

Dynamic Routing Trees with Energy Harvesting Constraints for Wireless Body Area Networks

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ABSTRACT

Routing under energy harvesting constraints is considered. A routing protocol based on Dijkstra's global routing algorithm is proposed and evaluated. The protocol dynamically modifies routing trees based on available energy accumulated through energy harvesting. Channel-state information is gathered in typical indoor environments using two experimental setups; one with eight nodes and on-body access point and the other with five nodes and an off-body access point equipped with four antennas. Collected data is used to evaluate network connectivity in conjuncture with throughput using computer simulations and models of energy harvesting. Energy sources of body heat, ambient light, direct sunlight and ambient airflow are considered. A threshold effect is observed for all energy sources and both experimental setups; if the throughput is set below threshold value the network is reliably connected. The thresholds are shown to be higher than 500 bytes/sec for direct sunlight and within 80-190 bytes/sec for other energy sources when using currently available energy harvesting technology.

Categories and Subject Descriptors

C.2.1 [Computer-Communication Networks]: Network Architecture and Design – *Routing Protocols*.

General Terms

Algorithms, Experimentation.

Keywords

Body Area Networks, Energy Harvesting, Routing Protocols.

1. INTRODUCTION

Applications of *Wireless Body Area Networks* (WBANs), from monitoring vital signs of patients to improving performance of athletes, are receiving increased attention by academia and industry. Round-the-clock observation of a person's health, ease of use, low energy consumption compared to traditional methods, low-cost and size of the sensor nodes are just a few of the benefits of WBANs.

Despite these advantages, one of the most significant constraints on the large scale adoption of WBANs stems from their limited

energy source. Unlike *Wireless Sensor Networks* (WSNs), all the nodes in a WBAN are critical and non-redundant; depending on the application, failure of a single node might prove to be catastrophic. In order to reduce the size of the wearable or implantable nodes, reduction of battery size is required. In WBANs, communication over wireless channels consumes the majority of the power compared to sensing or computation operations. Hence, smaller batteries limit the capabilities of sensor nodes to achieve reliable communications in the presence of fading channels and body shadowing. Furthermore, progress in computing, communications and battery technology are not on par. The result is that the smaller one makes a sensor node, the less time it has to function properly before its battery is depleted. Batteries have to be recharged or replaced periodically. This maintenance task proves to be a major obstacle to the widespread use of WBANs.

Energy harvesting methods could present the solution for long term operation of WBANs without the need for recharging batteries. Examples of energy harvesters include 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 [1]-[4]. For example, in [1] Ho et. al. propose stationary and generalized Markovian models to represent harvested energy. In another example, Seyedi et. al. [2]-[3] and Ventura et. al. [4] present a combined model for energy harvesting and data traffic.

In our previous works [5,6], we presented a global routing algorithm based on Dijkstra's algorithm with a specialized link cost function enabling efficient distributed use of energy by balancing energy consumption of all nodes across the network. The result is an increase in network lifetime for battery operated nodes. In the framework of a sustainable energy harvesting solution, there is no pre-charged battery and the network is expected to operate perpetually.

Network Lifetime is defined as the time it takes a single node in a network to deplete its battery from network startup. 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 accumulated energy. Due to this reason, network lifetime no longer applies as a reliable metric to measure network performance. Instead, network sustainability should be quantified using *Outage* as a performance metric which evaluates

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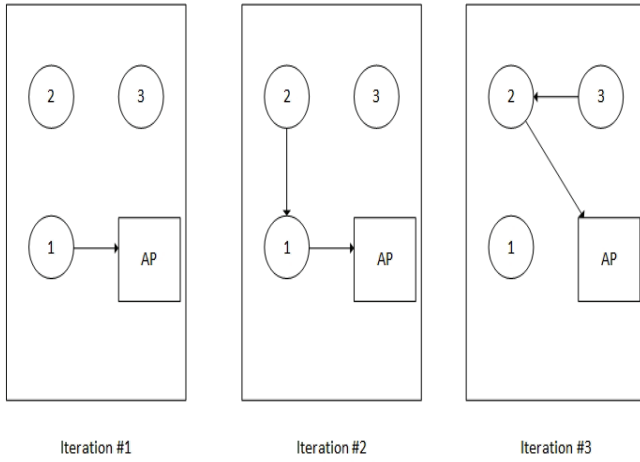


Fig. 1 – An example of the proposed algorithm

the relative number of events where the entire network cannot be connected using proper links.

