DUTY CYCLING IN WIRELESS SENSOR NETWORKS

5.1 INTRODUCTION

Duty cycle is an operational method of decreasing energy dissipation in Wireless Sensor Networks (WSNs) by periodically placing the node in the sleep mode. The lesser the duty cycle, the length the nodes can sleep and extra energy will be saved, whereas the smaller number nodes are available to participate in data routing at any given time, which will increase transmission latency and decrease the throughput. Thus, there is a trade-off between energy effectiveness, transmission latency, and throughput, determined by the nodes’ duty cycles.

Duty cycle is typically stationary throughout the network, with all nodes using the same duty cycle. Nevertheless, this may not provide the finest overall performance for the network. Many sensor network applications need converge cost communication, wherever the data from the sensors are transferred to a sink in the network. In this type of communication pattern, nodes close to the sink must transmit abundant data than nodes far from the sink, and therefore the duty cycles of the nodes should be accustomed suitably to ensure energy efficiency while meeting traffic demands and keeping latency low.
It has been perceived that idle energy plays an essential role in saving energy in WSNs. Maximum existing radios used for WSNs support dissimilar modes, such as idle mode, transmit/receive mode, and sleep mode. In idle mode, the radio is not interactive, but the radio circuitry is still turned on, resulting in energy depletion, which is somewhat less than that in the transmitting or receiving states. Thus, an enhanced way is to shut down the radio as much as probable in the idle mode. The typical energy consumption parameters are shown in Table 5.1.

Table 5.1 Energy consumption of different components

<table>
<thead>
<tr>
<th>Module</th>
<th>Power</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor/memory</td>
<td>1.8 mA</td>
<td>Active Mode</td>
</tr>
<tr>
<td>Processor/memory</td>
<td>5.1µA</td>
<td>Sleep Mode</td>
</tr>
<tr>
<td>Radio RX Mode</td>
<td>18.8 mA</td>
<td>Receiving</td>
</tr>
<tr>
<td>Radio TX Mode</td>
<td>17.4 mA</td>
<td>Transmission</td>
</tr>
<tr>
<td>Radio Idle Mode</td>
<td>21 µA</td>
<td>Idle Mode</td>
</tr>
<tr>
<td>Radio Sleep Mode</td>
<td>1 µA</td>
<td>Sleep Mode</td>
</tr>
</tbody>
</table>

Assume time is organized in successive and equal time slots. Now, two modes for low duty cycle operation can be recognized: slotted listening mode and low power listening mode. In the slotted listening mode, as shown in Fig. 5.1 (a), a node is entirely awake in select slots and asleep in the remaining slots when there is no data transmission or reception. In the Low Power Listening (LPL) mode, as shown in Fig. 5.1 (b), a node will be fractionally awake in every slot.
Duty cycle is defined as the proportion of time a node is active in the entire operation time. Generally, the duty cycle in the LPL mode is lesser than that in the slotted listening mode. Adaptive duty-cycling has been projected in the modern works on energy-harvesting technologies, such as solar power, in order to replace battery source in WSNs. Due to the high costs and the inaccessibility of a uninterrupted power supply, it is not achievable to have instantaneously sufficient energy output. Hence, saving the idle energy consumption is still necessary. The adaptive duty cycle is thus proposed to save energy depletion and to prolong the sustainable wake up time per node. The duty cycle setting can be based on the residual energy, node location, or the rechargeable energy on each node, independently. Although the low and adaptive duty-cycled operations can yield greater energy efficiency for WSNs, neighbour detection becomes more complex than the conventional works for always-on mechanisms (e.g., CSMA), since there is no guarantee that two nodes are awake instantaneously.

In order to support duty cycling, it is essential to introduce a wakeup scheduling pattern in which a node sleeps in more slots in the idle state, and also at the same time maintains network connectivity. Towards this objective, existing neighbour detection mechanisms fall into three categories: on-demand wake up, scheduled neighbour detection, and asynchronous neighbour detection.
In on-demand wake up mechanisms, out-of-band signalling or operational cycle is used to wake up sleeping nodes in an on-demand manner. For example, with the help of a paging signal, a node listening on a page channel can be awakened. As page radios can activate at lower power consumption, this policy is quite energy efficient. However, it suffers from enhanced implementation complexity.

