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Effect of Switching Energy in Different Low Power Modes in Duty Cycling Sensor Network

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Abstract

Duty cycling is one of the most efficient power saving mechanisms to prolong sensor network lifetime. In the existing duty cycling networks, low latency and high network connectivity are achieved by shortening the duty cycling parameter that means increasing the frequency of switching between sleep-awake states. However, switching energy is generally not considered in energy efficiency analyses of sensor network. In this paper, the energy cost for switching and different sleeping modes are investigated for sensor network lifetime. To this end, we present a linear programming (LP) formulation which allow to analyze the energy consumption of the sensor network while guarantying the optimum load distribution for maximum lifetime. Proposed mathematical programming model can be applied any synchronized duty cycling mechanism with a fixed duty cycling periods. Analytical results reveal that the switching energy is not negligible effect on network lifetime.

Keywords: Duty cycling; sensor network; network lifetime; switching energy.

1. Introduction

Duty cycling is one of the most important way of saving energy in wireless sensor networks (WSNs). Currently, none of the existing duty-cycling medium access control (MAC) schemes [1,2,3,7,8] investigated the effect of specific value of duty-cycling parameter and switching frequency. Instead they focused on minimizing latency and data loss due to sleeping nodes. However, low latency and low data loss is generally achieved by increasing the switching frequency by lowering duty cycling parameter [8].

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In this paper, the effect of switching energy consumption on network lifetime are investigated for different duty cycling parameters. Authors in [4] studied the switching energy for assessment of MAC protocols in a simulation environment with 3 node network scenario. Then, they introduced an adaptive radio low power sleep modes based on current traffic condition for selecting optimal MAC protocol by using an energy model that considers the switching energy in [6]. However, both of the studies are independent from the routing and network lifetime. In this study, we investigate the duty cycling for a more complicated network scenario where packet routing exists with the aim of maximum network lifetime. To this end, we developed a linear programming (LP) model for the problem of routing the packets for the maximum network lifetime in a duty cycling sensor network. Then, we use the model to analysis of the network lifetime for different low power modes and investigate the effect of switching energy on the network lifetime.

2. Mathematical Model

Each node n in the sensor network has an initial energy $E_{n_{initial}}$ (joule) and they generate data with a predefined rate g_n (packet/second). The problem is to determine the optimum total amount of flow (f_L) on each link L and to find the total switching number of each node in the allocated load for the maximum lifetime. The network lifetime T_{net} is defined as the time span in which all nodes of the network are alive, i.e., all individual node lifetimes, T_n, are at least equal to T_{net} or greater than T_{net}.

Sensor network is modeled as a directed graph $G(N, \check{L})$ where N is the set of all nodes, and $\check{L}$ is the set of the links between them. If two nodes i and j are connected by a link, they can communicate with each other. Let variables $f_L^{O_n}$ and $f_L^{I_n}$ are the total amount of flow (f_l) during the network lifetime on the outgoing (On) and incoming (In) links of a node n, respectively, and depicted as

$$f_L^{O_n} = \sum_{l \in O_n} f_l \, , f_L^{I_n} = \sum_{l \in In} f_l \qquad n \in N, L \in \check{L} \tag{1}$$

Lifetime T_n of the individual node n is formulated as being the sum of the time spent in transmission, reception, idle listening, sleeping, channel access, and switching and shown as follow;

$$T_n = f_L^{O_n} . t_{tx} + f_L^{O_n} . t_{cca} + f_L^{I_n} . t_{rx} + f_L^{I_n} . t_{cca} + t_{sleep}^n + t_{idle}^n + k_n . t_{swc} \tag{2}$$

$$T_n \geq T_{net} \tag{3}$$

where t_{tx} and t_{rx} are constants and represent the transmission time and the reception time of a data packet, respectively, t_{caa} is a constant and represents the time for clear channel assessment mechanism in the IEEE 802.15.4 technical standard. In the Equation 2, t_{idle}^n and t_{sleep}^n are variables that represent the total idle and sleep time of the node during its lifetime, respectively. Note that the variable t_{sleep}^n represents the total sleep time of the node *n* while the rest of the terms in the right hand side of the Equation 2 represents the total active time of the node *n* during its lifetime.

