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Supporting Mobility in Body Sensor Networks

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***Abstract*—Body Sensor Networks (BSNs) form a promising technology to supply healthcare to an ageing population. A large number of sensor devices, radios and MAC protocols are being developed. However, because of the small scale of a BSN, node mobility will arise frequently. This work presents the first algorithm to support such Mobile BSNs, while remaining energy efficient.**

I. Introduction and Related Work

A Body Sensor Network (BSN) can be defined as a network on the human body, comprised of wireless sensor nodes that monitor body parameters and transmit those data to a central device or sink. BSNs are an important development for ambulant patient monitoring, a key technology to improve support of a growing elderly population.

Currently, most BSN research focuses on single hop, star topology Time Division Multiple Access (TDMA) solutions [1]–[4]. Research points out that single hop is not always a viable solution, as channel conditions on the human body can be poor. Path loss measured around the human body is very high, compared to the well known values in free space [5], [6]. A number of protocols have been proposed to deal with multihop BSNs [7]–[10].

However, those solutions do not take node mobility into account, or only on a limited scale. When looking at the inferior channel conditions in a small-scale network like a BSN, nodes will be mobile, from a connectivity point of view. The network topology will rapidly change over time, at variable speeds.

The future IEEE 802.15.6 protocol can be considered a good illustration of the current status of mobility support in BSNs.

In November 2007, the IEEE formed the 802.15 Task Group 6, to develop a standard for communication around the body. In November 2009, this BSN standardisation task group issued a call for protocol proposals [11]. None of the submitted proposals described a protocol which is able to cope with mobility, only some described handling patient mobility [12]. This work wants to tackle mobility of individual nodes rather than mobility of the entire network.

The remainder of this paper is organised as follows. Section II presents algorithms to support mobility in BSNs, which are then analysed in section III. Section IV finishes with conclusions and future work.

II. Mobility Support Protocols

In order to support mobility, a number of requirements have to be fulfilled. Based on this, a Loose association Implicit reservation for Mobile Body Sensor Networks (LIMB) protocol will be defined. The protocol considers two node types and a phased frame structure.

A. Requirements

BSNs are small scale networks with large channel quality variation. Any small node movement could completely reorganise the network topology. As a result, a protocol for a Mobile BSN should support high mobility.

The node mobility is random, i.e. not deterministic. Human body movement is not predictable. The longer a human remains in the same position, the larger the probability of movement. Given the dynamic nature of the topology, a priori optimisation for certain movement patterns is not considered to be feasible.

The network is required to be connected, i.e. it is assumed a node always has another node nearby, it will never be completely isolated. Note that channel variations are taken into account, a node can be in range while channel conditions are poor.

B. Node Types

The LIMB protocol considers two node types, derived from the nomenclature of IEEE 802.15.4.

Reduced Function Devices (RFDs) are the mobile nodes, they require support for their mobility and have limited resources. As a result, RFDs run only the LIMB protocol. It is assumed nodes can be identified as requiring mobility support, e.g. for nodes located on the limbs.

Further, it is assumed a lightweight address allocation mechanism is available to uniquely identify each RFD. For small networks like a BSN, assigning a space efficient label should be possible.

Full Function Devices (FFDs), on the other hand, are rather static and have connectivity to the rest of the network by means of an existing BSN protocol. They run both the LIMB protocol and the protocol of this backbone network.

In order to allow acknowledgement mechanisms to work efficiently, the backbone protocol is required to be able to detect data duplication and to deliver acknowledgements within the length of one frame. More general, it should be possible to consider the backbone network as a one hop network. This assumption implies that the LIMB protocol can also be applied in a classical single hop star network.

Note that the LIMB protocol does not require addressing at the FFDs.

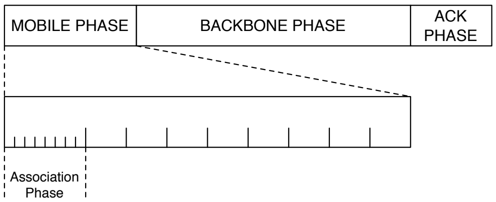

Figure 1. LIMB frame structure

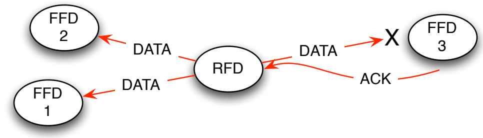

Figure 2. A data packet is received by two FFDs and acknowledged by a third.

C. Frame Structure

The LIMB protocol is based on one fixed frame structure, as shown in figure 1. It is composed of three phases: the mobile phase, the backbone phase and the acknowledgement phase. In phases where an RFD sends, reservation is *implicit* because of the unique node identifier.