In scheduled wakeup mechanisms, low-power sleeping nodes wake up at the same time, intermittently, to communicate with one another. Examples include the S-MAC protocol and the multi-parent patterns protocol. In such schemes, all nodes maintain periodic sleep-listen schedules based on the locally achieved synchronization. Neighbouring nodes form virtual clusters set up a common sleep schedule.

The third classification, asynchronous wake up mechanisms is also well studied. Compared to the scheduled neighbour detection wakeup mechanism, asynchronous wake up does not need clock synchronization. In this method, each node follows its own wakeup schedule in the idle state, as long as the wakeup intermissions among neighbours intersect. To meet this prerequisite, nodes usually have to wake up more repeatedly than in the scheduled neighbour detection mechanism. Nevertheless, there are many benefits of asynchronous wake up, such as easiness in implementation and low message overhead for communication. Furthermore, it can confirm network connectivity even in highly dynamic networks.
Fig. 5.2 Flow Diagram of energy efficient data transfers using the proposed Cyclic LEACH

Fig. 5.3 shows the wakeup time, awake interval and epoch at slot s1. Epoch is defined as the difference between the $i^{th}$ wakeup time and the $j^{th}$ wakeup time of the node.

Fig. 5.3 Duty Cycles and Decision Cycles over the timeline

The following mathematical notation is used to perform cyclic vague off and cyclic vague on.

$$t_s = epoch - t_D$$

$$t_D = d(TDMA)$$

$$epoch = t_j - t_i$$

Where $t_D$ – Data transfer time

$t_i$ – $i^{th}$ Wake up time of node

$t_j$ – $j^{th}$ Wake up time of node
The cyclic model is proposed to attain the energy efficiency which performs cyclic vague off and cyclic vague on for the sensor nodes in the network. Consider that the $x^{th}$ sensor has a data sequence of $b$ bits to transmit, the channel between it and the gateway is flat fading over $[0,T]$ with a co-efficient $c_x$, channel bandwidth is $W=1$ and the noise is additive white Gaussian. A time interval $T_x$ is assigned to sensor $x$. If $WT_x \gg 1$, then the minimum transmission power $P_{t,x}$ needed to transmit $b$ bits within this interval is

$$T_x \log_2 \left( 1 + \frac{p_{t,x}c^2_x}{X_0} \right) = b$$ (5.2)

where $X_0$ is the noise power spectral density. The energy depletion of the $x^{th}$ node is

$$E_x := \frac{p_{t,x}T_x}{X_0} = \frac{T_x}{|h|^2} \left( 2^{\frac{b}{T_x}} - 1 \right)$$ (5.3)

The total energy consumption over $T = \sum_{x=1}^{n} T_x$ is minimized. Written formally, the following constrained optimization problem needs to be solved:

$$\text{minimize} \sum_{x=1}^{n} E_x = \sum_{x=1}^{n} \frac{T_x}{|h|^2} \left( 2^{\frac{b}{T_x}} - 1 \right)$$ (5.4)

subject to

$$\sum_{x=1}^{n} T_x = T$$ (5.5)

5.2.1 DETERMINING THE LOCATION OF THE BASE STATION

A base station acts as the gateway between a wired network and the wireless network. It typically comprises of a low-power transmitter and a wireless router. An energy proficient usage of multiple, mobile base station concept is employed to increase the lifespan of wireless sensor networks. This algorithm in the base station is used to select the optimal cluster-heads of cluster members. In this, the cluster-head selection is performed with rotation (cyclic)
based algorithm with their probabilistic values. Based on these values, all the nodes are getting chances and then the cluster-heads are selected.

