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Global Routing Protocols for Wireless Body Area Networks

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Global Routing Protocols for Wireless Body Area Networks

by

Nikhil Argade

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of the

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Approved by:

PROF

(Dr. Gill R. Tsouri, Thesis Advisor)

PROF

(Dr. Andres Kwasinski, Thesis Committee Member)

PROF

(Dr. Sohail A. Dianat, Thesis Committee Member)

PROF

(Dr. Sohail A. Dianat, Department Head)

DEPARTMENT OF ELECTRICAL AND MICROELECTRONIC ENGINEERING

KATE GLEASON COLLEGE OF ENGINEERING

ROCHESTER INSTITUTE OF TECHNOLOGY

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Abstract

This work primarily consists of two parts. The first part deals with a wireless body area network with battery operated nodes. Global routing protocols are considered. The Dijkstra’s algorithm was modified using a novel link cost function in order to perform energy balancing across the network. The proposed protocol makes optimal use of the network energy and increases the network lifetime. Hardware experiments involving multiple nodes and an access point are performed to gather wireless channel information. Performance of two different types of network architectures is evaluated viz. on-body access point and off-body access point architectures. Results show up to 40% increase in average network lifetime with modest average increase of 0.4 dB in energy per bit. Proposed protocol lessens the need to recharge batteries frequently and as all the nodes deplete their energy source at the same time due to energy balancing, recharging can be done for all the batteries at the same time instead of recharging them one at a time. Network connectivity is evaluated using outage as a metric. Results show the cut-off effect which signifies the minimum amount of transmission power required to achieve reliable communication. The advantages of an off-body access point are demonstrated.

The second part presents a global routing protocol based on Dijkstra’s algorithm for wireless body area networks with energy harvesting constraints. The protocol dynamically modifies routing trees based on available energy accumulated through energy harvesting. Various harvesting methods are considered. The results show that low data-rate applications are achievable using existing energy harvesting techniques while high data-rate applications call for advancements in these methods.
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Summary of Contributions

- **Specialized link cost function for global routing protocol** – A novel link cost function was developed for global routing protocol based on the Dijkstra’s algorithm. Proposed link cost function treats energy as a distributed network resource and helps to balance the energy used by the network.

- **Routing protocol for on-body and off-body access point network architectures** – A routing protocol is developed which increases network lifetime and keeps the WBAN running by making the maintenance tasks infrequent.

- **Computer simulations for the use of energy harvesting methods in WBANs** – Existing methods of energy harvesting and the feasibility of their use in WBAN applications were evaluated using computer simulation using real wireless channels data. The maximum data packet length that can be transmitted using energy harvesters was found out.

- **Publications** –
  


Chapter 1

Introduction

In recent years, *Wireless Body Area Networks* (WBANs) are becoming the essential parts of modern health monitoring systems. Their portability, ease of use, round-the-clock observation of a person’s health, low cost and low energy consumption make them the perfect solutions for short or long term physiological monitoring of patients, athletes as well as military personnel. The applications of WBANs, ranging from monitoring vital signs of patients to improving performance of athletes, are receiving a lot of attention from academia and industry.

In spite of all these advantages, one of the main obstacles impeding wide adoption of WBANs as alternative monitoring systems is its limited energy source. Unlike *Wireless Sensor Networks* (WSNs), all the nodes in WBAN are critical and non-redundant. Based on the application, failure of a single node might prove to be fatal. The reduction in the size of wearable or implantable nodes warrants the reduction in battery size. Also the progress in computing and communication technologies is much greater than the progress in battery technology. This leads to the conclusion that, the smaller the sensor node, the less time it has to function before its battery is depleted.

In WBANs, energy is spent for doing three important tasks: sensing operations, computing operations and communication over wireless channels. Out of which, achieving reliable communications in the presence of fading channels and body
shadowing consumes the majority of the power compared to sensing or computations. A smaller battery limits the ability of a sensor node to accomplish this and hence leads to the failure of a node. The batteries need to be recharged or replaced periodically. So, maintenance of WBAN nodes becomes a real problem and prohibits their widespread use in health monitoring applications.

This work includes two different approaches to this problem. The first approach considers a battery powered sensor node while the second approach considers energy harvesting techniques and their feasibility. For battery powered WBAN, we propose a global routing protocol based on Dijkstra’s algorithm which improves the performance of the network by increasing the Network Lifetime (NL). We consider two different scenarios, namely, on-body access point and off-body access point. We compare the performance of these two scenarios and the results show the advantage of using off-body access point with multiple antennas. For energy harvesting approach, we propose a routing protocol which ensures the total connectivity whenever enough energy is available for the nodes. We evaluate the feasibility of such networks using the existing energy harvesting methods. The results show that the low data-rate applications can be implemented while high data-rate applications require advancements in the field of energy harvesting technology.
Chapter 2

Increasing Network Lifetime in Wireless Body Area Networks

2.1 Introduction

As mentioned earlier, wireless communication is the major consumer of battery power in WBANs. So, in order to extend the battery life and reduce the frequency of recharging/replacing the battery, power spent in transmitting data from the sensor nodes to the Access Point (AP) should be minimized. An efficient routing protocol which increases battery life is critical to reduce the maintenance requirements associated with recharging batteries.

In WSNs, there may be hundreds to thousands of sensor nodes which cover large areas and the network may offer ample degree of redundancy. Not all sensor nodes have to be involved in the task of monitoring the environmental parameters. In the past, power efficient routing for WSNs has received much attention. Due to the specific setting of WSNs, these routing solutions rely on dynamic network configurations involving many hops from the node to sink. On the other hand, WBANs lack such redundancy and are spread over an area limited to the human body. They also face unique signal propagation conditions such as mobility of sensors and body shadowing. Hence, efficient routing solutions specially outfitted for WBANs are required.

Several routing protocols were designed in the past specifically for WBANs—some prominent examples follow. The CICADA protocol, developed by Latre et al., consists of
a spanning tree architecture with a time-division scheme for transmission scheduling [1]. In CICADA, nodes closer to the root will deplete their energy source faster due to the need to relay messages from children nodes. Quwaider et al. developed a protocol tolerant to network changes [2]. They proposed a store-and-forward method that maximizes the likelihood of a packet reaching its destination. Each packet is stored by multiple nodes and retransmitted, which consumes more power. One solution to this problem was proposed by Ehyai et al. [3]. It consists of using dedicated, non-sensing, relay nodes with larger power sources. While this method increases NL, it requires additional dedicated hardware. This method was further improved by Maskooki et al. in [4], where body movement, such as hand motion while walking/running, was utilized to achieve NL improvement by taking the location of the nodes and periodicity of the movement into consideration. The approach requires additional hardware and a line of sight between various network components, which limits nodes positioning on the body. Nabi et al. proposed a similar store-and-forward method that integrates Transmit Power Adaptation (TPA) [5]. Nodes keep track of neighbors and utilize power control to consume minimal transmission power while maintaining a preset link quality. A slightly different approach was used by Guo et al. [6]. It proposes a Minimum Energy Packet Forwarding Protocol which implements the Transmission Power Control (TPC) similar to the method proposed by Nabi et al. with Automatic Repeat Request (ARQ), where a lost packet is retransmitted only when the link quality returns to acceptable level. Other work on relaying signals in WBANs includes the use of creeping waves by Tsouri et al., to maintain reliable on-body communication while reducing power consumption at the
nodes [7,8]. Recent work by Quwaider et al. moves in the direction of developing a routing method based on body posture. In [9] they proposed a delay tolerant routing protocol and compared it with various routing schemes. Finally, Razzaque et al. proposed a data-centric multi-objective QoS-Aware routing protocol (DMQoS) [10]. It categorizes a data packet into two different classes, namely, delay and reliability domains. Depending on the data type, a different routing scheme is applied to that specific packet. While this approach improves the delay and bit error rate statistics, energy consumption increases significantly, in turn decreasing the overall NL.

