A Modified Dijkstra's Routing Algorithm for Increasing Network Lifetime in Wireless Body Area Networks

Gill R. Tsouri
Communications Laboratory
Rochester Institute of Technology
Rochester, NY USA
+001-585-6452
grteee@rit.edu

Alvaro Prieto
Communications Laboratory
Rochester Institute of Technology
Rochester, NY USA
+001-585-6452
axp8664@rit.edu

Nikhil Argade
Communications Laboratory
Rochester Institute of Technology
Rochester, NY USA
+001-585-6452
naa8450@rit.edu

ABSTRACT
Dijkstra's routing algorithm is augmented with a novel link cost function designed to increase network lifetime by balancing energy consumption of nodes in the network. Performance is evaluated using a hardware experimental setup comprising 8 nodes and an access point placed on the body. The setup is used for real-time experiments implementing the routing algorithm in a residential environment. Results demonstrate efficient balancing of energy consumption across all nodes in the network and an average increase of 40% in network lifetime.

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

General Terms
Algorithms, Experimentation.

Keywords
Wireless Body Area Networks, Network Lifetime.

1. INTRODUCTION
Power-efficient routing for *Wireless Sensor Networks* (WSNs) received much attention in the past. However, porting routing solutions from WSNs to WBANs is problematic due the different network architectures and operating conditions. In WSNs hundreds to thousands of sensor-nodes cover large areas and offer considerable degree of redundancy. The task of monitoring the environment does not have to involve all sensor-nodes all the time. This setting brings about routing solutions which rely on dynamic network configurations involving many hops from sensor-node to sync. WBANs cover an area limited to the human body and offer no redundancy. Data must be collected reliably from all nodes placed on the body, while addressing unique signal propagation conditions not present in WSNs such as body shadowing and mobility of sensors. It follows that efficient routing solutions should be designed specifically for WBANs.

Nodes in a *Wireless Body Area Networks* (WBANs) are required to operate under strict resource constraints. Specifically, power for transmitting data from nodes to *Access Point* (AP) must be preserved so that battery life is extended and recharging is infrequent as possible. An efficient routing protocol is crucial for extending battery life. WBANs operate in a unique signal propagation environment including body shadowing, user mobility and short distance links. It follows that efficient routing protocols should be designed specifically for WBANs.

Several routing protocols were designed in the past specifically for WBANs, some examples follow. Latre et al. developed the CICADA protocol, which consists of 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 Ehyaie et al. [3]. It consists of using dedicated, non-sensing, relay nodes with larger power sources. While this method increases the network lifetime, it requires additional dedicated hardware. This method was further improved by Maskooki et al. in [4] where body movement was utilized to achieve network lifetime improvement. Nabi et al. proposed a similar store-and-forward method [5], where nodes keep track of neighbors and utilize power control to consume minimal transmit power while maintaining a preset link quality. A slightly different approach was used by Guo et al [6] with a minimum energy forwarding protocol utilizing *Automatic Repeat Request* (ARR). Relaying was also investigated by Tsouri et al [7] with a focus on creeping waves wrapping the body. Recent work by Quwaider et al. moves in the direction of developing a routing method based on the body posture. In [8] they proposed a delay tolerant routing protocol and also compared it with various routing schemes in delay tolerant networks. Finally, Razzaque et al. proposed a data-centric multi-objective QoS-Aware routing protocol (DMQoS) [9]. 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 network lifetime.

BODYNETS 2012, September 24-26, Oslo, Norway
Copyright © 2012 ICST
DOI 10.4108/icst.bodynets.2012.249929