Let given node for selecting a suitable cluster head be \( x \) node, another node is \( y \) node. Therefore, centrality is evaluated as follows:

\[
\text{Centrality} = (\text{Dist}(y^2) + \text{Dist}(x^2))
\]  

(5.6)

In order to decide the location of the base stations at the initial stages, the Base Station Location (BSL) problem is referred. The sensor network is depicted as a graph \( G(V, E) \) where \( V = V_s \cup V_f \) where \( V_s \) signifies the sensor nodes and \( V_f \) signifies the feasible sites and \( E \subseteq V \times V \) signifies the set of wireless links. Let \( BS_{\text{max}} \) be the maximum number of base stations, a round consists of \( TF \) timeframes, \( RE_i \) be residual energy, total energy spent by sensor node is \( \alpha RE_i \), where \( 0 < \alpha \leq 1 \) is a parameter.

An integer linear program (ILP) is described for formulating BSL problem. It is designated by \( \text{BSL}_{\text{min}}(G, \alpha, BS_{\text{max}}) \), minimizes the maximum energy spent, \( E_{\text{max}} \), by a sensor node in a round.

\[
\text{Minimize } E_{\text{max}}
\]  

(5.7)

Let \( a_l \) be 0-1 integer variable for each \( l \in V_f \) such that \( a_l = 1 \) if a base station is located at a feasible site \( l \); 0 otherwise. \( N(i) = \{ j ; (i, j) \in E \} \). With (7),

\[
\sum_{j \in N(i)} x_{ij} - \sum_{k \in N(i)} x_{ki} = TF, i \in V
\]  

(5.8)

\[
\sum_{l \in V_f} y_l \leq BS_{\text{max}}
\]  

(5.9)

\[
\sum_{l \in V_f} x_{lk} \leq TF|V_s|y_k, k \in V_f
\]  

(5.10)

\[
E_l \sum_{j \in N(i)} x_{ij} + \sum_{k \in N(i)} x_{kl} \leq E_{\text{max}}, i \in V
\]  

(5.11)

The above constraints reduce the maximum energy consumed by any sensor node for the duration of the round. Therefore, the total energy is preserved
in wireless sensor network by this approach. It also satisfies the detection of patterns and exclusion of redundant information. The next section shows the analysis of performance.

5.3 PERFORMANCE ANALYSIS

5.3.1 SIMULATION ENVIRONMENT SETUP

In this section, the performance of the recommended Cyclic LEACH protocol is experimented with and compared with the proposed ACR-LEACH and the existing LEACH protocol. The simulation environment is setup with 100 nodes deployed in the 100 X 100 meter. The implementation is performed with NS2, which is a discrete event simulator. The metrics considered in this section are Energy Consumption, Residual Energy, Variance of Energy, Packet Overhead, End-to-End delay, Throughput and Packet Delivery Ratio.

5.3.1.1 RESIDUAL ENERGY

Residual Energy is the total remaining energy at time t in ms. when residual energy is high, the time required for nodes in the network to be eliminated is also high. This implies that the lifespan of the network increases.

Fig. 5.4 shows the analysis of the residual energy of Cyclic LEACH, ACR-LEACH, R-HEED and the traditional LEACH and the results are tabulated. The proposed protocol Cyclic LEACH uses the energy efficient scheduling to allocate the TDMA (Time Division Multiple Access) slots, which minimizes the energy consumption among the nodes for data transmission. Therefore, the Residual energy of Cyclic LEACH is high compared to ACR-LEACH, R-HEED and traditional LEACH.
Fig. 5.4 Analysis of Residual energy with LEACH, R-HEED, ACR-LEACH and Cyclic LEACH

Table. 5.2 Analysis of Residual energy with LEACH, R-HEED, ACR-LEACH and Cyclic LEACH

<table>
<thead>
<tr>
<th>Residual Energy (nJ)</th>
<th>Network Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEACH</td>
</tr>
<tr>
<td>50000</td>
<td>5</td>
</tr>
<tr>
<td>100000</td>
<td>12</td>
</tr>
<tr>
<td>150000</td>
<td>18</td>
</tr>
<tr>
<td>200000</td>
<td>28</td>
</tr>
<tr>
<td>250000</td>
<td>35</td>
</tr>
</tbody>
</table>

5.3.1.2 VARIANCE OF ENERGY

Fig. 5.5 shows the comparison between the simulation time and the variance of energy for Cyclic LEACH, ACR-LEACH, traditional LEACH and R-HEED. The proposed LEACH takes lower energy variance than traditional LEACH and R-HEED.
Table 5.3 Time vs. Variance of Energy