Global routing algorithms are normally avoided in WSNs because of the number of nodes and the large distances covered by them. Sheer complexity, which increases exponentially with the number of nodes, and huge data overhead because of the need to exchange link-state information make such algorithms impractical.

A star-topology cannot be used in WSNs because of their large size and distances. However it is a conventional network architecture used in WBANs, where an AP (placed on body) acts as the central node while other nodes are scattered up to ~1.5 meters from the AP. Nodes send the generated data to the AP while AP collects it and performs the function of a gateway for remote access. Typically, the AP is a PDA-like device or a smartphone/tablet which has abundant energy source, computation power and memory space, while other nodes are simple devices without such luxuries. This asymmetry reflects in their functionality as well. The AP is usually a ‘master node’ coordinating all the network activities and possible data analysis whereas distributed nodes are ‘slave nodes’ performing the only functions of sensing and transmission. This helps slave nodes
conserve resources. This centralized star-topology architecture and small number of nodes in a network make global routing a reasonable option for data gathering at the AP. The steps required to implement a global routing algorithm involves periodic link-state information gathering (because of the changing wireless channel conditions), optimizing routes from nodes to the AP and conveying the routing information to all the nodes in the network.

Another network architecture involves the use of an off-body AP with either a single or multiple antennas. This architecture can easily be implemented in an indoor environment by providing supporting infrastructure. Controlled environments such as healthcare facilities and protected-living houses can be viewed as such environments where the integration of the off-body AP with other information services and hardware can be very easy. Using such off-body AP eliminates the need to have an on-body AP present on the person’s body all the time. In a hospital-like environment with multiple users of WBANs, upkeep of the on-body APs can be avoided reducing the need for patient compliance.

In this work, a global routing protocol based on Dijkstra’s algorithm is presented. The proposed protocol uses a novel cost function which balances energy consumption across the network and increases NL. NL can be defined as the time it takes a single network component to deplete its energy source completely from network startup. In the given asymmetric case of WBAN, NL is the time it takes a single node to deplete its battery, because the AP is considered to have an infinite amount of energy. In order for the NL to be optimum, no single node should deplete its battery when other nodes have
some amount of energy left unused. Hence, we look at the batteries of all the nodes as a
distributed network resource and our cost function makes sure that all the nodes deplete
their batteries at the same time, thereby utilizing the full quantity of network energy.

This work consists detailed results for on-body AP network architecture including
evaluation of NL as well as *Energy per Bit* (EpB). It also shows the results for finding
optimal value for protocol parameters. An off-body AP network architecture is also
considered with different number of antennas and network connectivity analysis is
performed.

For battery powered sensor nodes, we primarily concentrate on NL and EpB as
performance parameters. EpB is defined as the average energy spent globally to deliver a
single bit to the AP. EpB signifies the overall energy efficiency of the complete network.
Lower EpB means lower energy spent overall which in turn corresponds to less battery
size and improved wearability. Past works consider latency as a performance parameter
but we avoid using it as most of the applications of WBANs require data collection at a
very low bandwidth. Also, typically, with the proposed architecture, it will not take more
than three hops to relay the data from any node to the AP. This makes the latency
marginal compared to the dynamics of the physiological parameters of interest.

The proposed protocol is evaluated for both the network architectures mentioned
above. On-body AP architecture includes eight on-body nodes and an on-body AP while
the off-body AP architecture comprises five on-body nodes and an off-body AP with up
to four antennas. Performance parameters are evaluated using simulations with
experimentally gathered channel data in common indoor environments. Network connectivity is shown as a function of the normalized transmission power which provides insight on the reliability of proposed routing in WBAN applications.
2.2 Proposed Link Cost Function

In the traditional applications of the Dijkstra’s algorithm, the cost of each link between the nodes is the power required to transmit a packet within a reliable performance level. It follows that the optimal route from each node to the AP is the route with the least amount combined link energies across the nodes in the path. Assuming a specific node requires very small amount of energy to transmit its packet to the AP than all other links, which is usually the case with WBANs, many routes will include that node and as a result it will deplete its energy faster than all the other nodes in the network. In this case, NL will be very low even though there is a lot of energy left with other nodes. The proposed link cost function also takes into account the accumulated energy used by each node. It discourages the use of a node as a relay if a node has used more energy than the other nodes. This is achieved by increasing the costs of its outgoing links to other nodes or to the AP.

For any global routing protocol, link costs for all the links in the network should be known to the device running the algorithm. This link cost information is gathered periodically at the AP. Link cost depends on the attenuation of the channel for each link in the network. After gathering link costs for all the links, the AP calculates the necessary routes using the proposed protocol. This link state information or channel attenuation values should be measured more frequently for a dynamic network where users (nodes) are mobile or the environment changes resulting in different channel attenuations.
The channel attenuation for the link between node $i$ and node $j$ is given by the equation (1) as follows:

$$\alpha_{i,j} = \frac{\text{RSSI}}{P_{tx}}$$

where, RSSI is the Received Signal Strength Indicator (RSSI) value, i.e., the received power measured by node $j$ and $P_{tx}$ is the transmitted power used by node $i$.

For each node $i$, the normalized energy used by the end of $k^{th}$ data gathering round is calculated as:

$$E^k_i = E^{k-1}_i + \frac{\text{RSSI}^T}{\alpha_{i,j}}$$

where, $E^k_i$ is the accumulated energy of node $i$ at round $k$ normalized to packet time, $\alpha_{i,j}$ is the channel attenuation for the selected link and $\text{RSSI}^T$ is the predefined target RSSI which is essential in order to achieve required reliable performance level. Here, accumulated normalized energy is at the current round is given by the sum of the accumulated normalized energy at the previous round and the transmission power required to achieve the target RSSI.

The cost of the link between nodes $i$ and $j$ is calculated as:

$$C^k_{i,j} = \frac{\text{RSSI}^T}{\alpha_{i,j}} \times \left(1 + \left(\frac{E^k_j}{E^k_{\min}}\right)^M\right)$$

$$\left(\frac{E^k_{\min}}{2}\right)$$
where, $C_{i,j}^k$ is the link cost between node $i$ and $j$ for $k^{th}$ round, $E_j^k$ is the accumulated energy of the destination node $j$, and $E_{min}^k$ is the minimum accumulated energy across all nodes at the current round.

As can be seen from (3), link cost is calculated by multiplying the power required to meet the link budget (if that link is chosen) by the specialized cost factor. This cost factor is computed by dividing the accumulated normalized energy of the destination node by the minimum accumulated energy across all nodes. This ratio of energies is raised to the power of $M$ ($M \geq 0$), which determines the strength of the energy balancing effect. For example, if node $j$ has used more energy than the current minimum, then that node will be avoided as a relay for other nodes by increasing the cost of the incoming link. Cost factor is normalized in order to reduce the cost to conventional value, the power required to achieve reliable performance level, for $M = 0$ regardless of the accumulated energies across the network.