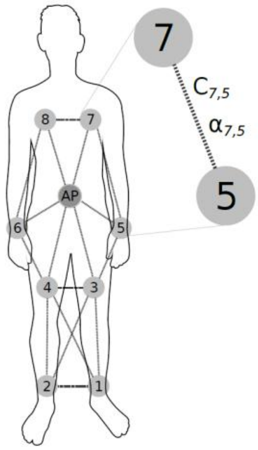

Fig. 1 – Network architecture for experimental setup

Global routing algorithms are usually avoided in *Wireless Sensor Networks* (WSNs) where hundreds to thousands of nodes comprise the network and cover great distances. The exponentially increasing complexity for an increasing number of nodes and the need to exchange large volumes of link-state information make such algorithms prohibitive. Unlike WSNs, a common network architecture used in WBANs is a star-topology, where an AP is placed on the body and the nodes are distributed no more than 1.5m away from the AP. The AP is typically a PDA-like device equipped with substantial computation power and memory compared to the simpler distributed nodes. This asymmetry between AP and nodes extends to their functionality as well: the AP is typically the coordinator of all network activities (master node), and the nodes' functionality is kept as simple as possible to preserve resources (slave nodes). The asymmetric star-topology architecture coupled with the low number of nodes (typically on the order of 10) makes global routing protocols a viable option for collecting data at the AP. Implementing the global routing algorithm would require gathering link-state information from nodes to AP, optimizing all the routing paths at the AP and sending routing instructions from AP to all nodes.

In this contribution, we propose to use a global routing protocol based on Dijkstra's algorithm [10] with a novel link cost function specialized for increasing network lifetime in WBANs. Network lifetime is defined as the time it takes a single component of the network to deplete its power source from network startup. Given the asymmetric WBAN topology, we consider the time it takes a single node to deplete its battery. We view the nodes' batteries as a distributed network resource. It follows that no single node should deplete its battery while there are other nodes with abundant battery power. Our proposed link cost function is designed to assure that all nodes deplete their power at the same time. To demonstrate the feasibility of the proposed global routing protocol, a real-time hardware implementation is used in a real-world residential scenario. Performance is compared between traditional Dijkstra's algorithm and the one augmented with the proposed link cost function. Results show that the augmented algorithm balances the energy consumption across the nodes and increases network lifetime.

2. PROPOSED LINK COST FUNCTION

When applying a conventional approach to power-efficient routing, the power required to transverse a link is used as the link cost. As a result the routing path from each node to AP is the

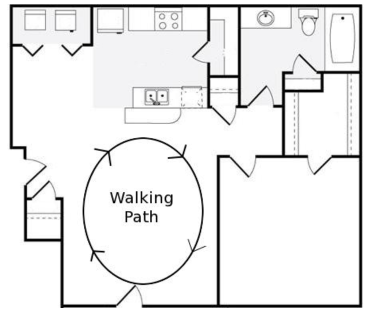

Fig. 2 – Experimental setups environment

one which requires the least amount of accumulated energy across the nodes in the path. A probable outcome would be that a single node would deplete its power source before all others, thereby ending network lifetime while other nodes still have energy to use. In the proposed cost function, the accumulated energy used by each node is factored in the link cost. If a node used more energy than the other nodes, its use as a relay for other nodes will be discouraged by increasing costs of its outgoing links.

As in any global routing protocol, link-cost information is periodically gathered at the AP in the form of channel attenuation for each link in the network, and all routing calculations are performed at the AP. Each node's normalized energy used thus far is calculated as shown in eq. (2), where j denotes the node ID, i is the current polling round, $\alpha_{j,k}$ is the channel attenuation for the selected link, and $RSSI^T$ is a predefined global target RSSI needed for a required performance level.

$$\alpha_{j,k} = \frac{RSSI}{P_{tx}} \tag{1}$$

$$E^j_{(i)} = E^j_{(i-1)} + \frac{RSSI^T}{\alpha} \tag{2}$$

The accumulated energy used is incremented by the energy used to transmit a single packet while maintaining $RSSI^T$. The channel attenuation for the selected link between node j and node k, $\alpha_{j,k}$, is noted in eq. (1), where RSSI is the received power measured by node k and Ptx is the transmitted power used by node j. Note that Ptx as defined in eq. (1) is a simple power control mechanism ensuring use of minimum required power to transverse a single link while meeting target RSSI. The link cost between node j and node k, Cj,k, is computed by calculating the energy that would be used by the node if that link is selected, and multiplying it by a cost factor as depicted in eq. (3).