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>LEACH</th>
<th>R-HEED</th>
<th>ACR-LEACH</th>
<th>Cyclic LEACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>560000</td>
<td>370000</td>
<td>285600</td>
<td>250000</td>
</tr>
<tr>
<td>20</td>
<td>620000</td>
<td>440000</td>
<td>358974</td>
<td>320000</td>
</tr>
<tr>
<td>30</td>
<td>750000</td>
<td>530000</td>
<td>406250</td>
<td>410000</td>
</tr>
<tr>
<td>40</td>
<td>870000</td>
<td>610000</td>
<td>579085</td>
<td>390000</td>
</tr>
<tr>
<td>50</td>
<td>960000</td>
<td>730000</td>
<td>702514</td>
<td>510000</td>
</tr>
</tbody>
</table>

5.3.1.3 END-TO-END DELAY

End-to-End delay is based on long distance communication and retransmission during packet loss. Fig. 5.6 shows that the proposed protocol takes lesser End-to-End delay than the existing protocol. In Cyclic LEACH, the number of communications with the base station is reduced due to cyclic vague off of the nodes which results in the decrease of end-to-end delay.
Table 5.4 shows the comparison of Cyclic LEACH, ACR-LEACH, traditional LEACH and R-HEED based on the performance metric end-to-end delay. The proposed Cyclic LEACH has less end-to-end delay than traditional LEACH and R-HEED.

5.3.1.4 PACKET DELIVERY RATIO

John Major et al. (2013) defined Packet Delivery Ratio (PDR) as the ratio of the number of packets received by the destination and the number of packets transmitted by the source. In Cyclic LEACH, the traffic load is minimum compared to the ACR-LEACH, R-HEED and traditional LEACH, which in turn
increases the PDR. Fig. 5.7 shows the comparison of the performance metric Packet Delivery Ratio for Cyclic LEACH, ACR-LEACH, traditional LEACH, and R-HEED. The Cyclic LEACH has a higher percentage than the traditional LEACH.

![Fig. 5.7 Time vs. PDR](image)

Table 5.5 Time vs. PDR

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Packet Delivery Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEACH</td>
</tr>
<tr>
<td>10</td>
<td>94</td>
</tr>
<tr>
<td>20</td>
<td>93.6</td>
</tr>
<tr>
<td>30</td>
<td>92.8</td>
</tr>
<tr>
<td>40</td>
<td>91.5</td>
</tr>
<tr>
<td>50</td>
<td>89.8</td>
</tr>
</tbody>
</table>

5.3.1.5 THROUGHPUT

Li and Dai (2005) defined throughput as the average number of successful transmissions per slot. Fig. 5.8 shows the throughput analysis between the proposed and the existing protocols. Cyclic LEACH has less delay and packet loss compared to ACR-LEACH, R-HEED and the traditional LEACH which results in an increase of throughput. The proposed ACR-LEACH and Cyclic
LEACH protocols yields a better throughput than the existing R-HEED and LEACH protocol.

Fig. 5.8 Time vs. Throughput

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>LEACH</th>
<th>R-HEED</th>
<th>ACR-LEACH</th>
<th>Cyclic LEACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>12</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>30</td>
<td>41</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>40</td>
<td>45</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>47</td>
<td>54</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>47</td>
<td>50</td>
<td>54</td>
<td>49</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>47</td>
<td>54</td>
<td>49</td>
</tr>
<tr>
<td>6</td>
<td>47</td>
<td>50</td>
<td>54</td>
<td>49</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>50</td>
<td>54</td>
<td>49</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>50</td>
<td>54</td>
<td>49</td>
</tr>
</tbody>
</table>

5.3.1.6 ENERGY CONSUMPTION

The energy consumption of the network for a period of time is based on the following categories:

- Sensing the channel all over the transmission range
- During the reception phase
- Error detection and recovery

Fig. 5.9 shows the simulation results for the energy consumption among
the proposed ACR-LEACH, Cyclic LEACH and the existing R-HEED and LEACH protocols. The proposed protocol uses the cyclic energy efficient scheduling to allocate the TDMA slots, which minimizes the energy consumption among the nodes for data transmission. Eventually, the proposed ACR-LEACH and Cyclic LEACH protocol energy consumption is decreased compared to the traditional LEACH and R-HEED, thereby improving the network lifetime among the nodes in the network.

