Demonstrating On-demand Listening and Data Forwarding in Wireless Body Area Networks

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***Abstract*—Adaptation of the network architecture through on-demand data forwarding is an efficient mechanism to provide robustness against long outages in WBANs. We developed an experimental testbed that provides online observation of the network behavior for different data propagation approaches in WBANs. The demonstration shows how different approaches deal with special challenges in WBANs such as low quality of wireless links, topology variations due to posture changes, and mobility. Moreover, sensor nodes can be configured online to investigate how different protocols react in various situations.**

I. WBANs

Communication protocols for Wireless Body Area Networks (WBANs) need to deal with specific challenging issues in these networks. Stringent power constraints and short transmission ranges of typical body sensor devices, low and time-variant quality of wireless links through and around the human body, and high mobility and frequent topology changes are important issues. The goal is to deliver sensed biological data to a gateway node on the body with an acceptable delivery ratio and latency in such a way that nodes consume as little energy as possible. The gateway node is usually a more powerful node that communicates with the outer networks as well.

There are several approaches for designing WBAN protocols. The first category is formed by star-based networks that rely on direct links from body sensor nodes to the gateway. All nodes are supposed to transmit their data directly to the gateway node on the body. These protocols are in general simple to implement and power-efficient, and provide low latency. In [1], for instance, a MAC layer is proposed for WBANs with a star architecture. In the second category of protocols, a variant of multi-hop data routing is exploited to improve the reliability of data delivery and prevent long outages. These protocols specifically take low transmission range and varying quality of wireless links into consideration. However, multi-hop protocols suffer from high complexity, high power consumption, and high latency. Table I compares the behavior of some existing protocols from several perspectives. In tree-based protocols such as [2], a spanning tree is autonomously maintained for data routing. In probabilistic data routing [3], nodes try to estimate the best quality links to the gateway and send their data through those links. In a full gossip approach [4], each node involves in forwarding other nodes' data using a gossip-based data dissemination, aiming to provide a high reliability of data delivery. Our On-demand listening and data forwarding (ODLF) mechanism uses a hybrid star/multi-hop approach. When sensor nodes have a sufficiently good link to the gateway, the protocol works like a star network. In addition, a specific multi-hop data forwarding is triggered in the case that some nodes cannot properly reach the gateway.

Experiments with real wireless motes installed on a body are of importance for investigating the behavior and evaluating the performance of a protocol architecture for WBANs. Modeling the radio channel and wave propagation through and around the body, and modeling the exact human mobility and postural movements are problematic issues that limit precision of computer simulation for WBAN protocols. So a testbed for implementing different protocols in a real-world WBAN is very useful for observing their performance. In this demonstration, we present our WBAN testbed and some implementation details. By the use of this testbed, different protocols with various configurations can be properly evaluated and the behavioral information can be observed online. The overall network performance can also be extracted through offline analysis of the data logged in the memory of wireless motes.

II. ODLF: On-Demand Listening and Forwarding

In [5], we proposed ODLF as a mechanism for automatically adapting the data propagation strategy in WBANs. All nodes are supposed to have a direct connection to the gateway (star network). However, the gateway continuously observes the quality of its incoming links and detects the nodes with poor links. Shadowing caused by posture changes and movements can bring a link to a situation in which the node cannot reach the gateway for a long period of time (a long outage). The goal is to detect such nodes as soon as the outage happens. Then other nodes start to listen and forward data to minimize packet losses the nodes in trouble.