One of the important topics in conventional networking applications is the Quality of Service (QoS). In most of the WBAN applications, all nodes are equally important, making the network non-redundant. These applications are also immune to latency as the number of hops times the transmission time is much less than the bandwidth of sampled physiological signals. Even then, by manipulating the cost factor on outgoing links from the preferred node, we can still implement QoS. For example, by decreasing the parameter $M$ on the direct link from the preferred node to the AP, we can lower the link cost on that link and encourage the use of that link. This, in turn, reduces the latency for
the preferred node by having fewer hops in its packet’s path. Another example can be given as – Consider a network with sensor nodes as well as a few dedicated relay nodes with a larger energy source. By adjusting the value of $M$ on the links connecting these relay nodes, we can make them preferred relays in the network so that their energy can be utilized in an optimum fashion. These examples show that the proposed protocol can be used to impose QoS restrictions on the network and can be used with the dynamic nature of the network by simple modification of the cost factor parameter. In the proposed protocol, we make sure that the data packet reaches the AP reliably by setting a reasonable target RSSI. Here we assume the equal priority for all nodes as is the case with physiological signal monitoring WBAN applications.
2.3 Performance Evaluation

The link cost function explained in the previous section was tested using the simulation as well as in the experimental environment. To evaluate the effect of the energy balancing cost function, we compared the results with the standard system with a conventional link cost function, where the link cost is equal to the transmission power required to meet the link budget of desired target RSSI ($M = 0$ in equation (3)). In order to evaluate the NL, we set an arbitrary threshold as the battery capacity. The time it takes any node’s accumulated normalized energy to cross this arbitrary threshold was measured and recorded as NL.

The network was comprised of an AP and End Devices (EDs) acting as nodes for all the simulations and experimental setups. Algorithm 1 depicts an elaborate pseudo-code for the routing protocol while the code for calculation of accumulated energy is given in Algorithm 2.

---

**Algorithm 1.** Dijkstra’s Algorithm with proposed link cost function

1: for $i = 1$ to # of Nodes do
2:   node$_i$.visited ← 0
3:   node$_i$.distance ← $\infty$
4:   node$_i$.previous ← node$_i$
5: end for
6: node$_{AP}$.distance ← 0
7: $\text{energy}_{\text{min}} = \min(\text{node}.\text{energy})$
8: while unvisited nodes available do
9:   node$_{source} ← \text{node with smallest distance}$
10: for $i = 1$ to # of Links do
11: if link$_i$.source = node$_{source}$ then
12: node$_{dest} \leftarrow$ link$_i$.destination
13: if node$_{dest}$.visited = 0 then
14: cost $\leftarrow$ link$_i$.power $\times (1 + (node_{dest}.energy/energy_{min})^M)/2$
15: newdistance $\leftarrow$ node$_{source}$.distance + cost
16: if distance $<$ node$_{dest}$.distance then
17: node$_{dest}$.distance $\leftarrow$ newdistance
18: node$_{dest}$.previous $\leftarrow$ node$_{source}$
19: end if
20: end if
21: end if
22: end for
23: node$_{source}$.visited $\leftarrow$ 1
24: end while

Algorithm 2. Accumulated Energy Calculation
1: for $i = 1$ to # of Nodes do
2: node$_{ptr} = node_i$
3: if node$_{ptr}$.previous $=$ node$_{ptr}$ then
4: No path to node$_i$
5: else
6: while node$_{ptr}$.previous $=$ node$_{ptr}$ do
7: link$_{ptr} \leftarrow$ link between node$_{ptr}$ and node$_{ptr}$.previous
8: node$_{ptr}$.energy$+ =$ link$_{ptr}$.power
9: node$_{ptr} \leftarrow$ node$_{ptr}$.previous
10: end while
11: end if
12: end for
2.3.1 Experimental Setup

In order to gather the link state information of the wireless channels and to run real-time experiment, we used an ultra-low power hardware platform EZ430-RF2500T developed by Texas Instruments (TI). This hardware platform consists of MSP430F2274 microcontroller and CC2500 2.4 GHz transceiver. CC2500 radio was set up to run at 250 kbps while the AP is connected to the host computer via a USB to a Serial link, running at 115200 BAUD. To imitate an AP with high computational power, the AP device only acts as a bridge between EDs and the host computer, transferring the computing responsibility to the host. Similarly, in order to fulfill the requirement of an AP with abundant energy source, the AP device is powered via USB connection. All other devices acting as EDs are battery powered. The host was given the task to run the routing algorithm and do the power control calculations as well as convey the calculated routes to EDs via the AP. A laptop computer with an Intel® Core™ i5-2410M CPU and 4 GB of RAM was used as the host.

2.3.2 On-Body Access Point Network Architecture

An AP and eight EDs were placed on a 170 cm, 70 kg male subject as shown in Figure 1. The host computer was carried in a backpack and connected to the AP via a USB cable. In order to support large dynamic range of power consumption, target RSSI (\(RSSI^T\)) for both simulations and hardware experiments was arbitrarily chosen to be -60 dBm. An approximate positioning of EDs and AP on the body along with an example of link cost and channel attenuation notations is depicted in Figure 1.
We used this experimental setup to implement the routing protocol in real-time taking the changing channel conditions into account. A couple of different values of $M$ were employed. Figure 2 depicts the partial floor plan of the residential apartment where the experiment was conducted. It shows the typical indoor environment where the applications of WBANs can be implemented. The subject walked around the room as shown in Figure 2.

Figure 1: Experimental setup for network architecture with access point on the body. Note that only neighboring nodes network connections are depicted for clarity of presentation.
The following procedure was carried out at a rate of 5 Hz:

1. The AP sends a synchronization beacon which includes routing and power control tables.
2. Each ED transmits its own RSSI table back to the AP, while simultaneously listening to other ED messages and storing the received power from each.
3. Once all EDs have transmitted their data, the AP transfers a table with the RSSI data from all devices to the host, see Table 1 for an example.
4. The host uses the RSSI table to compute the routes along with the required powers to meet the selected links using Dijkstra’s algorithm and the link costs depicted in Equations (1)–(3).
5. The host sends both routing and power tables back to the AP so that a new cycle may begin.

Figure 2: Experimental setup environment for network architecture with access point on the body.
Table 1: Sample RSSI [dBm] Table at the AP.