During the *mobile phase*, RFDs send data in a designated slot. Each RFD has its own slot, based on its identifier. In order to exploit its assigned slot, the mobile phase starts with a pure TDMA *association phase*. Each RFD has its own mini-slot, based on its identifier. A mini-slot duration is short compared to a normal slot, typically it can be 10 times shorter. Each node willing to send data uses its mini-slot to transmit an association message. All FFDs are awake during all mini-slots to listen for associations. This implies that one RFD can have associations with multiple FFDs.

After the mobile phase, during the *backbone phase*, slots are reserved for the FFDs to exchange data with the backbone network. LIMB explicitly reserves time for this, as it depends on the received data.

During the *acknowledgement phase* (or ACK phase), a fixed number of mini-slots is allocated with a round robin scheme to some FFDs. They use their mini-slot to broadcast acknowledgements, as received from the backbone in the previous phase. Successful reception of a data packet is indicated by a single bit, data of the last N frames is acknowledged by a number of bitmaps. Each RFD can sleep after having received just one acknowledgement, resulting in an energy efficient mechanism. Acknowledgements are location and association independent because of their distributed broadcast nature. An RFD does not have to receive an acknowledgement from the node it sent data to.

Figure 2 shows that during one LIMB frame, multiple nodes can be involved to handle the acknowledged delivery of one data packet and how this might generate duplicate packets on the backbone network. In the figure, an RFD sends a data packet, which is received by two FFDs. After the backbone phase, the RFD receives an acknowledgement from a third FFD.

III. Analysis

A. Feasibility and Overhead

The impact of clock drift as well as control packet overhead is important to analyse.

In general, when the node clocks heavily drift, the TDMA slot mechanism will fail. The IEEE 802.15.4 standard specifies clock drift tolerance of 40 ppm [13]. Within this boundary, clock drifting should not pose a problem.

The association phase of the LIMB protocol generates a small overhead for all nodes. The FFDs only have to be awake during the association phase, afterwards they can sleep until slots where RFDs have associated. Clocks of the FFDs are allowed to drift more, because the node will stay awake during the entire association phase. The mini-slots demand limited RFD clock drift, as the mini-slots are shorter so boundaries more strict.

B. Energy Efficiency

Energy efficiency is affected by four different sources of energy wastage: collisions, idle listening, protocol overhead and overhearing [14].

When limited clock drift is assumed, collisions are impossible in the LIMB protocol, because of the pure TDMA scheme. The LIMB protocol is quite sensitive to increased clock drift, as it could cause collisions at the mini-slot boundaries in the association phase.

Overhearing occurs when a node listens for packets and receives packets destined for another node. The LIMB protocol strictly specifies which node type should listen when. As a result, LIMB protocol nodes do not suffer from overhearing.

Protocol overhead can be defined as the amount of control packets required to transmit data packets. The LIMB protocol relies on association packets to handle slot use. The protocol overhead is still low, as the transmission of these packets is strictly defined in slots so in theory only a wakeup signal is needed.

To cope with possible clock drifting and for verification purposes, in simulations the association packets contained the sender identification. Given the limited number of devices in a BSN, this identification can be stored and transmitted in an efficient way.

Idle listening occurs when a node listens for packets and does not receive anything.
In the case of RFDs, this can only occur when listening for an acknowledgement transmitted by FFDs located elsewhere in the network. If absolutely random movement is assumed, this situation can not be prevented. In general, this situation is not expected to arise frequently as a small scale, connected network is assumed.
The probability of FFDs idle listening depends on the number of devices in the network.

The absence of a mechanism to explicitly join or leave the network causes unassigned slots where FFDs unnecessarily stay awake. FFDs will always wake up in those slots to listen for association messages. Section IV proposes a simple join mechanism to overcome this issue.

In general, the slots for the LIMB protocol are used in an energy efficient way. Moreover, as the backbone BSN protocol can be assumed to be more complex, the energy efficiency will largely depend on the energy efficiency of this protocol.

C. Mobility Support Boundaries

The mobility support of the LIMB protocol is not unlimited. One important limitation is that during a slot, a receiving node is required to stay in range of the sending node, to avoid receiving only a part of the transmitted data. In case of small packets like associations or acknowledgements, this does not pose problems.

In order to study this limitation for larger packets, the following situation is considered. When looking at a very small radio range of 20cm and a slot size of 1ms, the node speed should be limited to $20cm/1ms = 200m/s = 720km/h$. This is a very high speed for body movements. Even in case of large slots of 5ms, this speed remains very high.

The mobility support of the LIMB protocol is limited by the time between the association and the data transmission. During this period, an RFD should not move out of the range of the FFD it associated with. The worst case occurs for the last node to associate, which has to wait until the end of the mobile phase before transmitting. During this period, it could have moved over a significant distance. In general, this means the mobility support of the LIMB protocol scales inversely with the length of the period between the association phase and the last slot of the mobile phase.

