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# Sustaining the Life of Wireless Sensor Node with Energy Harvesting

**S. Viswanatha Rao, Sakuntala S. Pillai, Shiny G.**

***Abstract: Wireless Sensor Networks (WSN) play a significant role in a number of sensing and monitoring applications. It has also become a key enabling technology for Internet of Things (IoT). Most of the earlier works were focused on extending the battery life by reducing the energy consumption of the wireless node. Availability of small footprint devices capable of ambient energy harvesting has triggered renewed interest in enhancing the performance of WSNs. In this paper we propose a novel method that can be applied to duty cycle based Media Access Control (MAC) protocols in energy harvesting WSNs to sustain the life of the node. Our approach takes into consideration the solar energy available at any instant of time so as to maximize the performance. We have conducted detailed measurements and analysis of solar energy harvested under different conditions. Our results show significant enhancement in throughput achieved while sustaining the life of the node.***

***Keywords: duty cycle, media access control, solar energy harvesting, wireless sensor networks.***

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) are formed by large number of nodes capable of communicating with each other wirelessly. Conventionally, the wireless nodes are activated using batteries. Limited energy capacity of the battery is a constraint on the life of the node. It is not practical to replace the batteries due to the hostile application environment and the large number of nodes being deployed. Hence, the energy consumption by the nodes has to be kept at a bare minimum in order to have a prolonged life for these networks. A number of techniques were developed towards achieving this objective in terms of physical design as well as optimisation at different layers of software.

Conventional WSNs have been researched extensively in literature [1], [2]. MAC layer has been one of the more specific areas that have been addressed by researchers in order to reduce energy consumption in Wireless Sensor Nodes [3]. Among the different protocols addressed in MAC, controlling power consumption by different duty cycling schemes has been very popularly dealt with.

With the key focus on reducing the power consumption, performance in terms of throughput and latency are compromised in many cases. Recent studies show that ambient sources such as solar, vibration and thermal can be made use of for energising the wireless nodes. Though these ambient energy sources are unpredictable and inconsistent in nature, they can be utilised by properly converting and storing the energy or by supplementing the conventional sources such as the battery. In this paper we analyse how the solar energy can be effectively utilised to sustain the life of WSNs. In addition, we demonstrate using Sensor-MAC (SMAC), a widely used MAC protocol, that there is significant enhancement in throughput of the network.

The rest of the paper is organised as follows. Prior art related to energy harvesting WSNs is discussed in the next section. Section III details our solar energy measurements and subsequent analysis. A solar panel suitable for a WSN node was used for the measurements. Section IV analyses the performance of SMAC to find out parameters such as data rate, duty cycle and energy consumed corresponding to a desired throughput. The energy model and its application to SMAC to arrive at extended life of the wireless node is detailed in Section V. Results are discussed in section VI. Finally, the paper concludes with section VII.

## II. RELATED WORK

There has been continued research work related to solar energy harvesting for WSNs and studies related to performance of MAC. In [4], the authors have analysed the potential of solar cell to provide energy to wireless node. A solar tracking mechanism to improve the energy harvested is presented in [5]. Different Maximum Power Tracking (MPPT) techniques are explored in [6] with focus on Semi-Pilot Cell Fractional Open Circuit Voltage (SPC-FOCV). As mentioned above, there are independent works related to solar harvesting, its enhancement, and corresponding generic duty cycle approaches to MAC for WSNs. O. Yang and W.B. Heinzelman [7] have developed a model to analyse the performance of duty-cycled MAC protocols that includes SMAC. In [8], the authors have proposed a queuing based model for solar energy to analyse the performance of SMAC. Most of the works available in literature are either intended to minimize energy consumption or models to analyse the performance. Whereas our work is based on measured values of solar energy and is focused on effective usage of harvested energy to increase performance while extending the life of the wireless node. In our work, we have developed an approach that helps to increase the throughput of duty cycle based MAC protocols under solar energy harvesting environment.

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## III. SOLAR ENERGY MEASUREMENTS AND ANALYSIS

Solar has become one of the most significant sources of ambient energy. It should be noted that there is always a variation in the intensity of solar radiation depending on the geographical location, in addition to the temporal variations. We conducted measurements to find out the amount of energy that could be harvested from mini solar panels that could be used for activating wireless sensors. Solar power was measured at 30 minutes intervals to cover a total duration of 24 hours representing one day. A mini solar panel having dimensions of 60mm x 50mm was used for carrying out the measurements. Observations were made under different scenarios. This includes measurements during sunny days, cloudy days and under passing clouds to capture steady as well as fluctuations in energy harvested.

