Increasing Throughput by Duty Cycle Adaptation in Wireless Sensor Networks with Energy Harvesting

S Viswanatha Rao, Sakuntala S Pillai

Abstract: Limited lifetime of batteries is a major constraint in Wireless Sensor Networks (WSNs). Reduction in duty cycle to conserve energy resulted in reduced throughput. With the advances in energy harvesting technologies there is considerable research interest in enhancing the performance of WSNs by incorporating the energy harvesting scenario in wireless nodes. To ensure proper operation of the sensor nodes in WSNs with energy harvesting, the design of MAC protocols need special consideration. This paper evaluates the performance of an energy harvesting WSN node, based on IEEE 802.15.4 MAC. The study establishes the fact that by suitably adapting the duty cycle, throughput of the node can be increased in addition to extending its lifetime considerably.

Index Terms: duty cycle adaptation, energy harvesting, MAC, IEEE 802.15.4, Wireless Sensor Network.

I. INTRODUCTION

Wireless sensor networks (WSNs) consist of small sensor nodes capable of forming a network and communicating with each other over wireless channels. These sensor nodes are deployed to collect useful data such as temperature, humidity, stress, pressure etc depending on the application they are intended for. As the sensor nodes are wireless, they are generally battery-powered. Again, due to the small footprint of these nodes, the storage capacity of the battery is limited. Hence these battery operated wireless nodes have limited lifetime. Since the number of nodes in a WSN is likely to be large, it is not practical to replace batteries in such networks. Again, there are applications where it is difficult to access the sensors for maintenance after deployment. Energy harvesting has become an important factor in extending the life of WSNs. Energy can be harvested from a number of sources such as solar, RF and piezoelectric. However, the nature of availability of such sources for harvesting is not consistent. A number of techniques are being developed to optimise the harvesting, storage and utilisation of ambient energy. Media Access Control (MAC) is one of the critical layers that has been researched extensively in WSNs for reducing the energy consumption of wireless nodes. MAC takes care of the access to the wireless medium and helps in effectively sharing the medium among the nodes. An efficient MAC design tries to minimise energy consumption by addressing issues such as collisions, overhearing and idle listening. In addition, in order to minimise energy consumption and to extend lifetime, a node remains in an inactive state when it doesn't have any data to send or receive. However, in an energy harvesting scenario, the objective of a MAC design is to effectively make use of the harvested energy. Whenever the harvested energy is more, it can be utilised to increase the node activity. Under such a condition, more data can be transmitted or received. Care should be taken not to consume more energy than what is harvested.

In this paper, enhancement of throughput in WSN with solar energy harvesting is presented. The protocol considered is the IEEE 802.15.4 MAC, which is found to be ideal for low data rate applications. Solar energy available at different timing throughout a day is considered for simulation in an ns-2 platform. Prior art related to energy harvesting in WSNs is discussed in section II. The basic operation of the IEEE 802.15.4 MAC protocol is described in section III. Section IV presents the approach adopted in this work. The simulation settings and results are detailed in Section V. Finally, the paper concludes with section VI.

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II. RELATED WORKS

WSNs have been covered extensively in literature. There have been numerous publications which present research work in the area of WSNs. Survey papers and overviews help understand the technology and applications related to WSNs [1,2]. Researchers have spent considerable amount of time designing MAC schemes that minimise energy consumption in WSNs. Duty Cycle scheduling in MAC has been one of the popular methods adopted for reducing energy consumption in WSNs. Extensive research has been carried out to efficiently design MAC protocols for WSNs. A survey of MAC protocols for WSNs is provided in [3]. With advances in technologies related to energy harvesting, various such options to extend the life of sensors have been explored for different applications. Energy harvesting in WSNs has been of recent interest among researchers. Seah et. al. in [4] discuss about WSNs powered by Ambient Energy Harvesting (WSN-HEAP). According to the authors it is possible to have WSNs that depend on harvested energy alone. Super-capacitors have been considered for storage of charge. However, a major challenge in such a system is the magnitude of ambient energy available to keep the network alive on a continuous basis. It is important to adapt duty cycle according to the energy available in a node by adjusting the wake up and sleep up time. Yoo et al. in [7] propose two approaches for energy harvesting WSNs. First one is a duty cycle scheduling scheme based on residual energy. In a second approach, the prospective increase in energy is

