineering and Technology
Mody Institute of Technology & Science
(Deemed University)
Lakshmangarh, Dist. Sikar, Rajasthan, Pin-332311, India

ABSTRACT
In Wireless Sensor Networks (WSNs), most studies define a common duty cycle value throughout the network to achieve synchronization among the nodes. On the other hand, a few studies propose adaptation of the duty cycle according to uniform traffic conditions to decrease the energy consumption and latency. In this paper, the lifetime of the node based on overall energy consumption are estimated and the effect of duty cycle on expected energy consumption is studied.

Keywords
Wireless sensor network; Sensor nodes; Battery lifetime; Energy efficiency; Power management strategies; Low power listening; Node density; Lifetime prediction.

1. INTRODUCTION
The multi functional sensor nodes that are small in size and communicate unbounded in short distances have been developed due to the recent advances in microelectronic fabrication and wireless communication technologies. Wireless sensor network [1] consists of a large amount of small sensor nodes. These small sensors have the ability of data processing, sensing and communicating with each other and to the outside world through the external base station. These sensor nodes are widely used in residential, medical, commercial, industrial, and military applications [2]. Wireless sensor network devices have limited energy to complete large tasks. Efficient energy consumption in wireless sensor networks is one of the challenging issues.

Sensor node is a microelectronic device which can only be equipped with a limited power source [3]. Many techniques have been proposed in recent years for estimating and enhancing battery lifetime [4]. A variety of strategies is used to exploit battery characteristics for designing more “battery friendly” systems and communication.

In order to maximize the operating life of battery-powered systems such as sensor nodes, it is important to discharge the battery in such a way that maximizes the amount of charge extracted from it [5]. In order to maximize their operation lifetime, optimal resource management is an important challenge and its success requires methodical modeling of the factors contributing to the overall power consumption**.** Therefore, it is necessary to study the discharge rate of battery taking into consideration the battery type, capacity, discharge pattern and other physical parameters. Many researchers have proved that the only way a node can save substantial energy is by putting the radio in power off mode, since transmitting, receiving and listening to an idle channel are functions which require roughly the same amount of power. Duty cycling is one of the basic and most commonly used power management techniques where a node is periodically placed into the sleep mode which is an effective method of reducing energy dissipation in wireless sensor networks (WSNs).

The traffic load in typical wireless sensor networks is relatively low (0.01 to 10 packets/second) and packets are relatively short (less than 500 bits). The nodes spend most of their time idle for monitoring the channels. By introducing heavy duty cycling in each node the advantage of low activity rate can be taken. In duty cycled operation [6], a node follows a sleep-wake up-sample-compute-communicate cycle in which majority of the cycle spend their time in low power sleep state. The lower the duty cycle, the longer nodes can sleep and the more energy they will save, whereas the fewer nodes are available to participate in data routing at any given time, which will increase transmission latency and decrease the throughput. To reduce the duty cycle, we should decrease the active time of the node as much as possible taking into account some limitations. Duty-cycling does not require continuous sampling or communication which makes its operation possible in WSNs.

The rest of the paper is organized as follows. We briefly described related work in Section 2. Our proposed model is presented in Section 3. Results and discussion are reported in Section 4 and conclusion in Section 5.

2. RELATED WORKS
Energy is a very scarce resource for sensor systems and has to be managed wisely in order to extend the life of the sensor nodes for the duration of a particular mission. Many researches have been done to reduce the power consumption and lifetime of wireless sensor networks. In general two main enabling techniques are identified i.e. duty cycling and data-driven approaches. Duty cycling [6] is the most effective energy-conserving operation in which whenever the communication is not required, the radio transceiver is placed in the sleep mode.