The solar power measured at regular intervals of 30 minutes for the day is shown in fig. 1. The load was set to 42 ohms to maximize the power. This load was identified by making measurements across a wide range of resistance values. It can be seen that the solar power available reduces drastically in the presence of clouds.

We have used these measurements to analyse how effectively the harvested solar energy can be utilized to enhance throughput, in addition to extending the life of the wireless node. We have selected two representative conditions for rest of our analysis. The first one is a sunny day with maximum solar radiation that we denote as Scenario EH1 and the second one is a cloudy day with medium sunlight denoted as Scenario EH2. In addition, we have a third condition during night time, which is implicit, where there is no energy harvested. We have used SMAC as the MAC protocol for our study as it is one of the popularly used MAC for many WSN applications.

## IV. PERFORMANCE OF SMAC

SMAC is a synchronous MAC protocol that is widely implemented in WSNs[9]. In the following sections we

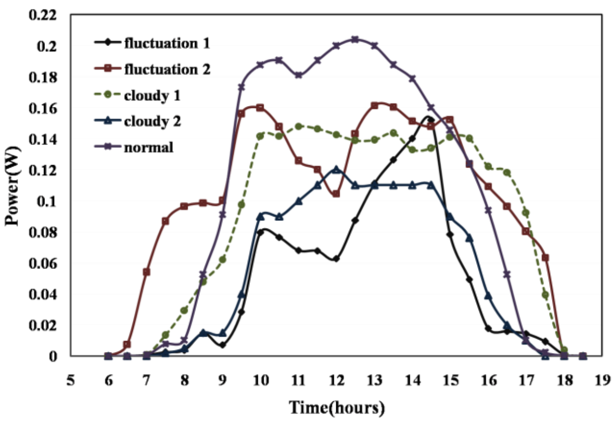


**Fig. 1. Solar power measurements over a day, under different weather conditions.**

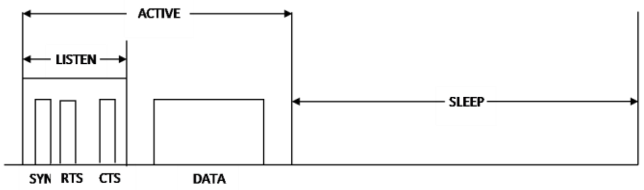


**Fig. 2. SMAC frame showing active and sleep periods**

analyse using SMAC, the impact of data rate and duty cycle on throughput of a wireless node from an energy harvesting perspective.

### A. SMAC Protocol

SMAC is specifically designed to take care of the requirements of Wireless Sensor Networks. A frame in SMAC is made up of an active period and a sleep period as shown in fig 2.

The handshaking, data transmission and reception take place within the active period. Thus substantial amount of energy is consumed during this period whereas minimum energy is required in sleep period to keep the wireless node alive. In our work, the consumption of energy is controlled by varying the active period of the SMAC depending on the quantity of energy available through harvesting.

### B. Simulation Set-up

Simulations were conducted in ns2 with a star topology to find out the energy consumed by a wireless node. The energy available in a node was obtained considering the measured values of solar energy harvested. SMAC was used for the MAC protocol. A transmit power of 0.1414W, receive power of 0.1012W, idle power of 1.8mW and sleep power of 18uW were used taking into consideration the values of typical commercial devices available. Other simulation parameters are given in Table I.

### C. Impact of Data Rate and Energy Consumed on Throughput

We have conducted studies to find out the throughput of SMAC under varying data rates and against different duty cycles. The throughput increases as the data rate increases until a cut-off point after which it remains the same. We have noticed that at lower duty cycles the throughput reaches a saturation point earlier compared to higher duty cycles. Thus, though the throughput can be increased by increasing both duty cycle as well as data rate, there is a cut-off data rate beyond which the throughput cannot be increased.

In order to assess the energy consumed, we have conducted simulations at different data rates and duty cycles. Energy consumed increases as the duty cycle is increased. This is as expected because more energy is consumed when the active period is increased. The energy consumed reaches a steady value in spite of increasing the data rates. This is due to the fact that the active period available for a given duty cycle limits the maximum number of transmissions and receptions possible.