Communication of sensed data in WBANs typically occurs in communication rounds. The gateway computes a quality factor $\rho^t_{i\to N}$ for all its incoming links as stated in Eqn. 1. $P^t_{i\to N}$ stands for the Packet Reception Ratio (PRR) of node i to the gateway over a certain number of previous rounds. $L^t_{i\to N}$ is a digital value that is one if the gateway has received the packet from node i in round t.

$$\rho^t_{i\to N} = \begin{cases} \rho^{t-1}_{i\to N} + (1-\rho^{t-1}_{i\to N}).P^t_{i\to N} & L^t_{i\to N}=1 \\ \rho^{t-1}_{i\to N}.P^t_{i\to N} & L^t_{i\to N}=0 \end{cases} \quad (1)$$

By comparing the calculated quality factor with a given threshold (ℓ_i), the gateway maintains a subset of nodes (Ψ^t) that need data forwarding help. Actually, parameter ℓ_i makes a trade-off between energy consumption and data delivery ratio in ODLF protocol and its value is set considering the reliability (data delivery) requirements for data items originating from node i.

$$\Psi^t = \{s_i \in S \mid \rho^t_{i\to N} < \ell_i\} \quad (2)$$

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TABLE I
A QUALITATIVE COMPARISON OF DIFFERENT NETWORK ARCHITECTURE APPROACHES FOR WBANS.

Metric	**Star architecture**	**Multi-hop architecture**			
		Tree-based routing	**Full gossip**	**Probabilistic routing**	**ODLF**
Implementation complexity	simplest	complex, tree construction and maintenance	simple	rather complex	simple
Energy consumption (radio activity)	low,if no acknowledgement is performed	high, unnecessary data forwarding when nodes can reach the gateway	high, always listen to all nodes and forward packets	high, packet exchanges for maintaining best routes to the gateway	depends on quality of links, low when nodes can reach the gateway properly
Latency of delivered packets	low, always one hop	high, always multi-hop	varying, low in networks with high-quality links	varying, depending on the link quality	varying, low (one hop) when it is possible
Robustness against node failures	robust, other nodes work as normal	not tolerated, tree reconstruction required	robust, no dependencies between nodes	best path should be updated	robust, no dependencies between nodes
Mobility support	always one hop, no route maintenance needed	frequent tree reconstruction is needed, which is time- and energy-costly.	native, no specific route, no assumption about node positions	by frequent updates of link quality estimates and best paths	native, no specific route, no assumption about node positions
Overall end-to-end PDR	low, some nodes may not directly reach the gateway	rather high, short distances between neighboring nodes in the tree	high, all nodes always receive and forward other node data	high, forwarding by selecting the paths with best quality links	high, forwarding only for nodes in trouble
Robustness against long link outages	no support, which may cause long burst packet losses	tree should be adapted, some burst packet loss may happen in this time frame	native, no effort to detect outages	best path to the gateway should be continuously updated by the nodes	native, outages are detected and data forwarding and listening is adapted

The gateway broadcasts a bitmap in each round, bit i of which states whether or not node i needs help. Nodes receive this bitmap, start listening to the nodes in need and then forward their data. If all nodes have a good connection to the gateway ($\Psi^t = \emptyset$), every node only transmits its own data. Otherwise, a gossip-based strategy is exploited for multi-hop data propagation of the data that needs forwarding. The approach does not rely on any specific routes. As the network topology of the WBAN is always prone to change, any assumption about the position of the nodes and their connectivity is not reliable.

III. DEMONSTRATION

A. Testbed Setup

The testbed uses *MyriaNed* [6] wireless nodes shown in Fig. 1(a). These motes feature an ATMEGA128 microcontroller and a *Nordic* nRF24L01 radio chip [7] as transceiver. The radio chip works in the 2.4GHz ISM band which is one of the proposed carrier frequency bands by IEEE 802.15.6 for WBANs, using a data rate of 2Mbps and a 32 bytes fixed packet size. The radio can be set in RX, TX, or Standby modes. In TX mode, four transmit power levels (-18, -12, -6, 0dBm) can be adopted for the radio. This allows us to test each protocol in various network conditions.