Many related works have been done to improve the energy efficiency of the sensor nodes. Honghai Zhang et. al [7] designed an algorithm based on the derived upper bound, an algorithm that sub optimally schedules node activities to maximize the α-lifetime of a sensor network where the time is normalized to be the lifetime of each sensor node. In [7], the node locations and two upper bounds of the α-lifetime are allocated. Based on the derived upper bound, an algorithm that sub optimally schedules node activities to maximize the α-lifetime of a sensor network is designed. Simulation results show that the proposed algorithm achieves around 90%

of the derived upper bound. This implies that the derived upper bounds are rather tight and the proposed algorithm is close to optimal. MS Pawar et. al [8] discussed the effect on lifetime, and energy consumption during transmission, listen (with different data packet size), idle and sleep states. The energy consumption of WSN node is measured in different operational states, e.g., idle, listen, transmit and sleep. These results are used to predict the WSN node life time with variable duty cycle for sleep time. They concluded that sleep current is an important parameter to predict the life time of WSN node. Almost 79.84% to 83.86% of total energy is consumed in sleep state. Reduction of WSN node sleep state current I_{sleep} from 64μA to 9μA has shown improvement in lifetime by 193 days for the 3.3V, 130mAh battery. It is also analyzed that the WSN node lifetime also depends on the packet size of data. Data packet size is inversely proportional to the life time of the node. As data packet size is increased, the lifetime of the battery is decreased. Yuqun Zhang et. al [9] proposed an adaptation method for the derived distance-based duty cycle based on local observed traffic. In this paper, the Packet Delivery Ratio (PDR) values are achieved by three methods. According to their simulation, in all the three methods the PDR results are very close and higher than 97% for light traffic loads. With an increase in traffic load, the constant duty cycle method performs the best because its higher duty cycle can provide more awake nodes to participate in data routing. The slightly worse performance of TDDCA (Traffic- Adaptive Distance-based Duty Cycle Assignment) compared to the constant duty cycle method indicates that the fixed increments and decrements in duty cycle is not efficient in terms of PDR. TDDCA and DDCA (Distance-based Duty Cycle Assignment) are more energy-efficient than the constant duty cycle method, and that DDCA performs better than TDDCA. DDCA reduces energy dissipation between 21% and 32% compared to the constant duty cycle method, while TDDCA reduces energy dissipation between 12% and 19% compared to the constant duty cycle method. Muralidhar Medidi and Yuanyuan Zhou [10] provided a differential duty cycle approach that is designed based on energy consumed by both traffic and idle listening. It assigns different duty cycles for nodes at different distances from the base station to address the energy hole problem, improve network lifetime, and also to maintain network performance. In [11], Francesco Zorzi et. al analyzed the impact of node density on the energy consumption in transmission, reception and idle–listening in a network where nodes follow a duty cycle scheme. They considered the energy performance of the network for different scenarios, where a different number of nodes and different values of the duty cycle are taken into account. In [12], Joseph Polastre et. al proposed *B-MAC*, a carrier sense media access protocol for wireless sensor networks, that provides a flexible interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization. To achieve low power operation, B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening. They compared B-MAC to conventional 802.11- inspired protocols, specifically S-MAC. B-MAC's flexibility results in better packet delivery rates, throughput, latency, and energy consumption than S-MAC is also shown.

3. PROPOSED MODEL

3.1 Evaluation of Lifetime of the Node Based on Overall Energy Consumption

In the present work, the lifetime of the nodes are evaluated by the overall energy consumption of the nodes such as in [12]. If the energy consumption decreases, lifetime of the node is increased. The total energy consumed by the nodes consists of the energy consumed for receiving E_{rx}, transmitting (E_{tx}), listening for messages on the radio channel (E_{listen}), sampling data (E_d) and sleeping (E_{sleep}). The values and notations listed in Table I and Table II are used throughout the paper.

Total energy consumed is given by

$$E = E_{rx} + E_{tx} + E_{listen} + E_d + E_{sleep} \quad (1)$$

TABLE I. Parameters used in calculation

Notation	Parameter	Default
C_{sleep}	Sleep Current (mA)	0.030
C_{batt}	Capacity of battery (mAh)	2500
V	Voltage	3
$L_{preamble}$	Preamble Length (bytes)	271
L_{packet}	Packet Length (bytes)	36
t_i	Radio Sampling Interval (s)	100E-3
R	Sample Rate (packets/s)	1/300
L	Expected Lifetime (s)	-