Many past works addressed routing for WSNs under energy harvesting constraints [7-11]. For example, in [7] 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 [8], 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 limited attention in the past despite their differentiating attributes and the clear benefits of powering WBANs using energy harvesting.

WSNs typically comprise hundreds to thousands of nodes. Because of the sheer complexity and huge overhead on the transmission of link-state information, global routing algorithms are typically avoided. On the other hand, WBANs consist of up to ~10 nodes and are spatially distributed close to each other. This makes global routing algorithms a viable option as was proven in the real-time implementation of [6].

WBAN's typical architecture is a star topology. In this architecture, the AP is a central unit that acts as a master while the *End Devices* (EDs) are connected to it and act as slave nodes. The AP could also be a gateway for remote access. Our network architecture consists of such AP and EDs where the goal is to periodically send packets from all EDs to AP. The AP is assumed to have substantial computation power as well as a large rechargeable energy source. The framework described above fits well with continuous physiological monitoring applications.

The AP gathers link-state information from all the nodes and sends a beacon at the start of each data gathering round. It runs the algorithm and computes the routes for the network. These routes are sent to all the nodes via the beacon packet. Each ED, in turn, receives the routing information and accordingly sends the packets to the destination node.

In the traditional applications of Dijkstra's algorithm [12], the cost of each link between nodes is the power required to transmit a packet with reliable performance level. The result is a routing tree optimizing for the overall accumulated energy consumption in the network. We look to optimize routing with regard to energy harvesting which means that the time-varying energy stored at each node must be considered in the routing decisions.

In this contribution, 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. In contradistinction to the protocol we reported in [5,6], the proposed protocol generates dynamic routing trees specifically addressing the varying energy levels available at each node due to the dynamic nature of energy harvesting. 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 two experimental setups to gather communication channel data; on-body *Access Point* (AP) with a single antenna and off-body AP with 4 antennas. The on-body AP corresponds to a fully contained network placed on the body, where the off-body AP corresponds to a scenario where infrastructure is used to support data collection from nodes placed on the body (such as that available in hospitals or residential areas). Collected data are used in computer implementations of the proposed protocol coupled with the energy harvesting model to estimate the reliability of connectivity as function of throughput.

2. PROPOSED PROTOCOL

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 packet reception. Thus, we calculate the total energy required to receive and transmit a packet as:

$$e_{i,j} = t_p * P_{R_i} + t_p * P_{T_{i,j}} \quad (1)$$

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 reliably transmit a packet from node i to node j , respectively.

The transmitted power is set to transverse the link according to a predefined level of reliability (link budget). Using a simple power control mechanism we have:

$$P_{T_{i,j}} = \frac{RSSI_T}{\alpha_{i,j}}, \quad (2)$$

where $\alpha_{i,j}$ is the channel fading attenuation across the link and $RSSI_T$ is the target *Received Signal Strength Indicator* (RSSI) at the receiver required to obtained a predefined level of reliability.

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

$$E_i^k = E_i^{k-1} + \Delta E - E_{se} \quad (3)$$

where, ΔE is the energy harvested since the previous round, and E_{se} is the energy spent by the microcontroller for sensing and all operations other than communication.

We propose a dynamic link cost function given by the following equation:

$$C_{i,j} = \begin{cases} \infty, & E_i^k < e_{i,j} * K_i \\ e_{i,j}, & E_i^k \geq e_{i,j} * K_i \end{cases} \quad (4)$$

where K_i is the number of transmissions by node i (its own data as well as relayed data) accumulated during a data-gathering round. The cost is infinity (no link) when there isn't enough energy to

support reliable transmission. 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 (1) and previously gathered link-state information.
2. Calculate available energy for each node in the network using equation (3).
3. Initialize K_i for each node to 1.
4. Add a single node to the routing table.
 - a) Compute link cost for each link using equation (4).
 - b) Run Dijkstra's algorithm until a new node is connected.
 - c) Increment K_i of all nodes transmitting in the current iteration.
5. Repeat step 4 for all nodes to form a complete network.
6. Update the available energies E_i^k of all nodes.

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. An example of the routing paths using the dynamic link cost function is demonstrated in Fig. 1: 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 ∞ for the third iteration forcing node 2 to send the relay packet directly to the AP.