<table>
<thead>
<tr>
<th></th>
<th>AP</th>
<th>ED1</th>
<th>ED2</th>
<th>ED3</th>
<th>ED4</th>
<th>ED5</th>
<th>ED6</th>
<th>ED7</th>
<th>ED8</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>−</td>
<td>−60</td>
<td>−60</td>
<td>−60</td>
<td>−60.5</td>
<td>−60.5</td>
<td>−60</td>
<td>−79.5</td>
<td></td>
</tr>
<tr>
<td>ED1</td>
<td>−66</td>
<td>−</td>
<td>−62</td>
<td>−75</td>
<td>−63.5</td>
<td>−69</td>
<td>−75.5</td>
<td>−73</td>
<td>−67.5</td>
</tr>
<tr>
<td>ED2</td>
<td>−72</td>
<td>−61.5</td>
<td>−</td>
<td>−80</td>
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<td>−70</td>
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<tr>
<td>ED3</td>
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<td>−80.5</td>
<td>−</td>
<td>−67.5</td>
<td>−70</td>
<td>−72.5</td>
<td>−70.5</td>
<td>−70</td>
</tr>
<tr>
<td>ED4</td>
<td>−39</td>
<td>−63</td>
<td>−69.5</td>
<td>−67</td>
<td>−</td>
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<td>−68</td>
<td>−71</td>
<td>−69.5</td>
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<td>−</td>
<td>−55.5</td>
<td>−51.5</td>
<td>−62</td>
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<tr>
<td>ED6</td>
<td>−67</td>
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<td>−55.5</td>
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<td>−62</td>
<td>−54</td>
<td>−51.5</td>
<td>−</td>
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</tbody>
</table>

During this whole process, only one control packet is used, the synchronization beacon. The beacon also contains the routing and power tables which tell each ED where to transmit a packet and how much power to use doing that, respectively. Using this approach instead of polling each ED individually minimizes the number of control packets in a given round. Using the beacon, all EDs synchronize their clocks. To avoid collision, they transmit their data packet on a fixed, pre-defined schedule. Each ED is assigned a network ID. The time between the consecutive synchronization packets is divided into smaller slots. During any single time slot, only one ED can access the channel. ED’s network ID determines which time slot is allotted to it. As long as we can keep the network IDs different, no collisions will occur. This pre-allocated scheduling scheme negates the need for scheduling during runtime.

After AP computes all the routes and required power for all EDs, it sends these routing and power tables to the EDs. Routing table is an array of numbers which tells each ED where
its packet is supposed to go. Every ED only needs to know the next node in its path so that it might be able to transmit its own packet or relay someone else’s packet to the next node. Power table is also an array of numbers telling each ED how much transmit power it should use in order to transmit the packet reliably. In this way, all the information an ED needs (address of the next node and the corresponding transmit power) is contained in the synchronization beacon. The size of the synchronization beacon depends upon how large these tables are and hence, is directly proportional to the number of nodes in the network.

2.3.3 Off-Body Access Point Network Architecture

Figure 3: Experimental setup for network architecture with access point off the body. Note that the drawing assumes a single antenna at the AP, but up to four antennas are considered.
This is the second type of network architecture that we consider, which is unusual in WBAN applications. During off-body access point experiments, five EDs (ED1-ED5) were placed on a 172 cm, 73 kg male subject as shown in Figure 3. Figure 4 depicts the floor plan of the indoor environment used to conduct these experiments. AP1, AP2, AP3 and AP4 are the locations of four devices placed on the walls. AP1 is directly connected to the host computer via a USB cable and the host computer sits on the desk near AP1. AP2, AP3 and AP4 can act as three additional optional antennas for the AP. They are not in fact the antennas and are not connected (wired) to the AP1 physically but are the same devices used for EDs. We implement the function of antennas by setting the link costs from AP2-4 to AP1 to zero. In other words, to transmit a packet from AP2-4 to AP1 will not consume any energy. This leads to the fact that routing a packet from ED1-5 to AP1 is same as routing a packet from ED1-5 to AP1-4. Due to the limited number of available devices at the time of the experiments, when we used three devices as AP antennas, we were left with five on-body EDs instead of eight as were used in the on-body AP experiments. Figure 3 also shows the approximate placement of the EDs on-body while Figure 4 shows the walking path of the male subject. Experiments were performed in a laboratory with quite a large area. This is similar to the typical hospital like environments.
Figure 4: Experimental setup environment for network architecture with access point off the body. AP1, AP2, AP3 and AP4 mark the position of the four antennas of the AP.

We implemented the routing algorithm in real-time, dealing with the dynamic channel conditions. Procedure was performed for a couple of different values of $M$ and the number of AP antennas was varied. Four types of experiments were performed using this setup. For the first type, only single antenna was used. This was achieved by using only AP1 while ignoring AP2-4. The second type involved the use of two antennas AP1 and AP3. Third type of experiment considered an AP with three antennas and was implemented using AP1, AP2 and AP4. This case was repeated with antennas AP1, AP2 and AP3. Both these cases were fairly similar to each other when performance was evaluated. The last type involved the use of all
four AP antennas. The data gathering procedure explained in the previous section was executed for each of these experiments.

2.3.4 Computer Simulations

Performing all the described experiments in real-time required a fixed single value of $M$ for each set of data gathering rounds. Hence, it was impractical to run an experiment for large set of values for $M$. A simulation environment, however, would be the perfect tool for evaluating the effect of changing the protocol parameter. Many simulation runs can be performed using a vast array of values for $M$ in a fraction of the time it takes to conduct real-time experiments. We also found that the real-time implementation results and the simulation results matched almost identically. Hence, the decision was made to evaluate the effect of changing the protocol parameter using simulations. The physical wireless channel attenuation data was gathered by running the same procedure described in the earlier sections. Only this time, neither power control nor routing was implemented while performing data gathering rounds. This forced all the nodes to transmit at the maximum available power level and to broadcast their packets instead of transmitting them to a specific node. Each ED received a packet from all the other nodes and sampled the RSSI data. This RSSI data was then transmitted to the AP which forwarded it to the host computer via a serial link. At the host computer, this data was stored in the form of RSSI tables (see Table 1). Such RSSI tables were then fed to the simulator which conducted the execution of routing protocol with power control. Outputs of the simulation included accumulated energy use data, required transmit power settings and the entire routes for all the nodes. This procedure was repeated for many different values of $M$. 
2.3.5 **Network Connectivity**

A global routing algorithm like Dijkstra’s algorithm is an iterative procedure. It builds a networking tree using the shortest distance, i.e., with minimal accumulated costs across all the possible routes in a network. Each iteration connects one other node to the already forming tree. These iterations continue until all the nodes in a network are connected to the networking tree. No matter what the link costs are (finite costs), eventually Dijkstra’s algorithm will find the route for all the nodes in the network to connect with each other. Dijkstra’s algorithm will not leave a node outside of the network tree. Even then, Dijkstra’s algorithm would fail if one of the nodes have link costs of $\infty$ on all its outgoing links. This will happen only in the case where a packet from that specific node cannot reach any of the nodes already in the forming networking tree. For example- let’s assume that there are five nodes in the forming tree out of total eight nodes. The remaining three nodes can send their packets to each other reliably but cannot transverse the links towards the five nodes already in the tree. Hence, they will be left out of the routing tree. This is basically a transmission power limitation constraint and holds true no matter which link cost function is being used. In WBAN applications, the cause of this kind of behavior is the severe channel attenuations occurring due to the dynamic multipath fading environment and body shadowing.

We define the outage, $P_{out}$, as the ratio between Dijkstra’s failed routing attempts over the overall routing attempts. This performance metric is an indication of the network connectivity under wireless fading channels environment and body shadowing constraints. A failed attempt can be taken as an attempt where any node cannot join the Dijkstra’s forming network tree due to transmit power limitation. We evaluated the outage probability by
running the simulations under transmission power constraints. In order to capture generic results, the maximum transmission power was normalized to target RSSI to obtain a maximum power ratio as given in equation (4) below:

\[ p_{ratio, max} = \frac{p_{max}}{RSSI} \] (4)

Simulations were ran for a range of values of \( p_{ratio, max} \) and the measurements for \( P_{out} \) were recorded. Looking back at the equation (1) and the power control mechanism, the channel instances, where \( \alpha_{j,k} < (p_{ratio, max})^{-1} \), result into a failed attempt. It means that the channel attenuation is more than what can be overcome using the maximum transmit power. We evaluate the probability of the occurrence of this event.
2.4 Results

2.4.1 On-Body Access Point Network Architecture

A. Balancing Energy Consumption

![Graph showing accumulated energy spent by each end device over time](image)

Figure 5: Accumulated energy spent by each end device over time for reference system ($M = 0$). Note that ED7 would eventually deplete its battery while energy still remains at other nodes of the network.