The studies conducted on throughput and energy consumption for a wireless node for different data rates as well as duty cycles provide us an insight into the required data rate,

**TABLE I**
**SYSTEM PARAMETERS**

| | |
|---|---|
| Topology area | 500mx500m |
| Propagation Model | Two ray ground model |
| Bandwidth | 11MHz |
| Frequency | 2.4GHz |
| Routing Protocol | AODV |
| Queue length | 50 |
| Initial Energy | 2500 J |
| Traffic | CBR |
| Duty Cycle | 20%-90% |
| Simulation time (single run) | 1800s |

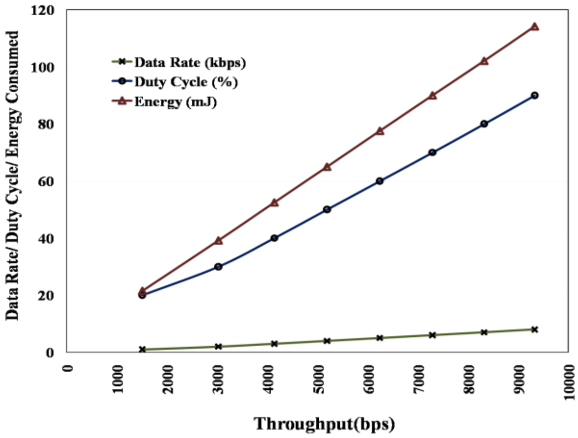


**Fig. 3. Energy, duty cycle and data rate required for desired throughput**

duty cycle and the corresponding energy required so as to obtain a specific throughput. This is depicted in fig. 3. Alternatively, we can also find out for a given energy that is available, the corresponding data rate and duty cycle that will provide the maximum throughput. Fig. 4 illustrates the cumulative energy consumed and that harvested over a period of 24 hours. The cumulative energy that is utilised by the node during the operation at various duty cycles increases linearly, but with different slopes depending on the amount of energy consumed. The cumulative energy harvested has a zero slope initially as there is no energy harvested in the absence of sunlight during night hours. The energy builds up subsequently with the availability of solar radiance and again flattens towards the end of the daytime. It can be seen that the total energy harvested over one day is more than that consumed at lower duty cycles but not sufficient to operate the node at higher duty cycles for the entire day. Again, this depends on the weather conditions prevailing during the day. It can be seen that when operated using harvested energy, the wireless node is required to operate under different duty cycles to make efficient use of the energy that is harvested, as the energy available is not steady in nature. Hence, based on the energy harvested, it is important to adapt the duty cycle to prolong the life of the wireless node.

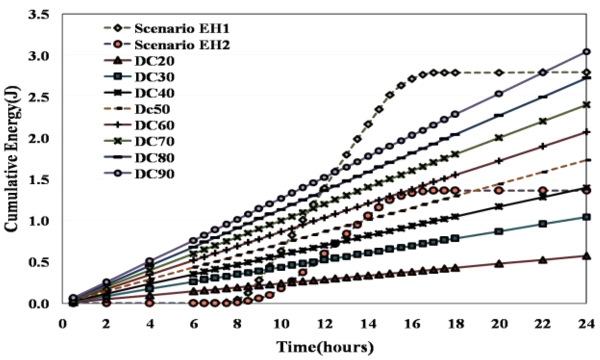


**Fig. 4. Cumulative energy consumed and harvested over 24 hours**

## V. THE ENERGY MODEL

We have looked at the energy model of a wireless node from three aspects, energy harvesting, energy consumption and energy discharge. The energy harvesting depends on the nature of ambient source. The energy harvested ($EH_t$) at time t varies from a minimum of zero to a maximum value depending on the harvesting module and the solar radiation. We have assumed that the node is capable of storing the harvested energy. Again, the maximum energy that can be stored is limited by the battery capacity. We have considered a typical 3 Volts rechargeable coin cell with 250mAh capacity that could provide more than 2500J.