![Graph showing energy consumption vs time](image)

**Fig. 5.9 Time vs. Energy consumption**

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>LEACH</th>
<th>R-HEED</th>
<th>ACR-LEACH</th>
<th>Cyclic LEACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>250000</td>
<td>240000</td>
<td>200000</td>
<td>190000</td>
</tr>
<tr>
<td>20</td>
<td>210000</td>
<td>205000</td>
<td>195000</td>
<td>180000</td>
</tr>
<tr>
<td>30</td>
<td>185500</td>
<td>198000</td>
<td>180000</td>
<td>170000</td>
</tr>
<tr>
<td>40</td>
<td>170000</td>
<td>179000</td>
<td>165000</td>
<td>160000</td>
</tr>
<tr>
<td>50</td>
<td>168000</td>
<td>162000</td>
<td>152500</td>
<td>150000</td>
</tr>
</tbody>
</table>

**Table 5.7 Time vs. Energy consumption**
5.3.1.7 PACKET OVERHEAD

The proposed protocol uses few nodes during transmission and remaining nodes are in the sleep state by scheduling TDMA slots which further reduces the packet overhead. The results of the proposed two protocols yield lesser overhead than the existing LEACH and R-HEED protocol. Fig. 5.10 shows the comparison between the traditional LEACH approach, RHEED, ACR-LEACH and the proposed Cyclic LEACH. The Cyclic LEACH has lower packet overhead than the existing traditional LEACH.

![Fig. 5.10 Number of nodes vs. Packet Overhead](image)

The Table 5.8 show the comparative analysis of the proposed ACR-LEACH, Cyclic LEACH and the traditional LEACH and R-HEED protocols.
Table 5.8 Comparison of ACR-LEACH, Cyclic LEACH and the traditional LEACH and R-HEED

<table>
<thead>
<tr>
<th>METRICS</th>
<th>LEACH</th>
<th>R-HEED</th>
<th>ACR-LEACH</th>
<th>CYCLIC LEACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance of Energy (nJ)</td>
<td>752000</td>
<td>536000</td>
<td>466484.6</td>
<td>376000</td>
</tr>
<tr>
<td>Packet Delivery Ratio (%)</td>
<td>92.34</td>
<td>93.46</td>
<td>94</td>
<td>96.02</td>
</tr>
<tr>
<td>Residual Energy (nJ)</td>
<td>445493.9</td>
<td>445497.5</td>
<td>446618.9</td>
<td>447743.9</td>
</tr>
<tr>
<td>Throughput (kbps)</td>
<td>36.78</td>
<td>47.67</td>
<td>43.33</td>
<td>49.89</td>
</tr>
<tr>
<td>Energy Consumption (nJ)</td>
<td>196700</td>
<td>196800</td>
<td>178500</td>
<td>170000</td>
</tr>
<tr>
<td>End-to-End Delay (ms)</td>
<td>0.41</td>
<td>0.36</td>
<td>0.28</td>
<td>0.24</td>
</tr>
</tbody>
</table>

The above values clearly indicate that the proposed protocol Cyclic LEACH provides better energy efficiency, thereby increasing the lifetime of the sensor network.

5.4 CONCLUSION

The proposed Cyclic LEACH performs the cyclic vague off and cyclic vague on using TDMA cycles (i.e.) half of the nodes in the cluster will be active and the remaining nodes will be in the sleep state. This behaviour of the node in the cluster helps to conserve energy which increases the lifespan of the network compared to the traditional protocol such as LEACH and R-HEED protocol. This approach produces the optimal results in selecting the cluster head for Wireless Sensor Networks. The experimental results prove that the proposed ACR-LEACH and Cyclic LEACH protocols yield better performance than the existing R-HEED and LEACH protocol.