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predicted and duty cycle is adapted accordingly. Here the individual nodes can adapt duty cycle independently. A linear decision graph has been used for prediction. In [8], thermal energy harvesting has been considered as a case of energy harvesting. A scheme to manage the power by adapting the duty cycle based on the energy harvested and the energy consumed. The authors in [9] analyse energy harvesting WSNs considering a combination of duty cycle optimization and transmission power control. The approach may appear to be complex but the authors claim to have improvement in energy efficiency and packet reception ratio. Issues and trade-offs related to solar energy harvesting for Wireless Embedded System is discussed in[11]. The authors have demonstrated with a prototype system, the management of harvesting and storage for improved usage of energy. IEEE 802.15.4 standard has been considered for applications in WSN because of its low data rate and low power consumption characteristics. The standard specifies the physical and MAC layer requirements for low-rate WPAN [5]. Mirza et al.[6] present a scheme to reduce energy consumption in IEEE 802.15.4 networks and extend lifetime by proper wake-up scheduling.

This paper presents the solar energy harvesting scenario and shows that excess energy available can be used to increase the node activity to enhance the throughput without compromising on the lifetime of the network. Further, it is shown that the performance doesn't suffer even with a limit on maximum energy storage.

III. IEEE 802.15.4 MAC

IEEE 802.15.4 is an IEEE standard for low rate Wireless Personal Area Networks (LR-WPAN). It addresses both the Physical and MAC layers. Though there are a number of MAC protocols designed for WSNs, no standard has evolved in this direction. Hence, IEEE 802.15.4 based devices have been used in many implementations of WSNs due to the low power consumption of such devices. Thus, IEEE 802.15.4 MAC has been used as the MAC protocol for the work described in this paper. A brief overview of the basic operation of IEEE 802.15.4 MAC is provided in this section. Based on the standard, there are two types of devices designed to support the needs of the application and minimise the cost. A Full Function Device (FFD) that supports all the functionalities defined in the standard and a Reduced Function Device (RFD). A FFD can be configured as a PAN coordinator or a router or even as an end device in a network. The RFDs are ordinary devices which can only communicate with FFDs and they are used as end devices. The IEEE 802.15.4 standard provides support to star, cluster tree and peer-to-peer network topologies.

In addition, the IEEE 802.15.4 standard defines two different modes of operation. They are the beacon-enabled mode and the non-beacon enabled mode. In beacon-enabled mode of operation periodic beacons are transmitted which help achieve synchronization and association among the nodes. This synchronisation is required to operate in a slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. In star and cluster tree topologies, nodes can make use of this mode. In contrast, no beacons are transmitted in the non-beacon mode. Hence, no synchronisation is possible in this mode leading to the use of unslotted CSMA/CA protocol. Non-beacon enabled mode is used in the peer-to-peer topology for communication.

The beacon-enabled mode uses a superframe structure, which is illustrated in figure 1. This superframe structure starts with a beacon and ends before the start of the next beacon. The superframe is divided into an active period and an inactive period. The active period is known as the Superframe Duration (SD). The SD is made up of the Contention Access Period (CAP) and the Contention Free Period (CFP). Slotted version of CSMA/CA algorithm is used by the nodes to access channel within the CAP. On the other hand, CFP consists of Guaranteed Time Slots (GTS). Nodes are assigned fixed time slots using GTS. Energy is conserved by the nodes by entering into the inactive state. No transmissions take place during this period. The active and inactive periods together form the Beacon Interval (BI) which is nothing but the duration between two consecutive beacons.