A TDMA-based MAC layer is used that provides a contention-free communication between sensor nodes. Every node in the WBAN is assigned a unique transmit slot. A short packet length and high transmission rate allow very short slots (approximately $900\mu s$). This leads to a very small duty cycle. In this sense the nodes consume very little energy per TDMA frame. The TDMA frame length is adjustable by programming the nodes. TDMA frames and slots are properly synchronized. Considering the limited number of nodes and the presence of the gateway node playing a coordination role, the synchronization process works well. Each node is equipped with a 4MByte Flash memory which is used to log data about the radio activity, the content of the cache, and other useful information at each round during the an experiment. The logged data is then analyzed to extract the efficiency metrics.

Up to $N = 11$ nodes (including the gateway) can be deployed on different positions of the body. The gateway always uses the highest available transmit power (0dBm). It always listens to all nodes to receive their packets. Body nodes listen to the gateway in any round independent of the used protocol. This is the minimum listening activity of each node which is crucial for keeping nodes synchronized. Besides that, more listening to the other nodes can be performed according to the selected protocol. Fig. 1(b) shows a deployment example of our testbed.

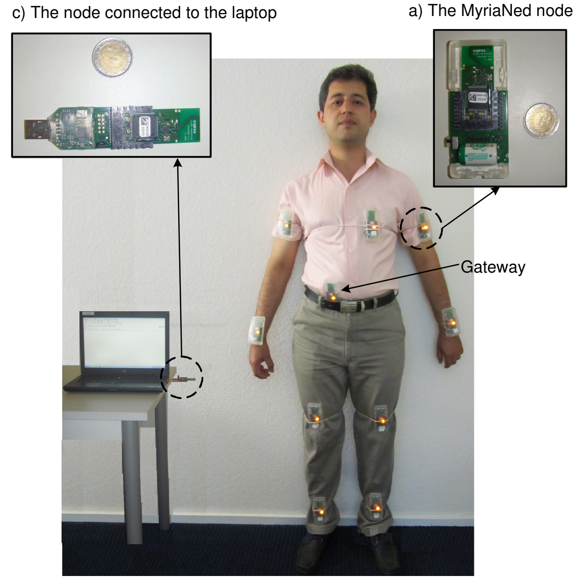

Fig. 1. The WBAN testbed setup.

We use one extra wireless node connected to a laptop (Fig. 1(c)) which is not really a part of the WBAN, but is necessary for conducting the experiments. Actually, this node provides the interface to the computer and Graphical User Interface (GUI). The first task of this node is to receive configuration commands from the computer and send these to the WBAN. Later we explain which configuration parameters we can set by the GUI. Besides setting parameters, commands for starting, logging data, or restarting an experiment are also relayed by this node. Secondly, this node behaves as a sniffer by listening to the channel to gather the radio activity in the WBAN and transmit this information to the computer. In particular, it receives useful data from the gateway about the quality of its incoming links, the nodes with link outages and so on. This

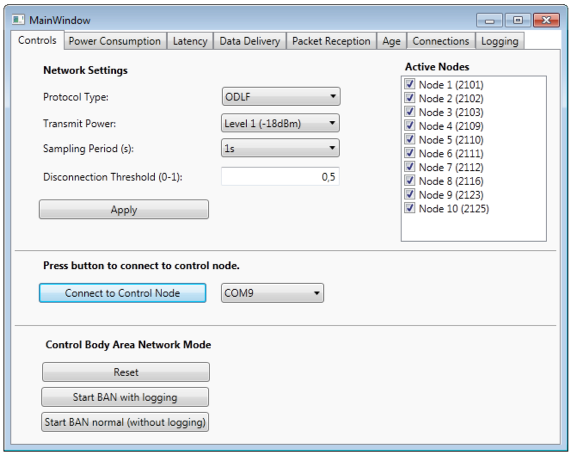

Fig. 2. A snapshot of the parameter setting GUI.