Note that Dijkstra's algorithm is not used to construct a single routing tree connecting all nodes to the AP. Instead, it is reset per iteration of Step 4 and runs until a single path is found to AP from a previously unconnected node. Once a path is found from a node to AP, it facilitated the next iteration of Step 4 as a potential relay for the next node. Each iteration in Fig. 1 represents a path found to a new node in the network following Step 4.

A possible drawback of the proposed 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.

2.1 Protocol Overheads

The overhead on communicating derived paths from AP to the nodes is limited to the single beacon packet send by the AP. Since we assume the AP has abundant power, there is no overhead on the nodes' energy other than receiving the beacon which we account for in (1). For each path from node to AP, each node needs to know the ID of the node to which it should transmit or relay, and the number of paths is the number of nodes. Assuming each node ID is 4 bits long, we require no more than 32 and 13 bytes for a network with 8 and 5 nodes respectively.

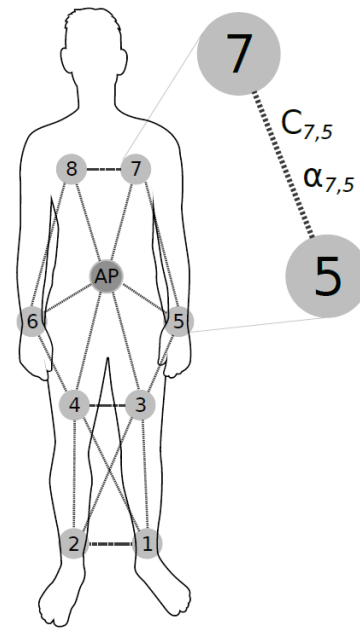


Fig. 2 – Network architecture for on-body AP

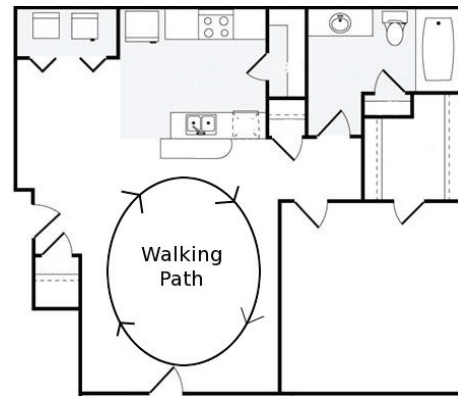


Fig. 3 –Indoor experimental setup (on-body AP)

When considering the overhead on gathering link-state information at the AP, once must make further assumption with regard to the dynamic wireless channel. Assuming a typical indoor environment corresponding to a Doppler spread of $\sim 5\text{Hz}$, we expect to require new link-state information at the AP every $\sim 200\text{ms}$. Link-state information traffic is proportional to the square number of nodes. Assuming half a byte is used to represent 16 levels of channel attenuation as channel-state information, then for our experimental setups comprising 5 nodes for on-body AP and 8 nodes for off-body AP, the overhead is ~ 3 bytes/sec and ~ 6 bytes/sec for each setup respectively.

The aforementioned overheads are much lower than the obtained throughput as would be shown in a later section. This is a vivid example of why global routing algorithms are feasible for WBANs. We assume link-state information is sent in the same packet payload data and comprises part of the throughput. The results depicted in a later section present much higher throughputs rendering this overhead fairly small.

Energy Source	Harvesting Rate (ρ_a)
Body Heat	$60 \mu W/cm^2$
Ambient Light (in office)	$100 \mu W/cm^2$
Direct Sunlight	$100 mW/cm^2$
Ambient Airflow	$1 mW/cm^2$

Table 1. Energy harvesting sources and their performance.

3. PERFORMANCE EVALUATION

3.1 Experimental Setups

In order to capture typical link-state information of wireless channels experienced by a WBAN, we used an ultra-low power hardware platform EZ430-RF2500T developed by Texas Instruments (TI). This platform consists of MSP430F2274 micro-controller and CC-2500 2.4GHz transceiver. For wireless communication between devices, CC-2500 radio is set up to run at 250kbps while the AP is connected to the host computer via a USB to Serial link running at 115200 BAUD. In this case, for high computational power, the AP is only acting as a bridge between the network and the host computer. To imitate an AP with a large energy source, AP is powered via USB connection while all the EDs are battery powered. All EDs and the AP were placed on a 170cm, 70kg male subject and a laptop computer was carried in a backpack (see Fig. 2). The subject walked around in a domestic environment as shown in Fig. 3 to gather the RSSI data.