TABLE II. Time and current consumption parameters

Operation	Time (s)		I (mA)	
Initialize radio(b)	350E-6	t_{rinit}	6	c_{rinit}
Turn on radio (c)	1.5E-3	t_{ron}	1	c_{ron}
Switch to RX/TX (d)	250E-6	$t_{rx/tx}$	15	$c_{rx/tx}$
Time to sample radio (e)	350E-6	t_{sr}	15	c_{sr}
Evaluate radio sample (f)	100E-6	t_{ev}	6	c_{ev}
Receive 1 byte	416E-6	t_{rxb}	15	c_{rxb}
Transmit 1 byte	416E-6	t_{txb}	20	c_{txb}
Sample sensors	1.1	t_{data}	20	c_{data}

The energy associated with sampling data E_d, is

$$E_d = t_d C_{data} V \quad (2)$$

where, $t_d = t_{data} \times r$,

t_d being the time of sampling data, t_{data} is the sample sensors, r is the sample rate (packets/s), C_{data} is the current in sample sensors (mA), V is the voltage.

The energy consumed for transmission (E_{tx}) is the length of the packet with the preamble times the packets rates and is given by

$$E_{tx} = t_{tx} C_{txb} V \quad (3)$$

where, $t_{tx} = r \times (L_{preamble} + L_{packet})t_{txb}$

t_{tx} is the time to switch the transmitter, $L_{preamble}$ is the preamble length (bytes), L_{packet} is the packet length (bytes), t_{txb} is the time (s) to transmit 1 byte, C_{txb} is the current required to transmit 1 byte, V is the supply voltage.

The density of neighbors surrounding a node is referred to as the neighborhood size of the node. Receiving data from neighbors shortens a node's lifetime. The total energy consumed by receiving data (E_{rx}) is given by

$$E_{rx} = t_{rx} C_{rxb} V \quad (4)$$

where, $t_{rx} \leq nr(L_{preamble} + L_{packet})t_{rxb}$

t_{rx} is the time (s) to switch the receiver n is the neighborhood size of the node, t_{rxb} is the time (s) to receive 1 byte, C_{rxb} is the current required to receive 1 byte.

In order to reliably receive packets, the low power listening (LPL) check interval, t_i, must be less than the time of the preamble, i.e,

$$L_{preamble} \geq [t_i / t_{rxb}]$$

The power consumption of a single LPL radio sample is considered as 17.3μJ [12]. The total energy spent listening to the channel is the energy of a single channel sample times the channel sampling frequency.

$$E_{sample} = 17.3\mu J$$

$$t_{listen} = (t_{rinit} + t_{ron} + t_{rx/tx} + t_{sr}) \times \frac{1}{t_i}$$

$$E_{listen} \leq E_{sample} \times \frac{1}{t_i} \quad (5)$$

where, t_{rinit} is the initialize radio time, t_{ron} is the turn in radio time, $t_{rx/tx}$ is switch to rx/tx time, t_{sr} is the time to sample radio.

The node must sleep for the rest of the time, so the sleep time t_{sleep} is given by

$$t_{sleep} = 1 - t_{rx} - t_{tx} - t_d - t_{listen}$$

and $$E_{sleep} = t_{sleep} C_{sleep} V \quad (6)$$

The lifetime of the node (L) depends on the capacity of the battery (C_{batt}) and the total energy consumed by the battery (E) and given by

$$L = \frac{C_{batt} \times V}{E} \quad (7)$$

The lifetime of the node is also dependent on the duty cycle (d) and the transmission energy (E_{Tx}), as the duty cycle increases the lifetime of the battery decreases. Lifetime (in seconds) may be given as

$$L = \frac{(C_{batt} \times 3600)}{(E_{Tx} \times d)} \quad (8)$$

3.2 Effect of Duty Cycle on Expected Energy Consumption

The traffic relayed at a node is related to its distance to the sink, the number of source nodes in the network, the packet traffic generated by each source node and the node density. The time required for a transmission and the energy efficiency of the network is closely related to the duty cycle values used. Higher values of duty cycle provide more nodes available for data routing and thereby energy consumption of the nodes increases.