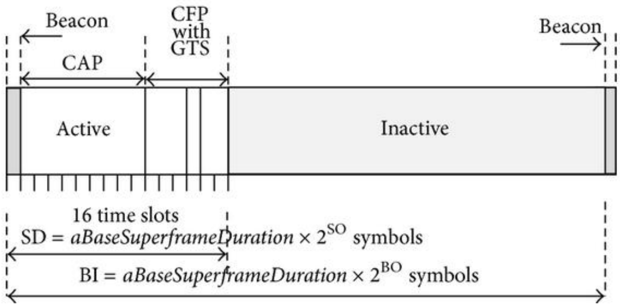

Fig 1 IEEE 802.15.4

The BI and SD are defined using the parameters Beacon Order(BO) and Superframe Order(SO). The expressions for BI and SD aregiven below:

$$BI = a\ Base\ Superframe\ Duration\ x\ 2^{BO}\ symbols \quad (1)$$

$$SD = a\ Base\ Superframe\ Duration\ x\ 2^{SO}\ symbols \quad (2)$$

where, *a Base Superframe Duration* is determined by multiplying the number of slots and the duration of a base slot. BI and SD should satisfy the condition $0 \le SO \le BO \le 14$.

The duty cycle can be defined as the ratio of active period to the sum of active and inactive periods. In the case of IEEE 802.15.4 MAC, this is nothing but the ratio of SD to BI. This is given as:

$$D = \frac{SD}{BI} = 2^{SO-BO} \quad (3)$$

Thus the duty cycle of the MAC can be varied by varying the values of the parameters SO and BO, within the range specified in the standard. The duty cycle will be 1 for SO = BO and minimum for SO = 0.

IV. SYSTEM DESIGN

An important design criterion for energy harvesting WSNs is that the energy consumed should always be less than the energy harvested. In such a case, the nodes are said to have achieved an Energy Neutral Operation (ENO) state [4]. Nodes having ENO will be able to extend their life forever. This is, however, an ideal condition. In practical scenarios it is difficult to get a consistent input of harvested energy. For

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example, solar energy varies during daytime and is not available during night. Again, during day time, there could be further fluctuations depending on whether it is a sunny or cloudy day. Similar conditions apply to wind energy or vibration energy – there is no continuous availability of harvested energy. Thus the wireless nodes require some mode of storage and in most cases, the storage is a battery. Three aspects are to be considered while designing energy harvesting system for WSNs. The battery discharge characteristics, energy consumption model of the node and the energy harvesting itself. For simplicity, in this study, a linear battery discharge model has been assumed. Energy consumption is assumed as per the values provided by low power zigbee devices that follow the IEEE 802.15.4 standard. Transmit, receive, sleep and idle state power consumption values have been considered based on typical values for devices as per above standard. The values of solar energy over a period of 24 hours without change in weather conditions have been included for the study.

V. SIMULATION SETTINGS & RESULTS

A. Simulation Settings

The simulation has been carried out using Network Simulator ns2[11]. In order to study the impact of energy harvesting, a standard star configuration with IEEE 802.14 having 6 sensor nodes communicating with a sink node has been assumed. Initial simulations were done over a period of 30 minutes followed by a detailed simulation for 24 hour duration. Though AODV has been selected as the routing protocol, the routing doesn't have much significance in this configuration. The simulation settings are as given in table 1.

B. Simulation Results

Simulation studies have been done to assess the performance of the node under solar energy harvesting scenario. Fig 2 shows a comparison of remaining energy of the sink node with and without energy harvesting over a period of 30 minutes. A linear energy consumption and a typical value of 190mW solar power during noon on a sunny day have been assumed.

Table 1 Simulation Settings

Parameter	Value
Simulation area	50 m x 50 m
Traffic	ftp
MAC protocol	IEEE 802.15.4
Routing protocol	AODV
Initial energy	250 J
Idle power	1.8 mW
Transmit power	0.1414 W
Receive power	0.1404 W
Sleep power	18 μW

The remaining energy in the node continuously increases if the harvested energy is more than the energy consumed. However, in a real time scenario, this condition will not persist as the energy harvested varies from zero to a maximum value depending on the time of the day and other weather conditions. Without energy harvesting the energy remaining in the node decreases continuously in a predictable manner.