We define the term Energy Available ($EA_t$) at any time t as the energy that is available in the chargeable battery at that instant of time t. The energy consumed by the node ($EC_t$) at time t depends on the active period that is related to the duty cycle at that time. $EA_t$ depends on $EH_t$ and the energy consumed ($EC_{t-1}$) during the previous instant of time (t-1).

$$EA_t = EH_t + (EA_{t-1} - EC_{t-1}) \quad (1)$$

In order to do our performance analysis, we have divided the energy available in the node into different energy bands. Based on our simulation, the minimum energy required for a node to be operational with SMAC is 0.012J. For any value of $EA_t$ below this, the node will be inactive. We have kept the simulation period as 30 minutes. We vary the duty cycle from a minimum of 20% to a maximum of 90%. We have found that energy of 1100J is required to keep the node active at 20% duty cycle for a period of 24 hours without any harvested energy. This is a safe limit when compared to the duration of night period where no energy is available for harvesting. With this as a reference and 2500J as the maximum storage capacity of the battery, we map duty cycles to different values of $EA_t$ as shown in table II.

It is to be noted that the discharge characteristics of the chargeable battery is non-linear. The value of discharge current affects the rate of battery discharge. This is known as the rate capacity effect. The rate capacity effect is defined using battery discharge parameter α that is current-dependent.


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α is obtained by dividing the effective capacity of the battery at the particular discharge current by the maximum capacity of the battery. If $E_t$ is

TABLE II ENERGY HARVESTED AND DC VALUES

| ENERGY AVILABLE(J) | MODE | DC |
|---|---|---|
| $E_A < 0.1$ | Inactive | - |
| $0.1 \leq E_A < 1100$ | Active | 20 |
| $1100 \leq E_A < 1300$ | Active | 30 |
| $1300 \leq E_A < 1500$ | Active | 40 |
| $1500 \leq E_A < 1700$ | Active | 50 |
| $1700 \leq E_A < 1900$ | Active | 60 |
| $1900 \leq E_A < 2100$ | Active | 70 |
| $2100 \leq E_A < 2300$ | Active | 80 |
| $2300 \leq E_A$ | Active | 90 |

the energy remaining in a battery at time t and $E_{t-1}$ that at previous time instant (t-1) then $E_t$ can be defined as

$$E_t = E_{t-1} / (1+ \alpha I_d) \quad (2)$$

where $I_d$ is the discharge current. $E_t$ and $E_{t-1}$ are expressed in Joules and $I_d$ in amperes.

## VI. RESULTS AND DISCUSSION

In order to understand the sustainability of the wireless node under solar energy harvesting scenario we have conducted simulation for a total duration of 96 hours and obtained values of $EA_t$ using (1) and (2) applying measured values of harvested energy. Both the scenarios EH1 and EH2 were considered for the study. Because of the diurnal nature of the source, the $EA_t$ values show a cyclic behavior. However, the node is able to sustain itself by operating at different duty cycle values in proportion to the amount of energy available. The maximum value of $EA_t$, in the case of scenario EH1 is limited by the storage capacity though, it could have been higher. This is reflected in the figure by the flat portion of the energy cycle for scenario EH1. This doesn't occur for the scenario EH2 because the value of energy harvested in this case is comparably less. From the cyclic nature of the remaining energy values in fig. 5, it can be seen that, with careful selection of duty cycle values in alignment with the energy available, the node is able to sustain its life. This, in turn, depends on the energy harvested. We have also done a comparison of the performance with and without the limit on the battery storage capacity. The energy