Results from a 5 minutes real-time run using the reference system using conventional approach ($M = 0$) are depicted in Figure 5. Results from the same real-time run using the proposed link cost function with $M = 100$ are depicted in Figure 6. In both the figures, accumulated energies of each node are represented as a function of time. By the end of the experiment (after 5 minutes) using conventional approach, ED7 consumed the most energy, 1.06 $\mu$J. It would deplete its battery while all other nodes have ample amount of energy still remaining available to them. On the other hand, using the proposed link cost function with
$M = 100$, all EDs consume energy at the same rate. They all spend less than $0.81 \mu J$ each during this 5 minutes run. It can also be seen that the proposed system consumed more overall energy ($6.31 \mu J$) compared to the reference system ($6 \mu J$). As the proposed link cost function is not optimizing the routes based on the energy efficiency of the overall route but looking for the most efficient path for balancing energy across all the nodes in the network, the increase in the overall energy consumption is expected.

![Accumulated Energy](image)

Figure 6: Accumulated energy spent by each end device over time for the proposed algorithm using $M = 100$. Note that energy consumption is balanced and all nodes consume the same amount of accumulated energy over time.

The fact that more overall energy is consumed by the network doesn’t carry a lot of significance because no single ED consumes more energy than others. Thus, all EDs are expected to deplete their batteries around the same time by optimally utilizing the network.
resources. As can be clearly seen from Figure 5, a substantial amount of energy still remains unused when ED7 completely runs through its battery. On the other hand, using the proposed system, when an ED depletes its battery, all the other EDs are very close to it in terms of the energy consumption. Hence, there is almost no energy left in the network. This optimal utilization of the network energy results in NL improvement. For example, assuming all EDs have a battery capable of supplying an accumulated energy of $0.625 \mu J$, the reference system ($M = 0$) would last for 175 seconds (until $0.625 \mu J$ are spent by ED7), while the proposed system ($M = 100$) would last for 240 seconds (until $0.625 \mu J$ are spent by all EDs almost simultaneously). Another advantage of the proposed system ($M = 100$) relates to maintenance of the network. Since all EDs deplete their batteries simultaneously, the network can be serviced once to replace/recharge batteries, instead of multiple times in the reference system ($M = 0$).

B. Protocol Response to Dynamic Conditions

To demonstrate the capability of the proposed link cost function, we turned a single ED off for several seconds and then again turned it on. Figure 7 shows the energy utilization for all EDs in these dynamic conditions. As soon as a single ED was turned off, the network lost an energy source. Hence, the slope of all other EDs increased indicating that the energy consumption rate for all EDs increased. During the time the ED was off, it didn’t spend any energy transmitting any packet. So, the accumulated energy for that node remained unchanged. When it rejoined the network after several seconds, it was the one with the least amount of accumulated energy. The proposed protocol encouraged the use of that ED as a relay for other nodes.
Looking carefully at the slope of all other nodes during the time from when the node rejoined the network till its accumulated energy matched the others, we can see that the slope is less than the normal value while the slope for the reconnected ED is very steep. All the other EDs used up reconnected ED’s surplus energy to balance their energy consumption. They achieved energy balancing by frequently relaying their packets through the reconnected ED. When the accumulated energy of the reconnected ED reached that of the other EDs in the network, this relaying slowed down. From that instance of time, slope of all the EDs in the network returned to normal. This behavior vividly demonstrates the ability of the proposed cost function to make use of the energy in the network as a distributed resource.
C. Gain in Network Lifetime and Evaluation of Energy per Bit

To evaluate the performance of the network using NL and EpB as metrics, we conducted a more comprehensive real-time run of over 37 minutes. The accumulated energy data from the run was processed and the ratios of EpB and NL for $M = 100$ vs $M = 0$ were calculated. Large set of data was divided into the smaller groups of 100 consecutive routing rounds (20 second run).

For $M = 100$ and $M = 0$, the total energy spent across all nodes in a network was calculated and then divided by the number of rounds giving us EpB normalized per routing round. Taking the ratio of the results for $M=100$ and the results for $M=0$, we end up with the EpB ratio.

Finding the NL ratio was accomplished by first defining the battery capacity for an ED. We defined the battery capacity for each group as the EpB result times 40. This means that each ED is equipped with the battery that can support an ED for an average of 40 routing rounds. After determining the battery energy, NL was calculated as the number of routing rounds it took the first node to accumulate enough energy to cross the defined threshold. This results into the NL normalized to the routing cycle time. Similar to EpB ratio calculations, dividing the results for $M = 100$ by the results for $M = 0$ gives us the NL ratio.

The NL ratio results are depicted in Figure 8. NL ratio value greater than 1 represent improvement because of the proposed link cost function. From the figure it is apparent that, out of 112 groups of 100 routing rounds, all groups showed the improvement in NL except for three. Average improvement ratio of $\sim1.4$ proves that the average improvement of 40% was observed in NL.
Figure 8: Improvement in Network Lifetime for $M = 100$ vs. $M = 0$. Note that the proposed system provides an average gain of approximately 40%.

Figure 9: Energy per Bit ratio for $M = 100$ vs. $M = 0$. Note that the proposed system exhibits an average 0.4 dB increase in energy per bit.
EpB ratio results corresponding the NL ratio given above are depicted in Figure 9. As expected, more energy was consumed overall using the proposed link cost function than using the conventional method. Hence, the EpB is higher for $M = 100$ than for $M = 0$. From the figure it can be seen that, on an average, 0.4 dB more energy was used in the proposed method. Interestingly, EpB was lower for $M = 100$ for the instances where the NL wasn’t improved. This indicates the occurrence of such network links that no relaying was available for energy balancing.

D. Finding Optimal Protocol Using Off-Line Computer Simulation

Both the off-line simulations and on-line hardware experiments processed real wireless channel data. Because of this similarity, simulation results match the real-time hardware experiment results. As power control was employed for the experiments, each ED only uses just enough transmission power to transverse the link to a specific ED. Therefore, other EDs might not pick up its transmission. It follows that the other EDs might not have the RSSI information for that ED. Hence, the RSSI table for hardware implementations is the shortened version of the one used for simulations. Because of this, there was a negligible disparity between hardware and simulation results.

To find out the optimal value of the protocol parameter, simulations were performed for many values of $M$ using the RSSI data collected with the experimental setup. We use on-body AP network architecture. Figure 10 presents the NL ratio as a function of protocol parameter $M$. Similar to NL improvement analysis, higher NL ratio corresponds to better performance. As can be seen from the figure, there is a considerable performance improvement up to $M = 60$. Beyond that point, NL ratio values decrease gradually. Even
though the performance is better than for $M = 0$, improvement is to a diminishing extent as $M$ increases. NL improvement of around 40% is observed for $10 < M < 110$.

![Graph showing the effect of $M$ on improvement in Network Lifetime](image)

Figure 10: Effect of $M$ on improvement in Network Lifetime. Note that highest improvement is obtained for $10 < M < 110$.