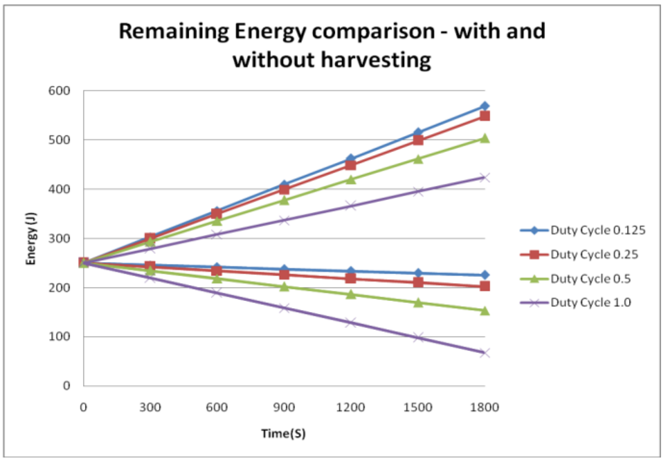

Fig. 2. Remaining energy of node over a period of 30 minutes with and without energy harvesting

One of the objectives of the simulation study is to understand the possibility of utilising harvested energy to increase the throughput. This may be achieved by reducing the duty cycle when remaining energy is low and incresing the duty cycle as the remaining energy increses. Simulation studies done over a period of one day gives a more clearer picture of the remaining energy in a node with solar energy harvesting. Here again, clear sky conditions have been considered. The readings of remaining energy over a period of 24 hours starting from 6am have been taken. Energy harvested varies from a minimum value of 16mW to a maximum of 197mW during the day. Fig 3 shows the remaining energy over time for duty cycles 0.25 and 0.5 along with that of varying duty cycle. In the case of varying duty cycle, the node operates with a duty cycle of 0.25 to begin with, switches to a duty cycle of 0.5 as the enrgy increses and subsequently remains continuously on for a long period till the remaining energy starts decresing.

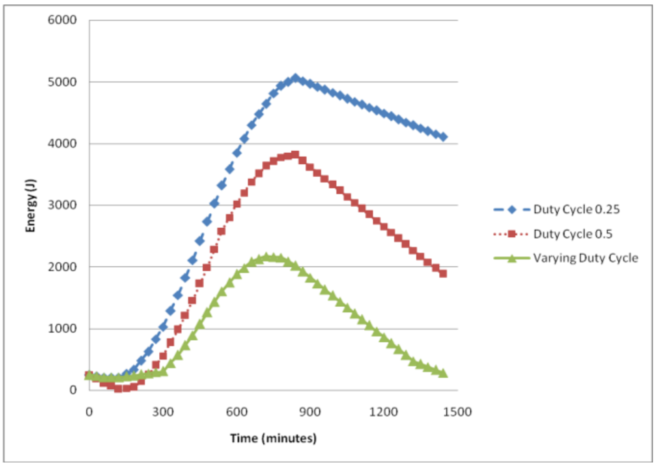

Fig. 3. Remaining energy of node with energy harvesting over a period of 24 hours with different duty cycle conditions

Table 2 provides the throughput values for the three cases considered above. It is obvious that there is a considerable amount of improvement in throughput by effectively utilizing the harvested energy available in a node.

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Table 2 Throughput

0.25 Dury Cycle	0.5 Dury Cycle	Variable Dury Cycle
3596.44 bps	8174.76 bps	15676.53 bps

One of the constraints related to solar energy harvesting in WSN is the footprint of the node and the corresponding storage limit. Fig 4 illustrates a scenario with energy limited to a maximum of 250 Joules. Even with a duty cycle of 0.25, the life of the node is less than 4 hours in this case whereas, it is extended to longer hours under energy harvesting with varying duty cycle.