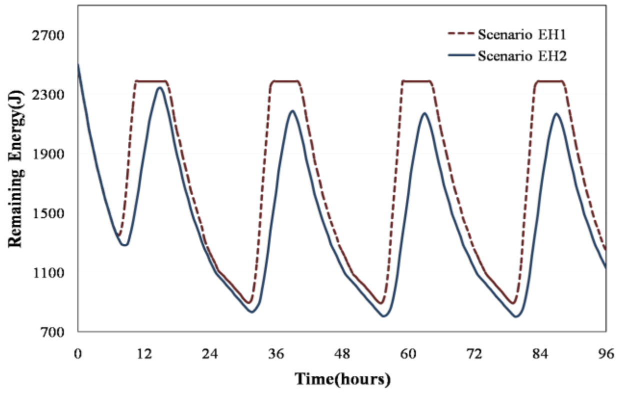


**Fig. 5. Remaining energy over time**

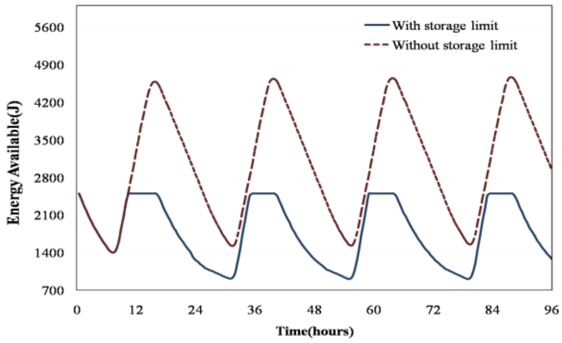


**Fig. 6. Energy Cycle over a period of 96 hours: same activation time with and without limited storage**

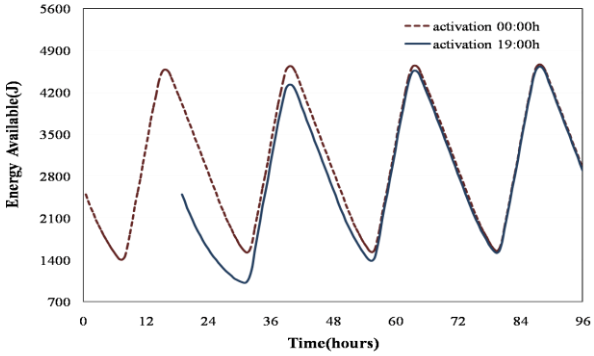


**Fig. 7. Energy Cycle over a period of 96 hours: different activation time with maximum storage**

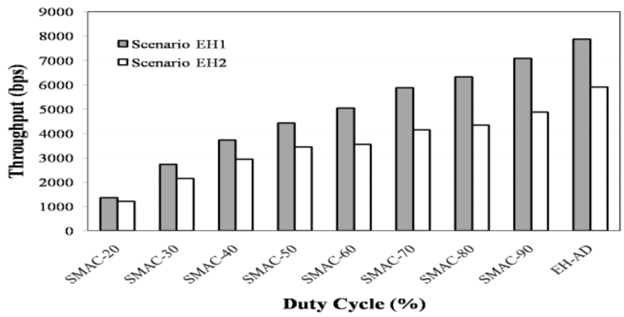


**Fig. 8. Comparison of throughput with fixed cycle operations**

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available is higher without the limit when the intensity of sunlight available is high. This is illustrated in figure 6. Alternatively, we can increase the storage capacity to a higher value that utilizes the harvested energy to the maximum extent. This could improve the throughput further. However, the increase in the storage limit does not affect the performance under conditions where energy harvested is low.

Further studies were conducted to find out the effect of deployment time under the condition that there is no limit on storage capacity. Similar to the observations made in the case of fig. 6, the energy stored in the battery will be discharged on a continuous basis without any harvesting if the node is activated during night period due to non availability of solar radiation. On the other hand, the discharge occurs along with energy harvesting when the node is activated during daytime. From fig. 7, it can be seen that the time of activation does not affect the life of the wireless node. After the initial time period, when the harvesting takes place both the energy graphs converge and the cycles continue without any difference. In comparison to the case with limited storage the initial time period required by the two graphs to get aligned is longer since the difference in energy available at the initial stage is higher.

We have found out the throughput of the network, achieved with the nodes operated at each of the duty cycle values and compared with the throughput obtained by varying the duty cycles in proportion to the energy harvested under the two different scenarios EH1 and EH2. This is illustrated in fig. 8. EH-AD represents the proposed duty cycle adaptive approach discussed above. It can be seen that, under scenario EH1, there is a significant improvement in throughput varying from 1.86 times to 9.74 times that obtained from 90% to 20% duty cycles respectively. Similarly, the throughput is enhanced by a factor of 2.06 to 8.26 for scenario EH2

## VII. CONCLUSION

In this paper we have proposed an approach to sustain a wireless node using harvested solar energy. SMAC protocol commonly used in many WSN implementations was used to demonstrate the outcome. The findings were ascertained based on solar power measurements done at different weather conditions using small footprint solar panel suitable for a wireless node. We have shown that, in addition to extending the life of the node, the throughput of the energy harvesting node is considerably increased.

The effectiveness of the approach depends on understanding the behaviour of different components of the system such as characteristics of the energy source and energy consumption in the node, in addition to the specific MAC protocol. Based on the approach proposed, an optimisation algorithm can be developed for energy consumption and the study can be further extended to other MAC protocols and energy harvesting scenarios.

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