$$C^i_{j,k} = \frac{RSSI^T}{\alpha_{j,k}} \times \left(\frac{1 + \left(\frac{E^k_i}{E^{min}}\right)^M}{2} \right) \tag{3}$$

The cost factor is derived by dividing the accumulated energy used by the destination node, E^k, with the minimum accumulated energy across all nodes, E^{min}. This ratio is then raised to the power of M>=0 , which determines how strong the effect will be. If a node's energy is much greater than the current minimum, it will be avoided as a relay for other nodes, because its outgoing link cost would be very high. The cost factor is normalized so when M=0, it reduces to the conventional cost function which is the power required to transverse the link regardless of accumulated energy use across nodes in the network.

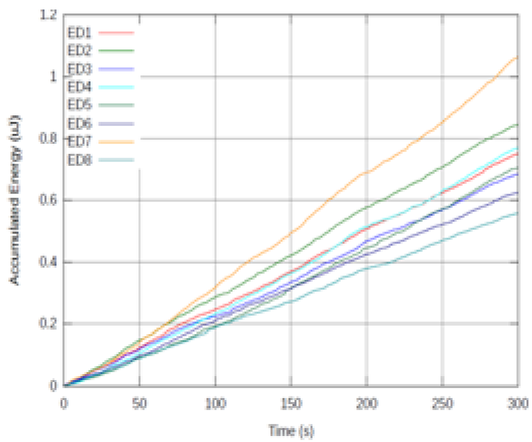

Fig. 3 – Accumulated energy spent by each end device over time for the reference system (*M*=0).

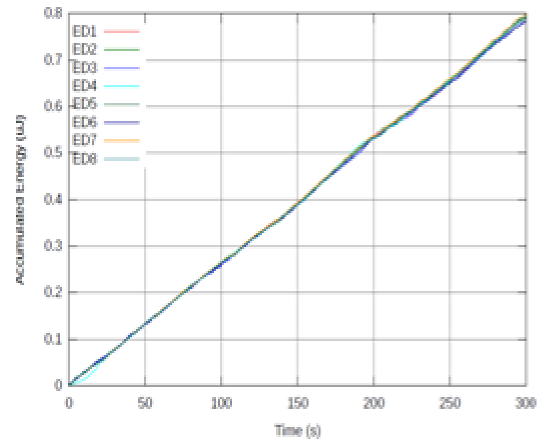

Fig. 4 – Accumulated energy spent by each end device over time for the proposed algorithm using *M*=100.

3. PERFORMANCE EVALUATION

The proposed protocol is compared to a reference system using a conventional link cost function, where the link cost is the required power to meet a link with the desired $RSSI^T$ (*M*=0 in eq. (3)). Network lifetime is evaluated by measuring the time it takes any node's accumulated normalized energy to cross an arbitrary threshold. The threshold represents the amount of energy stored in a device battery. In all experiments the network was comprised of an AP and 8 *End Devices* (EDs) acting as nodes. Positioning of EDs and AP along with link-cost notation is depicted in Fig. 1.

The experimental setup was based on a hardware platform with *Texas Instruments* (TI) EZ430-RF2500. This device includes both an MSP430F2274 microcontroller along with a CC2500 2.4GHz transceiver. The CC2500 is configured to run at 250kbps. A single device, labeled as AP, is connected via a USB to Serial link, running at 115200 BAUD, to the host computer. All other devices, labeled as EDs, are battery powered. In this implementation, the AP acts only as a bridge between the host and the end devices. All routing and power control calculations are done on the host. The host is a laptop computer with an Intel(R) Core(TM) i5-2410M CPU and 4GB of RAM. Eight EDs were placed on a 170cm, 70kg male subject as shown in Fig. 1. The host computer was carried in a backpack and connected to the AP via a USB cable. The target RSSI was arbitrarily chosen to be −60dBm.

The experimental setup was used to implement the routing algorithm in real-time using various values of *M*. The subject walked around a room depicted in Fig. 2, while the following procedure was carried out at a rate of 5Hz:

1: AP sends 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 sends a table with the RSSI data from all devices.