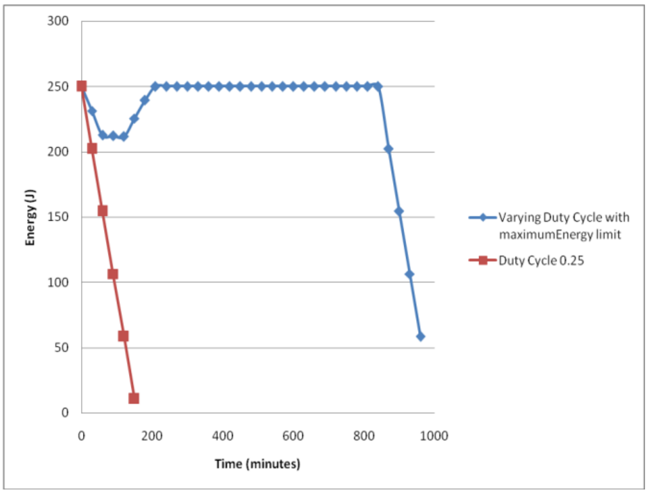

Fig. 4. Remaining energy of node with and without energy harvesting limiting the energy to 250 J.

In the varying duty cycle scenario, initially the energy harvested is less than the energy consumed and hence the remaining energy decreases. As the energy harvested increases and becomes more than the energy consumed the slope of the graph becomes positive. In spite of more energy available for harvest, the value is limited to 250 Jouls subsequently. At the end of the day, when there is no energy available for harvest, the remaining energy falls continuously.

VI. CONCLUSION

Limited energy source has been one of the major constraints in WSNs. Initial research focus has been to conserve energy by compromising on some of the other parameters such as throughput. A number of schemes have evolved addressing minimisation of energy consumption in WSNs. With the advance in energy harvesting techniques the focus has now shifted to protocols that optimise the utilisation of available energy from the environment. This paper looks into the utilisation of harvested solar energy to increase the throughput of WSNs without compromising on the lifetime of the nodes. IEEE 802.15.4 standard has been selected for the study. The remaining energy available with variations in solar energy harvested over a period of 24 hours has been studied. Based on the energy available, the duty cycle has been varied. Simulation results show a significant increase in throughput. Future work includes designing suitable algorithms to predict the availability of energy for harvesting and optimising its usage to enhance throughput, at the same time, extending life of the sensor nodes.

REFERENCES

1. David Culler, Deborah Estrin, Mani Srivastava, “Overview of Sensor Networks”, Computer, August 2004
2. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” IEEE Communications Magazine, Vol. 40, No. 8, pp. 102-114, August 2002
3. Demirkol, C. Ersoy, and F. Alagoz, “Energy efficient medium access control protocols for wireless sensor networks and its state-of-art,” in IEEE International Symposium on Industrial Electronics, Vol. 1, pp. 669-674, May 2004.
4. W. Seah, Z. Eu, and H. Tan, “Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP) - survey and challenges,” in Wireless VITAE 2009, pp. 1–5, May 2009.
5. IEEE Std. 802.15.4-2006: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), IEEE Std., September 2006.
6. Mirza, M. Owrang, and C. Schurgers, “Energy-efficient wakeup scheduling for maximizing lifetime of IEEE 802.15.4 networks,” in Proceedings of First IEEE International Conference on Wireless Internet (WICON), pp. 130-137, 2005.
7. H. Yoo, M. Shim, and D. Kim, “Dynamic duty-cycle scheduling schemes for energy-harvesting wireless sensor networks,” in IEEE Communications Letters, Vol. 16, No. 2, pp. 202-204, February 2012.
8. T. N. Le, A. Pegatoquet, O. Sentieys, O. Berder, and C. Belleudy, “Duty-cycle power manager for thermal-powered wireless sensor networks,” in IEEE 24th International Symposium on Personal Indoor and Mobile Communications (PIMRC), pp. 1645-1649, 2013.
9. Castagnetti, A. Pegatoquet, T. N. Le, and M. Auguin, “A joint duty-cycle and transmission power management for energy harvesting WSN,” in IEEE Transactions on Industrial Informatics, Vol. 10, No. 2, pp. 928-936, May 2014.
10. V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. B. Srivastava, “Design considerations for solar energy harvesting wireless embedded systems,” in IEEE Information Processing in Sensor Networks (IPSN), pp. 457-462, 2005.
11. “The Network Simulator – NS-2,” http://www.isi.edu/nsnam/ns/

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