For the on-body AP architecture, a total of 8 devices are employed as EDs while 1 device is dedicated to be an AP. For the off-body AP architecture, 5 EDs were placed on body and the AP was placed off body with three devices acting as additional antennas for the AP. See Fig. 4 and Fig. 5 for setup. The purpose of these setups was to collect the RSSI values for all the links to be used in the computer simulation of the proposed dynamic routing algorithm. A total of 3000 link-state gathering rounds were performed for each network architecture at a rate of a single round per second.

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 [2] by Seyedi et al. In this model, time is divided into slots in which an energy harvester can either be in the active (energy is harvested) or inactive (no energy is harvested) state. The energy harvesting process is modeled using 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:

$$\mu = \frac{w}{r+w} \quad (5)$$

It is assumed that there is a perfect battery attached to the harvesting board and there are no losses due to battery leakage. Such a 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

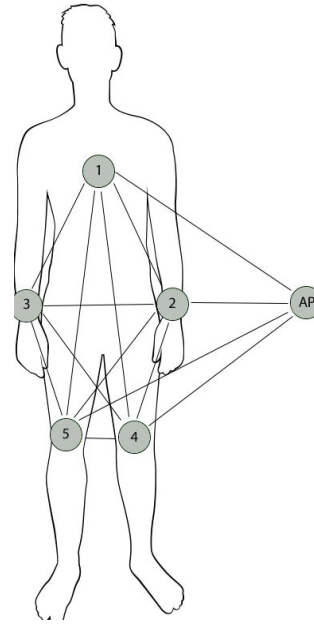


Fig. 4 – Network architecture off-body AP

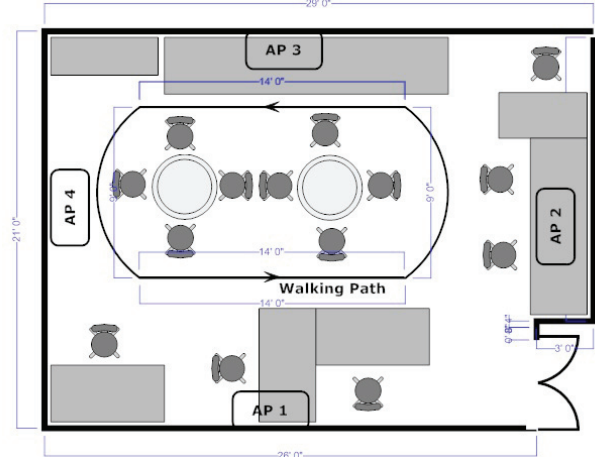


Fig. 5 – Indoor experiment setup (off-body AP)

battery recharging) occurs only during the active time slots. The harvesting rate is defined as the power charging the battery and is noted as ρ_a (in Watts).

There are many sources of energy which can be used for harvesting purposes in WBAN systems: 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 Simulation Setup

Matlab was used to simulate the operation of the WBAN with energy harvesting and implement the routing protocol. 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. Link-state information in the form of channel attenuations $\alpha_{i,j}$ was then used to run the protocol with power

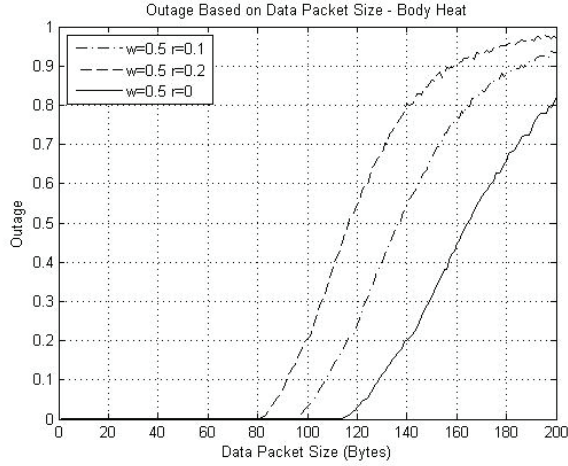


Fig. 6 – Performance using body heat (on-body AP)