It should be noted that acknowledgements do not limit mobility. They are broadcast by multiple FFDs, an RFD is not required to wait at the same location for acknowledgements.

D. Simulation Results

In order to evaluate protocol performance, a simulation study was performed in Castalia [15]. This network simulator is based on OMNeT++ [16] and was specifically designed to simulate sensor networks.

The simulation was set up as follows. 15 nodes have Castalia standard CC2420 radios (data rate: 250 kbps, RX power: 62 mW, listen power: 62 mW, sleep power: 1.4 mW), run on 2 AA batteries and have a temperature sensor generating data at 1 sample per second. The realistic interference wireless channel, which comes with Castalia by default, is used to connect the nodes.

Only the LIMB protocol is run by the nodes. Data packets received by FFDs are immediately passed to the sink without transmission over a backbone network, to eliminate the impact of a specific backbone protocol.

The sink broadcasts a beacon every frame, which is only received by the FFDs, the RFDs synchronise on the acknowledgement messages. In total 23 RFD identifiers are available, 33 out of 100 slots are allocated to the LIMB protocols. Slot length is set to 5 ms and mini-slot length is set to $5/7$ ms to be sufficiently small, 5 acknowledgement slots are used. All simulations are performed with 200 different random number seeds, variance is mentioned when it is large. All scenarios ran for 120 seconds, which corresponds to 240 frames. The mean percentage of slots the nodes are not sleeping during the mobile phase is studied, to avoid dependency on specific radios or frame length and to present clear numbers. Mini-slots were counted as one fifth of an entire slot.

Table I
MEAN PERCENTAGE AWAKE SLOTS PER NODE IN STATIC AND MOBILE SCENARIOS

Type / Speed	number of packets
Sink	3.013
FFD	35.963
RFD	4.311
$1m/s$	4.344
$8m/s$	4.347
$64m/s$	4.339
$512m/s$	4.347

A static scenario with 6 RFDs and 8 FFDs was studied to study the LIMB protocol in a static topology, where all but two RFDs had good connectivity to the network. Results are shown in the upper half of table I. Similar scenarios produced similar results, variance remained low.

The energy consumption of the sink is low, because it only transmits a beacon. As the FFDs handle the mobility support, they remain awake for about one third of the time. This comes down to 10 slots per frame in this scenario, which is acceptable given the 6 used and the 17 unused identifiers. Due to the association phase, the FFDs have to stay awake quite long.

When looking at the packet arrival statistics for static nodes on the first line of table II, a high reception rate but a large number of duplicates can be noticed. This shows that the LIMB protocol performs properly in a static scenario, but duplicates arise when nodes have high connectivity. A large number of FFDs will receive packets. When deploying the LIMB protocol in sparse networks like BSNs, this is not a problem.

To validate the mobility support, mobility was introduced in the static scenarios. Four RFDs move in repetitive lines along exactly the same path through a fixed backbone network, at speeds of 1, 8, 64 and $512m/s$. Two other RFDs have good connectivity and remain static. For reasons of clarity, this is the only scenario considered below.

The very high speed tests the boundaries of the mobility support. The lower part of table I shows the mean energy consumption of the mobile nodes and table II the number of packets and duplicates received at the sink. The energy consumption of the other nodes and the number of packets received from static RFDs did not vary when nodes were mobile.

The energy consumption of mobile nodes is hardly influenced by speed, the protocol handles mobility very well. The small differences in energy consumption and received packets can be explained by the different channel conditions

Table II
MEAN RECEIVED PACKETS AND DUPLICATE RATIO IN STATIC AND MOBILE SCENARIOS

Speed (m/s)	Received Packet ($pkts$)	Duplicates ($pkts$)
0	237.8	7.710
1	238.3	7.684
8	238.3	7.683
64	238.1	7.606
512	238.3	7.511

encountered when moving, they are independent of speed. In general, even from extremely fast moving nodes a high amount of packets is received.

IV. CONCLUSIONS AND FUTURE WORK

This paper presented the first protocol for mobile Body Sensor Networks. With this extensions to existing BSN protocols, it is shown that mobility support is possible, while keeping energy consumption and overhead low.

Simulation has shown that the protocol performs very well in mobile scenarios. Supporting mobility while staying energy efficient is feasible with the LIMB protocol.

Currently, purely random movement is considered. It will be interesting to study possible improvements when some pattern can be detected, either when speed is low or when a fixed pattern arises. Detection will have to be sufficiently fast, because of the dynamic nature of BSNs.

Because of its low complexity, the LIMB protocol is believed to be resilient to packet loss. More detailed analysis and simulations will be performed to validate this claim.

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