The objective function of the optimization model is defined as the network lifetime, T_{net}, and all individual lifetimes has to be longer or equal to the network lifetime (Equation 3). Equation 4 represents the conservation of the data during the lifetime of the network (i.e total flow out of a node is equal to the sum of the total generated data at the node and the total flow into the node.

$$\mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}} = g_n.T_{net} + \mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}} \quad n \in N\ . \tag{4}$$

The total energy consumption of a node throughout the network lifetime is the sum of the energy consumption in each operation mode and cannot exceed its initial energy. It is formulated with the help of the flow variables and unit energy consumptions as follow;

$$\mathrm{e_{tx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}}.\mathrm{t_{tx}} + \mathrm{e_{tx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}}.\mathrm{t_{cca}} + \mathrm{e_{rx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}}.t_{rx} + \mathrm{e_{rx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}}.\mathrm{t_{cca}} + e_{sleep}.t_{sleep}^{n} + e_{idle}.t_{idle}^{n} + \mathrm{k_n}.e_{swc} \leq E_{n_{initial}} \tag{5}$$

where $\mathrm{e_{tx}}$, $\mathrm{e_{rx}}$, e_{sleep}, e_{idle} (joule/second) are constants and represent the energy consumed per unit time when radio is in transmission, reception, sleeping, and idle mode, respectively. The constant parameter e_{swc} (joule) is energy consumption for switching and its value depends on the preference of low power mode.The model can represent any synchronized duty cycling mechanism with a fixed duty cycling periods such as SMAC [1]. Individual lifetime for a node n consist of k_n number of constant duty cycling period t_{cycle} as shown in Fig. 1.

The relationships between active time and sleep time are determined by a constant duty-cycling parameter dc, and depicted as

$$T_n - dc.T_n = t_{sleep}^{n} \tag{5}$$

$$T_n = k_n.t_{cycle} \tag{6}$$

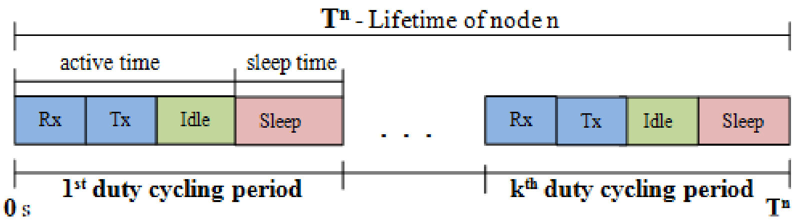

Figure 1: Duty cycling mechanishm for a node in the sensor network

The problem of maximizing the network lifetime, given the data generation rate g_n, is formulated as a linear programming problem as follows

max T_{net}

subject to

$$T_n = \mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}}.\mathrm{t_{tx}} + \mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}}.\mathrm{t_{cca}} + \mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}}.t_{rx} + \mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}}.\mathrm{t_{cca}} + t_{sleep}^{n} + t_{idle}^{n} + \mathrm{k_n}.\mathrm{t_{swc}}$$

$$T_n \geq T_{net}$$

$$\mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}} = g_n . T_{net} + \mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}} \quad n \in N \ .$$

$$\mathrm{e_{tx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}}.\mathrm{t_{tx}} + \mathrm{e_{tx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}}.\mathrm{t_{cca}} + \mathrm{e_{rx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}}.t_{rx} + \mathrm{e_{rx}}.\mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}}.\mathrm{t_{cca}} + e_{sleep}.t_{sleep}^{n} + e_{idle}.t_{idle}^{n} + \mathrm{k_n}.e_{swc} \leq E_{n_{initial}}$$

$$T_n - dc.T_n = t_{sleep}^{n}$$

$$T_n = k_n . t_{cycle}$$

$$T_{net}, T_n, \mathrm{f}_{\mathrm{L}}^{\mathrm{O_n}} , \ \mathrm{f}_{\mathrm{L}}^{\mathrm{I_n}}, \mathrm{k_n} \geq 0$$

3. Numerical Study

In this section, the switching energy and effect of sleeping modes on the network lifetime is investigated in an example network. The most of radios for sensor network support multiple low power modes for sleeping. For example, CC2420 radio has three low power modes (LPM). LPM1 saves energy by turning off the radio frequency synthesizer which control the channel selection and up/down RF conversion. In addition to the frequency synthesizer, LPM2 also turns off the crystal oscillator which provides the timing reference for the entire radio chip. LPM3 is power off mode and turning off the voltage regulator which powers the radio chip. Transition to active mode from LPM1 is the fastest but the most energy expensive while transition from LPM3 is less energy expensive but has longest delay. Therefore preference of the low power mode is important as much as choosing the optimum duty cycling parameter. We explore the effect of switching energy on network lifetime for different low power modes in a network which consist of 10 nodes located in a 50m-by-50m area in a random manner. Transmission range is chosen as 35 m. The sink node lies at the one corner of the area. All nodes have 1.8V AA batteries with 2200 mAh current capacity. They have CC2420 radio and data transmission rate is 250kbps. Packet size is 100 bytes (t_{tx} and $t_{rx}$are 3.2ms).Each node has the same packet generation rate (sense every 3s). The time for clear channel assessment mechanism is taken as 0.128 ms for default 4 bytes preamble length at 250 kbps. Table 1 shows the energy consumption characteristics and switching time for the CC2420 radio [5].