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 eq. (1-3).

5: The host sends both routing and power tables back to the AP so that a new cycle may begin.

To minimize the number of control packets being transmitted, the EDs are not individually polled. The only control packet sent is the synchronization beacon, which also carries the routing and power tables. Once the EDs are synchronized, they transmit their data on a pre-defined schedule to avoid collisions. Each ED has a network ID. The time between synchronization packets is divided into time-slots, where each slot is used by a single ED. The time slot used depends on the network ID of each device. This avoids the need for scheduling during runtime.

The routing table is a simple array which lists the destination for each ED packet. The ED does not need to know the entire route its packets will take, but only the next device in the path. Similarly, the power table lists the transmit power setting each device needs to use. The size of these tables is directly proportional to the number of devices in the network.

4. Results

Fig. 3 presents results from a 5 minutes real-time run using the reference system (*M*=0). Fig. 4 presents the same real-time run using the proposed cost function with *M* =100. The accumulated energy of each ED is presented as a function of time. Note that at the end of the 5 minute sampling run of the reference system, the device which consumed the most power was ED7 with approximately 1.06 µJ and would be depleted of its power source before all other EDs. On the other hand, with *M* = 100, all EDs consume energy at the same rate and end up with less than 0.81 µJ each. It is clear that the reference system consumed less overall power (6 µJ) than the proposed system (6.31µJ). This is expected, due to the fact that the new cost function specifically avoids the most efficient path for a specific node in favor of the most efficient path for balancing energy across all nodes in the network. While more energy is consumed overall, no single ED consumes much more energy than others and it is expected that all EDs would deplete their power source at the same time. In the reference system, when ED7 depletes its energy source, there is a significant amount of energy left unused in the network. However, when an ED depletes its power source in the proposed system, there would be almost no energy left in the network. This results in a network lifetime improvement. For example, assuming all EDs have a power source capable of supplying an accumulated energy of 0.625 µJ, the reference system (*M* =0) would last for 175 seconds (until 0.625 µJ are spent by ED7), while the proposed system (*M* =100) would last

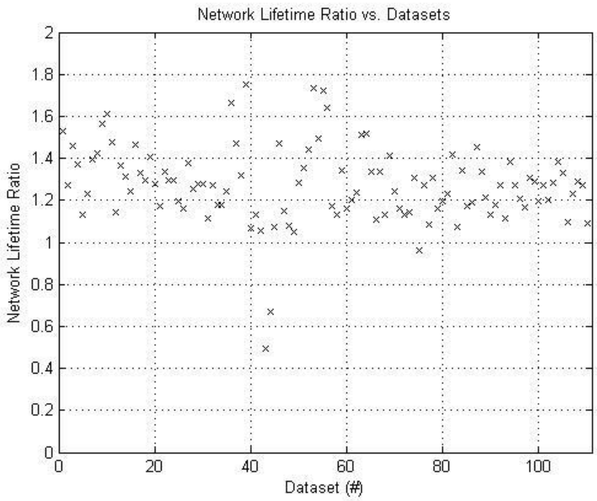

Fig. 5 – Improvement in Network Lifetime for *M*=100 vs. *M*=0.

for 240 seconds (until 0.625 μJ are spent by all EDs almost simultaneously).

Fig. 5 presents results from a more comprehensive real-time run taken over 37 minutes. The accumulated energy data was processed to evaluate the ratio between network lifetime for *M*=100 and *M*=0. The recorded data was partitioned into groups of 100 consecutive routing cycles (each group spans 20 seconds). We first found the average energy spent per routing cycle for each group of cycles by taking the total energy spent across all nodes across the group cycles and dividing it by the number of cycles in the group. For finding the network lifetime ratio per group, the battery energy was defined to be 40 times the average energy per cycle. This is equivalent to assuming that each ED would be able to sustain an average of 40 routing rounds during network lifetime. The network lifetime was then extracted by finding the number of routing rounds it took a single ED to accumulate energy equal to the battery energy. This provides the network lifetime normalized to the routing cycle time. The result for *M*=100 was divided with the result for *M*=0, providing the network lifetime ratio. From Fig. 5, it is evident that network lifetime was improved for all groups of 112 groups of 100 routing rounds except 3. The average improvement ratio is 1.4 meaning that on average network lifetime was increased by 40%.