In [9], a circle area is assumed with the sink located in the center and the nodes including the sources which are uniformly randomly allocated as illustrated in Figure 1, where r_T is the transmission range. The nth ring is defined as the ring whose inner circle is $(n-1)r_T$ away from the sink with width r_T.

N_n nodes are considered in this ring. The average traffic that must be relayed by all of the nodes located in the nth ring per unit time, Γ_n, is the summation of the traffic generated by the source nodes in the nth ring and within the rings outside of the nth ring per unit time, i.e.,

$$\Gamma_n = \lambda_g \rho_s \pi (R^2 - [(n-1)r_T]^2), \quad (9)$$

where, λ_g is the average traffic generation rate of the source nodes, ρ_s is the density of source node, R is the radius of the network area, r_T is the transmission range.

The traffic relayed at a node is depended on the node distance from the sink, the node density, the radius of the network area, and the transmission range. The average traffic rate of a node at distance r, λ_r, is

$$\lambda_r = \frac{\lambda_g \rho_s \pi \{R^2 - \left[\left(\left\lceil \frac{r}{r_T} \right\rceil - 1\right) r_T\right]^2\}}{\rho_r \pi \{\left[\left(\left\lceil \frac{r}{r_T} \right\rceil\right) r_T\right]^2 - \left[\left(\left\lceil \frac{r}{r_T} \right\rceil - 1\right) r_T\right]^2\}} \quad (10).$$

In this work, a constant power value P is assumed for idle listening, transmission, and reception. The expected total time for the complete RTS, CTS, DATA, and ACK packet communication is given by

$$t_c = t_{RTS} + x t_{CTS} + t_{DATA} + t_{ACK} \quad (11).$$

The expected energy consumption $\overline{P}$ is defined as:

$$\overline{P} = P\{d + \lambda_r \left[\left(e^{\xi dN} - 1\right)^{-1} N_p N_r t_{CTL} + 2t_{DATA}\right]\} \quad (12)$$

where, P is the constant power, d is the duty cycle, λ_r is the average traffic rate of a node at distance r, ξ is the ratio of the relay region, N denote the average number of nodes within a node's transmission range, $t_{RTS} \cong t_{CTS} \cong t_{ACK} = t_{CTL}$ and it is the total expected time for a complete RTS, CTS, DATA and ACK packet communication.

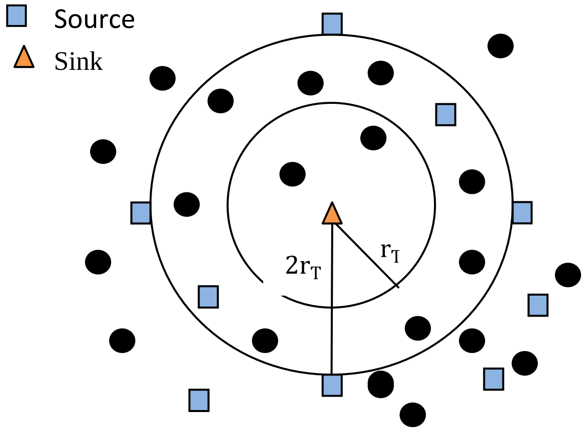


Fig 1: Sample Network Topology

The relay region [13] is divided into N_P priority regions, and each region is assigned a contention slot. In [9], each priority region is assigned N_r CTS contention slots, such that priority region i is assigned the slots $(((N_i - 1) \times N_r, N_i \times N_r - 1)$. The values used in calculation are listed in Table III.

Table III. Parameters used for calculation

Notation	Parameter	Values
Power	P	40E-6
Average traffic rate of the node	λ_r	0.1
Priority Regions	N_p	4
CTS contention slots	N_r	4
Ratio of the relay region	ξ	0.4
Total expected time for transmission	t_{CTL}	1*exp(-6)
Expected time for transmission of data	t_{data}	1.1

4. RESULTS AND DISCUSSION

The main objective of this study is to evaluate the lifetime of the battery sensor nodes and dependency of energy consumption of the nodes on duty cycle. The computation is carried out using MATLAB 7.0.