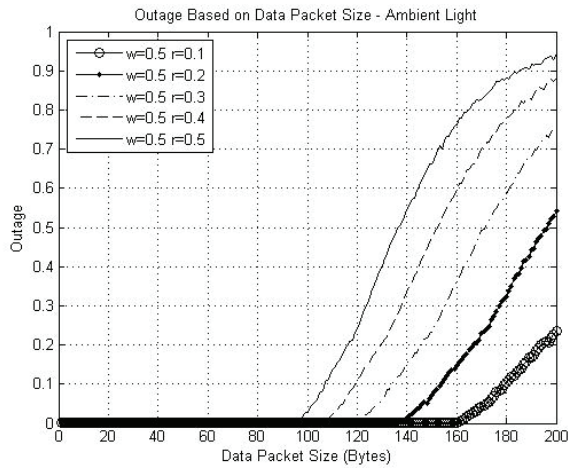


Fig. 7 – Performance using ambient light (on-body AP)

control set to achieve target RSSI of $RSSI_T = -65dBm$. Initial accumulated energy for all nodes was assumed to be 0. Simulations were run for each of the above mentioned energy sources. Table 1 shows the harvesting rates for these sources as given in [13].

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.

$$Outage = \frac{\# \text{ of rounds without full connectivity}}{\text{total \# of rounds}} \quad (6)$$

Typical representative pairs of r and w were chosen for simulations of each energy source. To capture the strong positive time correlations in the physical processes behind energy harvesting, probabilities were chosen such that $r, w \leq 0.5$ [3]. 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

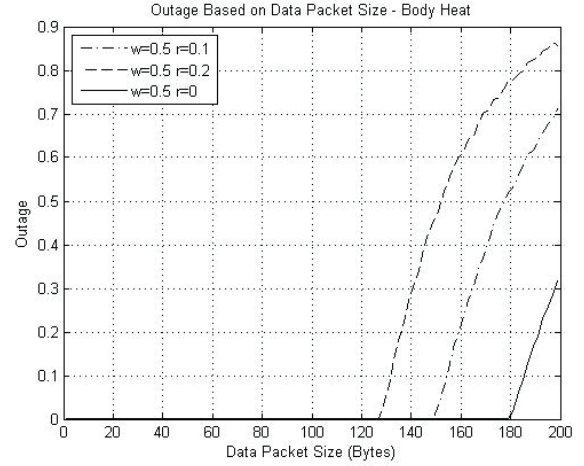


Fig. 8 – Performance using body heat (Off-body AP)

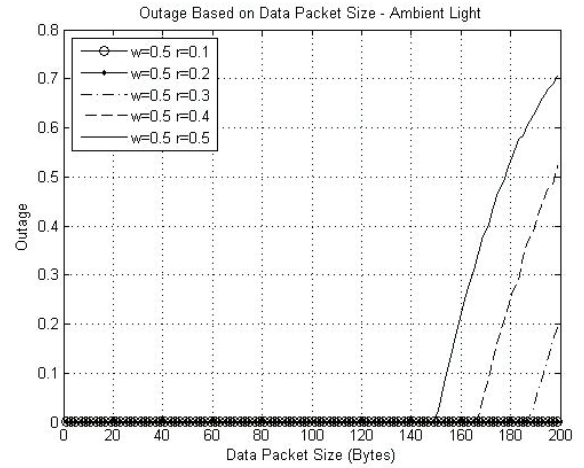


Fig. 9 – Performance using ambient light (Off-body AP)

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 [14], we calculated E_{se} to be $6.444 \mu J$.

4. Results

Fig. 6 and Fig. 7 show outage as a function of data packet size for the case where body heat and ambient light are used as energy sources respectively for the on-body AP architecture. 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), the threshold 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.

Fig. 8 and Fig. 9 present the results for the off-body AP architecture for body heat and ambient light 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 as for the on-body AP architecture. The positive shift in the thresholds indicates the advantage of using the off-body AP with multiple antennas compared to the on-body AP

Harvesting rate from the direct sunlight is much larger 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. Figures are omitted for the sake of brevity.

The presented results are useful for determining which application can be supported using current state-of-the-art energy harvesting capabilities. For example, most applications requiring motion data from accelerometers (gait analysis, fall detection, etc.) can be supported given a throughput of 80-180 Bytes/Sec which is supported using body heat and ambient light. Note that high data rate applications such as ECG measurements (requiring a data rate of approx. 300 bytes/sec) are close at hand. Moderate improvements in energy harvesting rates presented in Tab. 1 would allow harvesters to reliably support high data rate applications using the proposed routing protocol.

5. CONCLUSION

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 a 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. Future work includes the integration of energy harvesters into our experimental setup and accurate battery level measurement techniques.

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