5. DISCUSSION

The proposed link cost function allows WBANs to run efficiently for longer periods of time. WBANs requiring all devices to be active in order to function will greatly benefit from this routing method. Due to the balancing of energy use in the network, devices will deplete their energy sources at approximately the same time. This offers an additional benefit when considering maintenance of the network as all devices can be recharged or replaced simultaneously, instead of constantly monitoring and replacing individual devices.

In its current form, the protocol is optimizing power use solely with regard to the transmission power required to transverse the wireless link. A future modification would make use of actual battery status in the algorithm. This would allow devices with different power sources and power requirements to be addressed in the energy balancing process.

An additional avenue for future research is to find the optimal value for *M* in the proposed cost function. Other cost functions could be considered as well. Finally, the ability of the algorithm to compensate for nodes leaving and entering the network would be evaluated (node failures, dynamic networks, etc.).

6. CONCLUSION

Global routing using Dijkstra’s algorithm was augmented with a novel cost function specialized for increasing network lifetime in WBANs. The cost function was designed to avoid relaying through nodes which spent more accumulated energy than others. As a result, each link costs are dynamically set to balance energy use in the network. The algorithm was evaluated through real-time implementation in a dynamic residential environment. Results depicted balancing of energy consumption across nodes in the network and an average increase of 40% in network lifetime.

7. REFERENCES

[1] B. Latre , B. Braem , I. Moerman , C. Blondia , E. Reusens , W. Joseph and P. Demeester "A low-delay protocol for multi-hop wireless body area networks, " *Proc. 4th Int. Conf., MobiQuitous*, pp.1-8, 2007.

[2] M. Quwaider and S. Biswas, "On-body packet routing algorithms for body sensor networks", *Proc. 1st Int. Conf. on Networks & Communications*, pp. 171–177, 2009.

[3] A. Ehyaie , M. Hashemi and P. Khadivi "Using relay network to increase lifetime in wireless body area sensor networks", *Proc. IEEE Int. Symp. World Wireless, Mobile Multimedia Netw. Workshops*, pp.1 -6, 2009

[4] A. Maskooki, C. B. Soh, E. Gunawan and K. S. Low, "Opportunistic Routing for Body Area Network," *Proc. 1st IEEE International Workshop on Consumer e-Health Platforms, Services and Applications*, pp. 237-241, 2011.

[5] M. Nabi, T. Basten, M. Geilen, M. Blagojevic and T. Hendriks, "A Robust Protocol Stack for Multi-Hop Wireless Body Area Networks with Transmit Power Adaptation, " *Proc. 7th Int. Conf. on Body Area Networks*, 2010.

[6] C. Guo, R. V. Prasad and M. Jacobsson, "Packet Forwarding with Minimum Energy Consumption in Body Area Sensor Networks," *Proc. IEEE 7th Int. Consumer Communications and Networking Conference*, pp.1-6, 2010.

[7] G. R. Tsouri, A. E. Sapio and J. Wilczewski, “An Investigation Into Relaying of Creeping Waves for Reliable Low-Power Body Sensor Networking”, *IEEE Transactions on Biomedical Circuits and Systems*, Aug. 2011.

[8] M. Quwaider, M. Taghizadeh and S. Biswas, “Protocol Modeling for On-body Delay Tolerant Routing in Wearable Sensor Networks”, *Proc. 2nd Int. Conference on Information and Communication Systems*, May 2011.

[9] M. A. Razzaque, C. S. Hong and S. Lee, “Data-Centric Multiobjective QoS-Aware Routing Protocol for Body Sensor Networks”, *Sensors*, vol. 11, pp. 917-937, 2011.

[10] E. W. Dijkstra. “A Note on Two Problems in Connexion with Graphs”, *Numerische Mathematik*, 1(1):269–271, December 1959.