### 2.4.2 Off-Body Access Point Network Architecture

Performance analysis for off-body AP network architecture was performed using the data gathered during multiple 37 minutes runs of the hardware experiments. We considered multiple cases for varying number of antennas at the AP ranging from one to four. To evaluate improvement ratios of NL and EpB for $M = 100$ vs $M = 0$ (as described in the previous section), the accumulated energy data was analyzed.

NL ratio results are depicted in Figure 11. For the vast majority of groups and for any number of antennas at the AP, it is clear that NL was improved. For a single antenna AP, the average NL improvement was 25%. Compared to the NL improvement for on-body AP
(40%), improvement for off-body AP was observed to be lower. A link from on-body ED to off-body AP is more likely to have higher cost than an on-body link because of the body shadowing and the distance between the nodes and the AP. Hence, off-body link cost is the predominant factor in the path cost calculations. Given the dynamic nature of the experimental environment (subject moving continuously), the best off-body link varied frequently. Balancing the network energy often means that the link with the least cost is not chosen. By taking high cost off-body link and energy balancing technique into account, this decrease in the improvement can be explained. This setup is in fact a type of spatial diversity and the diversity branches are the links from on-body EDs to the AP. Hence, for single antenna AP, we have five diversity branches. This automatically improves the performance of the reference system. When we increased the number of antennas to 2, 3 and 4 antennas, improvement in NL decreased further from 25% to 22%, 20% and 16%, respectively. For every additional antenna, we introduce five more diversity branches from the body to AP. Hence, as explained above, we attribute the continual decrease in improvement to the increase in spatial diversity gains.

Results for the EpB ratio for any number of antennas are depicted in Figure 12. Similar to the on-body results for EpB, we can see the expected increase in EpB for $M = 100$ as energy balancing consumes more overall energy to improve NL. An average of 0.025 dB more energy was consumed across all groups and number of antennas. This is a promising result as it shows that the use of multiple antenna off-body AP network architecture not only negates the need to carry an AP on the body but also sustains the network longer by improving NL at no cost in terms of battery size.
Figure 11: Improvement in Network Lifetime for $M = 100$ vs. $M = 0$ and varying number of antennas at the off-body access point. The straight horizontal lines depict the mean value.

Figure 12: Increase in Energy per Bit for $M = 100$ vs. $M = 0$ and varying number of antennas at the off-body access point. The straight horizontal lines depicts the mean value.
2.4.3 Reliable Network Connectivity

![Network connectivity outage ratio as a function of normalized maximum transmission power.](image)

Figure 13: Network connectivity outage ratio as a function of normalized maximum transmission power. Note the threshold effect, where beyond a normalized power level the network is almost always connected.

To analyze network connectivity, we use outage probability as the performance metric. Results of the outage ratio, $P_{out}$, are depicted in Figure 13 as a function of normalized maximum transmission power. Normalization of the maximum transmission power doesn’t limit the result to a specific WBAN platform but makes it generic. It simply provides the difference between maximum possible transmitted power and the received power.

As can be seen from the figure, a threshold effect is clearly visible. It means that, in order to achieve reliable routing in the network via ensuring that the algorithm almost always...
forms the complete network tree, a specific normalized maximum transmission power threshold must be crossed. For an on-body AP network architecture, if the transmission power is more than 70 dB higher than the target RSSI, then the outage probability falls below 0.1. However, if the transmission power is less than 60 dB higher than the target RSSI, then the outage probability rises above 0.9. This example tells us to keep the minimum difference of 70 dB in these power levels if we want to achieve acceptable level of reliability (outage = 0.1). For an off-body AP network architecture with single antenna, this threshold reduces to 67 dB for the outage probability of 0.1. As we increase the number of antennas, the threshold value consistently decreases and ends up with 62.5 dB in the case of an AP with four antennas.

2.4.4 Performance Comparison with Previous Work

The past works on routing in WBANs mentioned in the literature survey assumed a specific application and specific system conditions. Based on these assumptions, routing algorithms were developed and thus evaluated. While designing the proposed protocol, we do not assume a certain application but we consider any and all physiological monitoring applications. We cut down on the maintenance tasks by accomplishing the infrequent recharging of batteries while our proposed protocol still maintains reliability and wearability. To achieve this goal, instead of focusing on latency, we focus on network lifetime (infrequent recharging), energy per bit (small battery size and thus wearability) and outage probability (network connectivity and thus reliability) as performance parameters.

Previous works on routing in WBAN did not consider global routing. The works involving routing did not consider the same parameters as are presented in this work. Due to
the assumptions used in the previous works, there is no meaningful way to compare the performance of the proposed protocol with that of the others. However, we have summarized the performance parameters and results of a few relevant methods in Table 2. These works involved the use of energy consumption and network lifetime as metrics. Summary tells us that the proposed protocol excels at achieving its design goal, increasing NL without extra hardware.

Table 2: Summary of WBAN routing algorithms performance.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Parameter</th>
<th>Performance Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy per bit</td>
<td>25% less than Multi-hop routing.</td>
</tr>
<tr>
<td></td>
<td>Network lifetime</td>
<td>Increases somewhat.</td>
</tr>
<tr>
<td>Minimum Energy Packet Forwarding Protocol [6]</td>
<td>Energy per bit</td>
<td>A 10% reduction due to power control and a 1.7% reduction due to ARR.</td>
</tr>
<tr>
<td>Proposed Modified Dijkstra’s Global Routing Algorithm</td>
<td>Network lifetime</td>
<td>Up to 40% increase.</td>
</tr>
<tr>
<td></td>
<td>Energy per bit</td>
<td>A slight increase.</td>
</tr>
</tbody>
</table>
Chapter 3

Dynamic Routing Trees with Energy Harvesting Constraint in WBANs

3.1 Introduction

It has been established earlier in this work that the major energy consuming operation in WBANs is the reliable communication over the fading wireless channels in the presence of body shadowing. Usually, WBAN nodes are designed to consume relatively very low power for computing as well as for communication. Hence, energy harvesting methods could present the solution for long term operation of WBANs without the need for recharging batteries. If we can use energy harvesters as a source of energy then the expensive high capacity, small form factor battery won’t be required to keep the nodes alive. Examples of energy harvesters include but are not limited to thermoelectric generators (body heat as an energy source), photoelectric transducers (light) and piezoelectric transducers (body motion).

Energy harvesting models are critical for evaluating the performance and limitations of existing energy harvesters. Various Markovian models have been developed to characterize the performance of energy harvesting techniques [11]-[14]. For example, in [11] Ho et. al. propose stationary and generalized Markovian models to represent harvested energy. In another example, Seyedi et. al. [12]-[13] and Ventura et. al. [14] present a combined model for energy harvesting and data traffic.

In the previous chapter, we presented a global routing protocol for WBANs which resulted in an increase in NL for battery operated nodes. In the framework of a sustainable
energy harvesting solution, however, there is no pre-charged battery and the network is expected to operate perpetually.

In battery operated nodes and after network lifetime has passed, a failed node cannot rejoin the network and cannot transmit its packet until the battery is replaced. However, in the case of energy harvesting, even if a node fails to transmit its packet in a particular transmission round, it may be able to transmit again once it has enough energy accumulated. Due to this reason, network lifetime no longer applies as a reliable metric to measure network performance. Instead, network sustainability should be quantified with the help of Outage as a performance metric which directly counts the number of events where the entire network cannot be connected using proper links.