Table 1: CC2420 Energy and Switching Characteristics.

Mode of operation	Power	Switching Time	Switching Energy
Tx@0 dBm	$\mathrm{e_{tx=}}$31.32 mW		
Rx	$\mathrm{e_{rx}}$=33.84 mW		
Idle Listening	e_{idle} =33.84 mW		
LPM 1	e_{LPM1} =0.7668mW	0.03 ms	1.035 µJ
LPM 2	e_{LPM2} =0.036 mW	1.2 ms	42.3 µJ
LPM 3 (max)	e_{LPM3} =1.8 µ W	2.4 ms	85.7 µJ

In Figure 2, network lifetime difference in percentage is shown for different sleeping modes preferences. Figure 3 shows the difference in percentage when LPM3 is chosen instead of LPM2 and it is seen that the difference on network lifetime has maximum value of 11% at 1% duty cycle and minimum value of 1% at 10% duty cycle. Figure3 shows the difference when LPM2 (max 200%-min20%) or LPM3 (max 230% -min 22%) is chosen instead of LPM1. For instance, for %10 duty cycling, choosing LMP2 or LPM3 instead of LPM1 results in 20% increase on network lifetime. It has been observed that the effect of sleep mode preference on network life is reduced by high duty cycles due to short sleeping durations

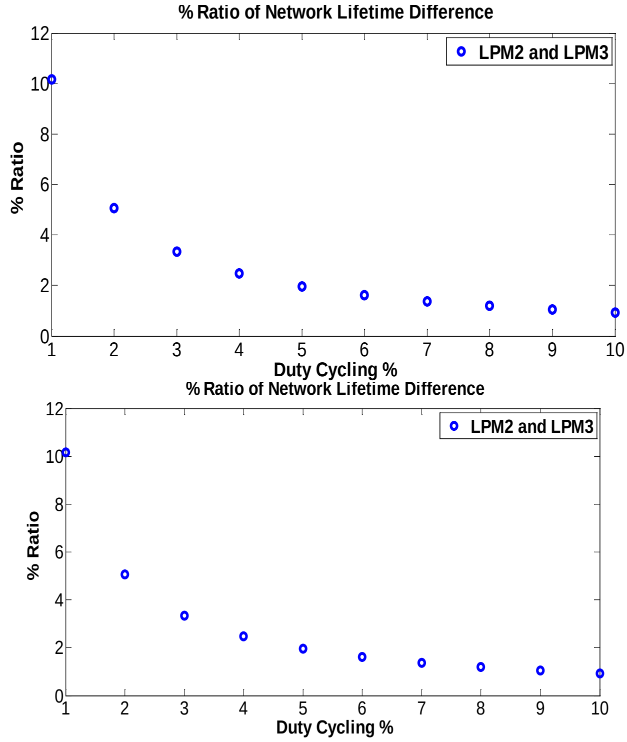

Figure 2: Difference of network lifetime between preferences of two low power modes LPM2 and LPM3

In Figure 3, the graph shows the percentage decrease on network lifetime when switching energy is considered for three sleeping modes. In the Figure 3., it is seen that the switching energy consumption of LPM1 does not affect the network lifetime. It takes maximum value of 0.009%. However, in LPM3 mode the switching energy causes higher decrease on network lifetime compared to LMP2.

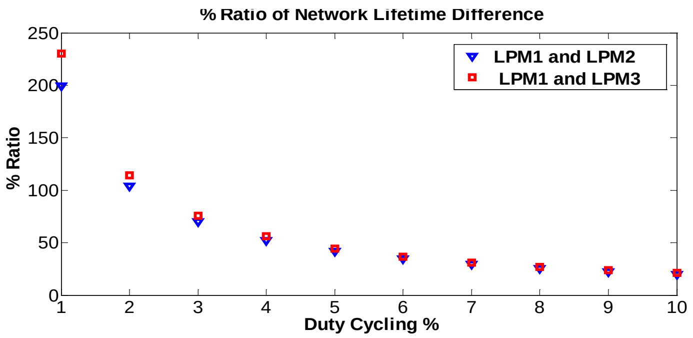

Figure 3: Difference of network lifetime preference of LPM1 or other two modes.