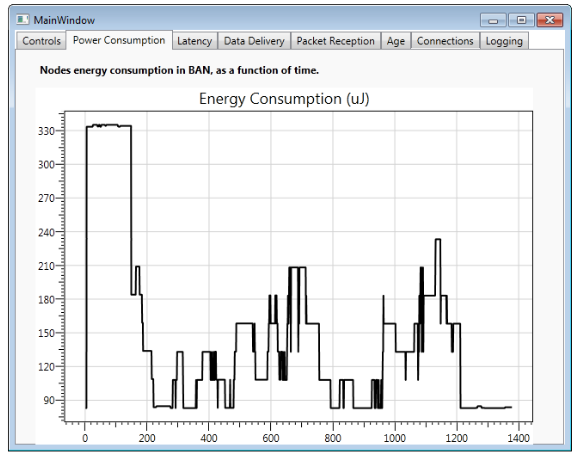

Fig. 3. A snapshot of the energy consumption plot in the GUI.

data is analyzed by the computer and is visualized online in the GUI. Note that after configuration of the network, the radio activity of this node has no influence on the performance and behavior of the protocol.

B. Configuration

Several parameters and commands can be set by the GUI to determine the behavioral mode of the WBAN. Fig. 2 is a snapshot of the parameter setting interface. The following are the controllable parameters.

Protocol type: Three protocols are implemented and can be set through the computer GUI. Star topology, a full-gossip data propagation, and the ODLF mechanism are selectable. In the star network, every node only transmits its own data to the gateway. In the full-gossip protocol, every node listens to all other nodes and if it receives any packet, it propagates that as well as its own sensed data. In each frame, a node can at most transmit two data items in addition to its own sensed data. The ODLF approach works as explained above.

Transmit power: There are four transmit power levels in the sensor nodes. A uniform power level is set for all nodes except for the gateway that always uses the highest power. By performing experiments with different power levels, we can evaluate a protocol in networks with different connectivity.

Sampling period: The period of data generation by nodes can also be set. At the moment, a uniform sampling period is set for all nodes. This parameter is important to observe the data delivery provided by each protocol. If the sampling period is equal to the frame length, each data item has only one opportunity to be transmitted by the source node. In contrast, when the sampling rate is a multiple of the frame length, each data item has more than one opportunity to be sent. Such retransmissions can deal with intermittent disconnections that are very likely to happen in wireless communication.

Disconnection threshold: This parameter is only sent to the gateway and is used for maintaining the list of the nodes without a sufficiently good links to the gateway. This actually is parameter ℓ_i in Eqn. 2 and is only used when the ODLF protocol is performed. In the demo, we use a uniform value for all nodes in the WBAN.

C. Online Performance Observation

Several online plots show different performance metrics. Fig. 3 shows a snapshot of the plot for radio energy consumption, for instance. The following information is presented.

Performance graphs: The latency of arrived data items to the gateway, the packet reception and data delivery ratio, and the age of data items from each node in the WBAN at the gateway can be observed online. This information is extracted from the data that the gateway sends to the node connected to the laptop. This data includes the time stamp attached to the last data item received from each body sensor node.

Disconnected nodes: At each round the gateway announces the requested set which contains the nodes that do not have a proper link to the gateway. This is then shown by the GUI.

Radio energy consumption: Depending on the active protocol and the connectivity level of the network, nodes may perform different amounts of radio activity and so consume different amounts of energy. The radio energy consumed by the sensor nodes is shown online (Fig. 3). Eqn. 3 calculates the radio energy in each TDMA frame.

$$E_{radio} = E_{tx} + L \times E_{rx} + E_{pd} \qquad (3)$$

E_{tx} and E_{rx} are transmitter and receiver energy per frame. E_{pd} stands for the energy consumption in the inactive part of the frame, where the node are in standby mode. Parameter L represents the number of listening slots in a frame and its value is 1, N, and $1 + |\Psi^t|$, for the star, full-gossip and ODLF mechanisms, respectively.

More Information

http://www.es.ele.tue.nl/nes/

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