The node's lifetime is determined by its overall energy consumption. If the lifetime is maximized, then the energy consumption is minimized. The lifetime of the sensor node is inversely proportional to the duty cycle. Figure 2 shows the relation between energy consumption and duty cycle. It is concluded from the simulation results that for duty cycle which is less than 0.01%, the energy consumed by the nodes decreases curvy linearly and for duty cycle beyond 0.01% the energy consumed by the sensor nodes increases linearly

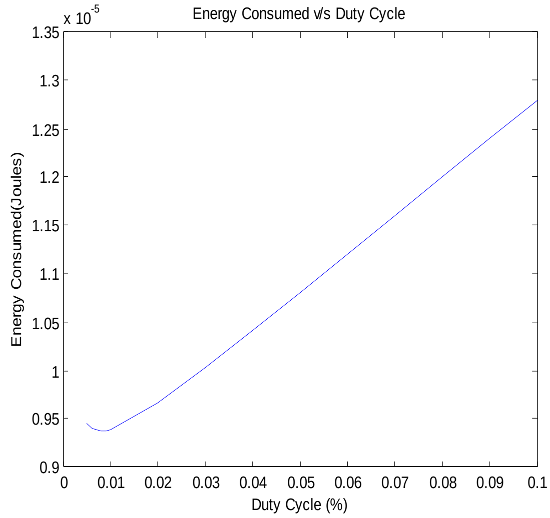


Fig 2: Energy consumed vs Duty cycle

Figure 3 shows the relation between lifetime of the node and the duty cycle (10%-100%) and it is concluded from the simulation result that as the duty cycle increases, the lifetime of the node decreases.

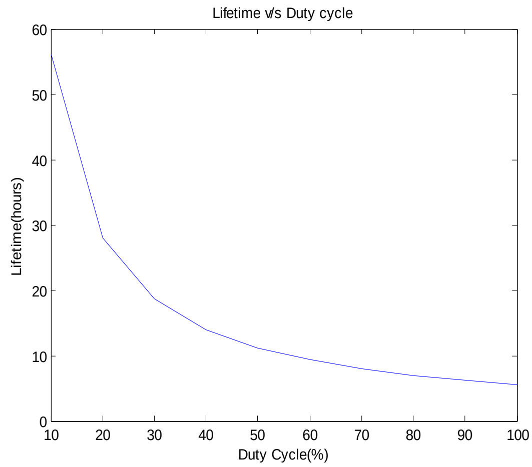
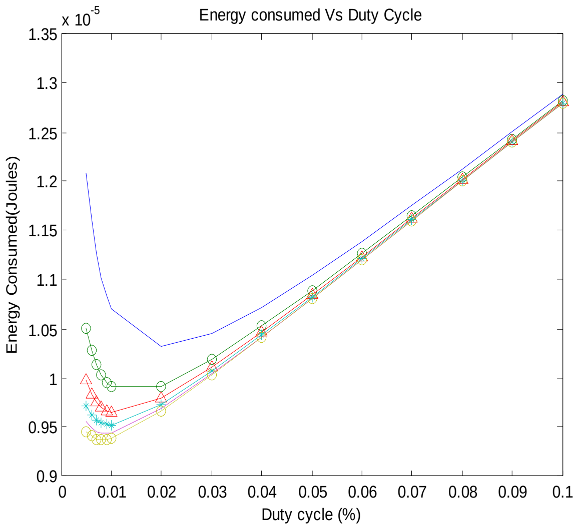
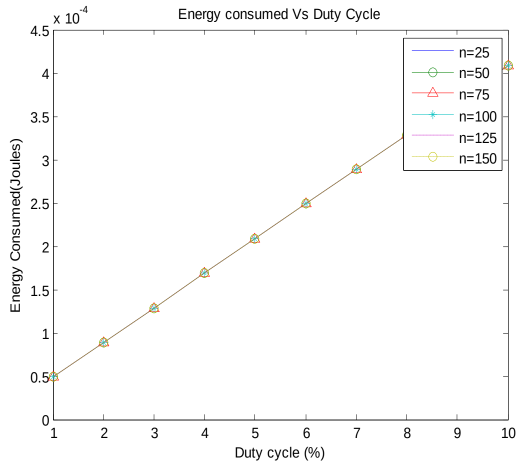