Many past works ([15] – [19]) addressed routing for WSNs under energy harvesting nodes. For example, in [15] Jakobsen et. al. present a Distributed Energy Harvesting Aware Routing Algorithm which changes routes based on available energy of neighboring nodes. In another example, Noh et. al. in [16], proposed an algorithm which determines the route based on geographic duty-cycle information of neighbors. Whilst there are many routing algorithms for WSNs, routing protocols for WBANs with energy harvesting constraints received little attention in the past despite their differentiating attributes and the clear benefits of powering WBANs using energy harvesting.

In this chapter, we propose a dynamic global routing algorithm based on an augmentation of Dijkstra’s shortest distance algorithm to address the dynamic nature of energy harvesting solutions. We consider body heat, ambient light, direct sunlight and ambient airflow as energy sources. A Markovian model presented in earlier works is used to
characterize the energy harvesting performance. Our purpose is to evaluate the feasibility of sustaining data gathering from all nodes based solely on energy harvesting. To this end, we make use of an experimental setup to gather communication channel data which forms the basis for computer simulations of the proposed protocol coupled with the energy harvesting model. Results show that low data-rate applications can be implemented using existing energy harvesting methods, while high data rate applications, such as wireless ECG, require further advances in energy harvesting solutions before they can be supported.
3.2 Proposed Protocol

We use star-topology for the architecture of WBAN. Also because of the differences between WSNs and WBANs, unlike in WSNs, we can implement global routing protocols in WBAN applications. As explained in Section 2.1, we employ an AP as a ‘master node’ and EDs as ‘slave nodes’.

In the traditional applications of the Dijkstra’s algorithm, the cost of each link between nodes is the power required to transmit a packet with reliable performance level. During each data gathering round, an ED may act as a source or a relay or both. As a source, an ED receives the beacon and transmits its own packet, while as a relay an ED receives a packet from another node and re-transmits it over the wireless channel. Hence, each packet transmission is always coupled with a packet reception. Thus, we calculate the total energy required to receive and transmit a packet as:

\[ e_{i,j} = t_p * P_{R_i} + t_p * P_{T_{i,j}} \]  

where, \( i \) is the source node, \( j \) is the destination node, \( t_p \) is the transmission time per packet, \( P_{R_i} \) and \( P_{T_{i,j}} \) are the powers required to receive a packet at node \( i \) and transmit a packet from node \( i \) to node \( j \), respectively.

We calculate the energy available at each node for the \( k^{th} \) round as:

\[ E^k_i = E^{k-1}_i + \Delta E - E_{se} \]  

where, \( \Delta E \) is the energy harvested during the previous round, and \( E_{se} \) is the energy spent by the microcontroller for sensing and other miscellaneous operations.
We consider a dynamic link cost function given by the following equation:

\[
C_{i,j} = \begin{cases} 
\infty, & E_i^k < e_{i,j} \times K_i \\
e_{i,j}, & E_i^k \geq e_{i,j} \times K_i
\end{cases}
\]

(7)

where, \(K_i\) is the number of transmissions taking place at node \(i\). Note that the cost function would change after every packet received at the AP. This means that the routing tree must change per packet in a data gathering round. It follows that each data gathering round would require a different routing tree per node.

A step-wise protocol for implementing the proposed algorithm based on Dijkstra’s algorithm and the dynamic link cost function is given below:

For every data gathering round,

1. Calculate required energy for each link using equation (5) and previously gathered link state information.

2. Calculate available energy for each node in the network using equation (6). Initiate \(K\) for each node to 1.

3. Add a single node to the routing table.
   a) Compute link cost for each link using equation (7).
   b) Run Dijkstra’s algorithm until a new node is connected.
   c) Increment \(K\) for the nodes transmitting in the current iteration.

4. Repeat step 3 for all nodes to form a complete network.

5. Update the available energies at the end of the round.
The link cost changes within every data gathering round because of the energy harvesting constraint. For example, in a single round, a node might have enough energy to send its own packet but might deplete its accumulated energy and won’t be available to relay other nodes’ packets. Hence, in order to accommodate this behavior, we change the link cost as soon as a node transmits a packet. This dynamic link cost allows us to successfully construct a routing table without the possibility of errors. This is shown in Figure 14 where node 1 has enough accumulated energy to transmit its own packet as well as relay the packet from node 2. But it depletes its energy after two transmissions. Therefore, cost for the link between node 1 and the AP becomes $\infty$ for the third iteration forcing node 2 to send the relay packet directly to the AP. This protocol can be viewed as a mesh networking approach where the routing tree changes per iteration, hence the name ‘Dynamic Routing Trees’.
A possible drawback of this algorithm is the increased computation requirement at the AP. Although taking the abundant computational power and small number of nodes into account, this shouldn’t prove to be a major problem.
3.3 Performance Evaluation

3.3.1 Experimental Setup

The same setup explained in Section 2.3.1 - 2.3.3 with both on-body and off-body AP network architectures was used for the data gathering purposes. This setup is based on TI’s EZ430-RF2500T hardware platform. On-body AP architecture comprised of eight EDs and an on-body AP while off-body AP architecture comprised of five on-body EDs and an off-body AP with four antennas. The total of 3000 data gathering rounds were performed for each scenario. The purpose of this experiment was only to collect the RSSI values for all the links which would be used in the simulation of the proposed dynamic routing algorithm.

3.3.2 Energy Harvesting Model

There are many different theoretical models for assessing performance of energy harvesting methods in the literature. We used the energy model developed in [12] by Seyedi et al. In this model, time is divided into slots in which an energy harvester can either be in the active or inactive state. The energy harvesting process is characterized as a Markov chain. Whether a harvester board will harvest energy in a particular time slot or not depends on the previous state of that board. Transitional probabilities are given as $r$ and $w$, where $r$ is the probability of a harvester board to transient to inactive state given the current state is active and $w$ is the probability of a board to transient to active state given the current state is inactive. Accordingly, the probabilities that the system stays in the active or inactive states are given by $1 - r$ and $1 - w$, respectively. The steady state probability for a harvesting board to remain in active state is given by:
\[ \mu = \frac{w}{r + w} \quad (8) \]

It is assumed that there is a perfect battery attached to the harvesting board and there are no losses due to battery leakage. This battery can be implemented using a super capacitor. All the harvested energy is stored in this rechargeable battery and the capacity of the battery is infinite. This is a common assumption in the analysis of energy harvesting systems. Energy harvesting (or battery recharging) occurs only during the active time slots and the harvesting rate is defined as the power charging the battery and is noted as \( \rho_a \) W.

There are many sources of energy which can be used for harvesting purposes in WBAN systems. Prominent examples are ambient radio frequency, body heat, ambient light, solar energy (direct sunlight), body motion, ambient airflow etc. Out of these sources, we consider body heat, ambient light, solar energy and ambient airflow. We selected harvesting parameters of readily available energy harvesters for obtaining timely performance results. As harvesting technology improves, performance would improve accordingly.

### 3.3.3 Simulation Setup

Matlab was used as a tool to simulate the operation of the WBAN with energy harvesting. RSSI data gathered using the experimental setup was used to simulate the wireless propagation environment. Making use of this RSSI data and pre-known transmit powers, link state information was derived. This link state information was then used to run the protocol. Initial accumulated energy for all nodes was assumed to be 0. Simulations were
run for each of the above mentioned energy sources. Table 3 shows the harvesting rates for these sources as given in [20].