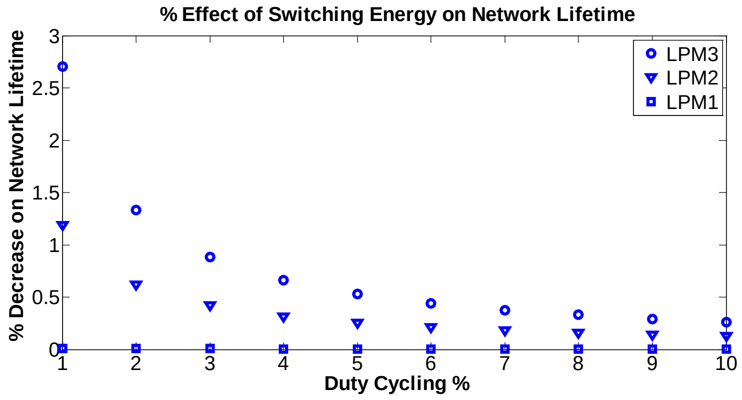

Figure 4: Effect of switching energy on network lifetime for different low power modes

Figure 5 and Figure 6 show the comparison of switching and sleeping energies at different duty cycles. In the Figure 5, it is showed that for LPM2 the switching energy consumption is less than the sleeping energy and it corresponds to 1% of total energy consumption of the network. In Figure 6, it is seen that for LPM3 compare to the sleeping energy the switching energy consumption accounts for higher percentage of total energy consumption.

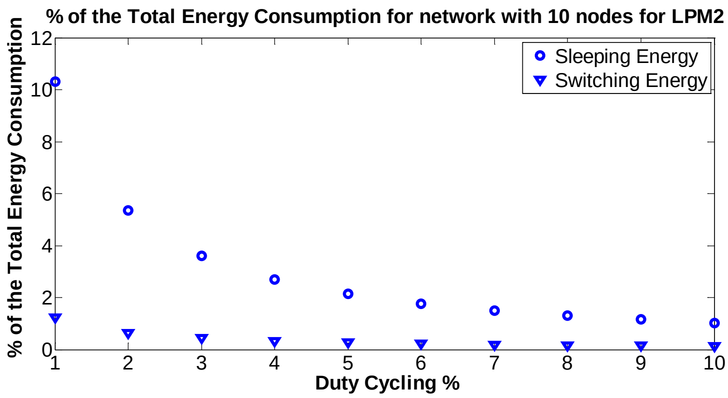

Figure 5: Ratio of sleeping and switching energy to the total energy consumption when LPM2 is chosen. (Average of ten randomly generated network with 10 nodes.)

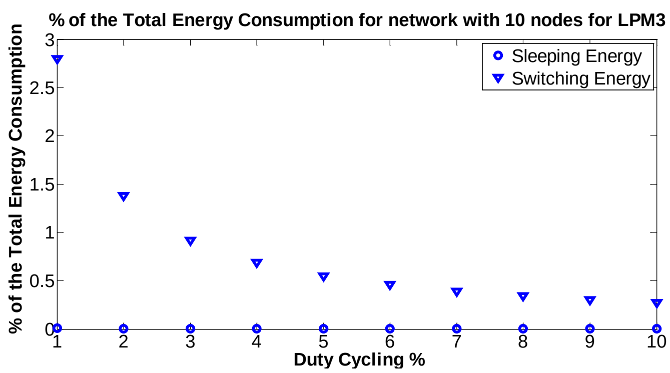

Figure 6: Ratio of sleeping and switching energy to the total energy consumption when LPM3 is chosen. (Average of ten randomly generated network with 10 nodes.)

4. Conclusion

In this paper, the energy cost of switching in duty cycling sensor networks was investigated. Firstly, using a linear programming the optimum total amount of flow was determined for each link to be assigned by a routing algorithm that leads the maximization of the network lifetime. Then, the effect of switching energy and different sleeping modes on network lifetime are evaluated with the proposed LP through a numerical example. As a conclusion, the switching energy has not negligible effect on network lifetime. Therefore neglecting the switching energy in energy consumption analysis misleads the performance assessment of different duty cycling schemes and sleeping modes.

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