Fig 3: Lifetime vs Duty cycle

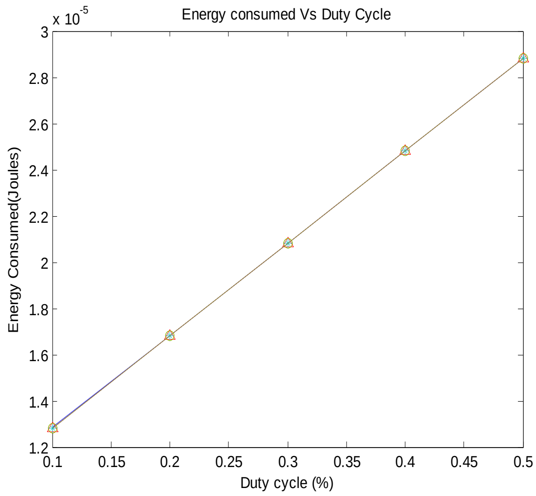
As the duty cycle increases the energy consumption of the nodes also increases, so for the optimum power management of the sensor nodes the duty cycle must be reduced. Figure 4(a) shows that for denser network, if the duty cycle is less than 0.01%, energy consumption decreases. For other networks with lower density, same is true for duty cycle value of less than 0.02%. Then the energy consumption increases linearly. It is also evident from the figure that minimum energy consumption is also achievable even for a denser network. In figures 4(b)-4(e), as the duty cycle increases beyond 0.1% the energy consumption by the nodes become congruent even if the traffic rate and the density of node increases. Thus, based on the observations, the optimum value for the duty cycle can be chosen.



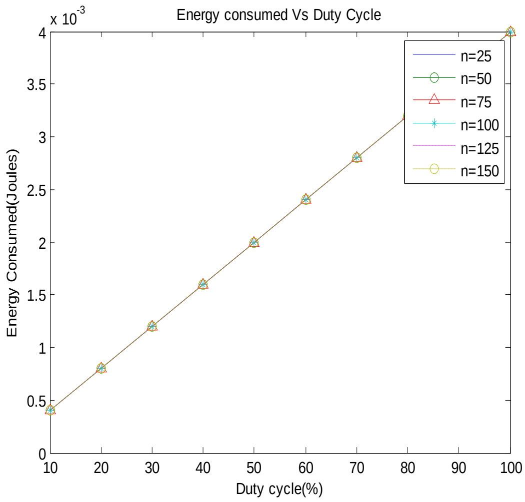
4(a)



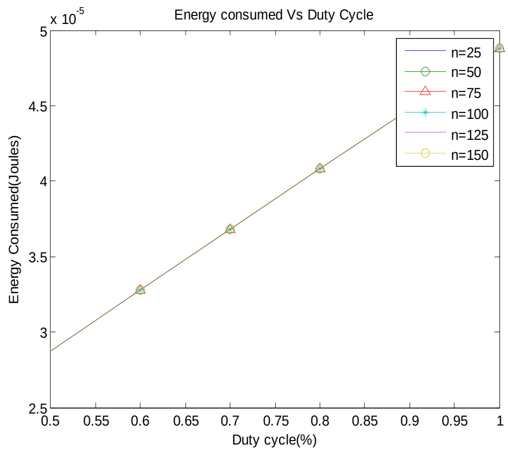
4(d)



4(b)



4(e)



4(c)

Fig 4: Energy consumed vs duty cycle for (a) d=0.01%-0.1%, (b) d=0.1%-0.5%, (c) d= 0.5%-1%, (d) d= 1%-10%, (e) d=10%-100%

5. CONCLUSION

In this paper, the lifetime of the node based on overall energy consumption and effect of duty cycle on expected energy consumption are discussed and evaluated. Simulation results show that for denser network, if the duty cycle is less than 0.01%, energy consumption decreases. For other networks same is true for duty cycle value less than 0.02%. Otherwise, energy consumption increases with duty cycle. This study will, therefore, help in assigning a proper duty cycle value for WSNs.

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