Table 3: Energy harvesting sources and their performance.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Harvesting Rate ($\rho_a$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Heat</td>
<td>$60 \mu W/cm^2$</td>
</tr>
<tr>
<td>Ambient Light (in office)</td>
<td>$100 \mu W/cm^2$</td>
</tr>
<tr>
<td>Direct Sunlight</td>
<td>$100 mW/cm^2$</td>
</tr>
<tr>
<td>Ambient Airflow</td>
<td>$1 mW/cm^2$</td>
</tr>
</tbody>
</table>

As previously explained, we use outage to evaluate performance instead of network lifetime. Outage is defined as the fraction of data gathering rounds where at least one node fails to transmit its packet all the way to the AP, i.e., there is no route from that node to the AP.

$$Outage = \frac{\#\ of\ rounds\ without\ full\ connectivity}{total\ \#\ of\ rounds} \quad (9)$$

Typical representative pairs of $r$ and $w$ were chosen for simulations for each energy source. To capture the strong positive time correlations in the physical processes behind energy harvesting, probabilities were chosen such that $r,w \leq 0.5$ [13]. To gauge the performance of the network (throughput), we varied the packet sizes from 1 byte to 200 bytes for body heat, ambient light and human motion scenarios and up to 500 bytes for solar energy scenario. Data gathering rounds occurred at a frequency of 1 Hz. These settings correspond to a typical physiological monitoring scenario where data is periodically sampled, stored and
sent in a transmission burst. A special \((r, w)\) pair with \(r = 0\) (always ON energy source) was taken into consideration for the body heat scenario because we can always harvest energy given a sufficient temperature gradient between the body and the ambient temperature. We assume 3cm x 3cm energy harvesting surface for both body heat and solar energy to represent a practical harvester. Based on the datasheets for EZ430-RF2500T and application notes provided by TI [21], we calculated \(E_{se}\) to be 6.444 \(\mu J\).
3.4 Results

Figure 15 and Figure 16 show outage as a function of data packet size for the case where body heat and ambient light are used as energy sources respectively. Both figures show a threshold effect. Below a threshold packet size, outage is almost 0 but increases rapidly as the data packet size increases beyond the threshold. If we assume an outage of 0.05 to be an acceptable value, then for body heat, in unfavorable harvesting conditions \((w = 0.5, r = 0.2)\), we can transmit a packet of 87 bytes. In the favorable body heat harvesting conditions where a sensing node continuously harvests energy (a sufficient temperature gradient exists always), this limit increases to 123 bytes/packet. Similarly, for ambient light, packet size limitation varies between 102 bytes for \(r, w = 0.5\) and 170 bytes for \(r = 0.1\) and \(w = 0.5\). These results are expected because as \(r\) increases, probability of a node remaining in active state decreases which directly translates to a decrease in the amount of harvested energy.

Figure 17 and Figure 18 present the results for off-body access point network architecture for body heat and ambient light energy sources, respectively. For body heat, data packet size values range from 131 bytes \((w = 0.5, r = 0.2)\) to 183 bytes \((w = 0.5, r = 0)\). Similarly, for ambient light, these values vary between 152 bytes \((w = 0.5, r = 0.5)\) and 200+ bytes \((w = 0.5, r = 0.1)\). We see the similar threshold effect in both the scenarios. The positive shift in the thresholds indicates the advantage of using the off-body AP with multiple antennas compared to the on-body AP.
Figure 15: Performance of the network with body heat as an energy source (on-body AP).

Figure 16: Performance of the network with ambient light as an energy source (on-body AP).
Figure 17: Performance of the network with body heat as an energy source (off-body AP).

Figure 18: Performance of the network with ambient light as an energy source (off-body AP).
Harvesting rate from the direct sunlight is much higher than body heat or ambient light. Therefore, as expected, we can transmit over 500 bytes/packet for an outage of 0.05. In case of ambient airflow, the results proved to be very similar to the ambient light case. This shows that for direct sunlight as energy source, outage is close to zero for all practical sizes of data packets.

The presented results are indicative to which application can be supported using which energy harvesting source. For example, a high data rate application such as ECG measurements (which requires a data rate of approx. 300 bytes/sec) cannot be implemented using the current harvesting techniques using body heat and ambient light. On the other hand, we can easily implement low data-rate applications such as body temperature measurements or heart rate measurements and motion detection even with low power harvesting methods using body heat or ambient light.
Chapter 4

Conclusions

4.1 Increasing Network Lifetime in Wireless Body Area Networks

Global routing using Dijkstra’s algorithm [22] was augmented with a novel cost function specialized for balancing energy consumption at the nodes and increasing NL in WBANs. The cost function was designed to avoid relaying through nodes which spent more accumulated energy than others. As a result, each node’s link costs are dynamically changed to balance energy use in the network. The algorithm was evaluated through real-time implementation in dynamic indoor environments and computer simulations using real channel RSSI data. Two network architectures were evaluated: on-body AP and off-body AP with multiple antennas. Results for the on-body AP network architecture depicted efficient balancing of energy consumption across nodes in the network and an average increase in NL of 40%. The corresponding average increase in EpB was a moderate 0.4 dB. Results for the off-body AP network architecture depicted an increase in NL of 25%, 22%, 20% and 16% for one, two, three and four antennas, respectively. The increase in EpB across all configurations was a marginal 0.025 dB.

Network connectivity analysis revealed a threshold effect. It was shown for all network architectures that if the ratio between maximum transmitted power and target RSSI is higher than about 65 dB, then Dijkstra’s algorithm results in full connectivity almost all the time. If the ratio is below the threshold, network connectivity is severely hindered. This result holds for any link cost function being used.
The proposed global routing approach allows WBANs to operate efficiently for longer periods of time before recharging of batteries is required. Due to the balancing of energy use in the network, devices would deplete their energy sources at approximately the same time. This is highly beneficial since all devices can be recharged or replaced simultaneously, instead of constantly monitoring and servicing individual devices. Since NL is increased as well, depletion of batteries is less frequent, decreasing maintenance requirements even further. The moderate increase in $E_pB$ indicates that the wearability of the WBAN is unhindered. [23].
4.2 Dynamic Routing Trees with Energy Harvesting Constraint

We proposed a novel global routing protocol based on Dijkstra’s algorithm where link costs and thus routing trees dynamically change during each data gathering round based on the available energy at each node due to energy harvesting. The dynamic cost function was fashioned to ensure efficient routing through nodes with enough available energy. Network sustainability was demonstrated using outage as a metric of performance as function of required data traffic in the network. Results show that while the low data-rate applications can be implemented using the current energy harvesting technology, high data-rate applications warrant further improvements in harvesting methods.
4.3 Future Work

During this work, actual energy usage was never used. For the NL improvement approach, the protocol optimized the energy use solely with regard to the transmission powers required to traverse the links while maintaining acceptable level of reliability. For the energy harvesting approach, we determine energy use by referring to the data sheet and application notes. A future modification could implement the measurement of actual battery level status. This would be useful when dealing with different platforms with different battery sizes and various energy harvesting methods.

Another future modification would include the integration of the actual energy harvesting board in the experimental setup.
References


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The dream begins with a teacher who believes in you, who tugs and pushes and leads you to the next plateau, sometimes poking you with a sharp stick called “truth”. – Dan Rather.

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