An analysis of requirements to supporting mobility in body area networks

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***Abstract*—Body Area Networks (BANs) form a strongly growing research field, motivated by increasing need for remote and improved patient healthcare solutions and driven by the development of the IEEE 802.15.6 standard. While most research focuses on single hop star topologies, more studies point towards multi-hop topologies as more preferable. Related with this multi-hop topology however, comes the cost of supporting mobile nodes. Initial research shows the feasibility of adapting protocols to support mobility. This work analyzes two requirements to fulfill mobility support, more specifically location independence and increased clock drifting resiliency. Simulations show the need to fulfill both requirements and motivate that location independence should always be strived for, while clock drift resiliency is shown to be required in larger networks.**

I. Introduction

The field of Body Area Networks (BANs) is growing rapidly, pushed by the cost of supporting a growing, aging population in developed countries. While the initial BAN research focus lied on novel radio chip and application development[1], [2], it now shifts towards Medium Access Control (MAC) protocol development. [3] proposed a multi-level scheme, with one *Monitoring Station* which communicates with multiple *Master Nodes*, which on their turn communicate with *Sensor Nodes*. motivated by the standardization efforts of the IEEE 802.15 task group 6[4], [5], [6].

The draft IEEE 802.15.6 standard describes both single hop and multi-hop BANs, by means of a flexible Time Division Multiple Access (TDMA) and Carrier Sensing Multiple Access (CSMA) based approach. TDMA is preferred over CSMA with respect to reliability, however an implementation tends to be more difficult. Moreover, support for mobility in BANs is completely absent.

BANs are small scale networks designed to be energy efficient and deployed over a lossy, strongly time-varying channel[7]. To obtain a high energy efficiency and to limit exposure of the human body to strong radio signals, the transmission power of the radio has to be limited strongly. As a result, links will be set up over distances in the order of tens of centimeters and multi-hop topologies will arise. Compared to the typical large scale deployments of other wireless networks, this illustrates the distinctive nature of BANs. Because of the typical radio usage over the lossy channel, a moving person is expected to generate large link quality variations. From a MAC level point of view, this will cause mobility in the network, i.e., quickly appearing and disappearing links.

Previous work has shown the feasibility of mobility support in BANs. One interesting example is the work proposed in [8], where communication is controlled by gossiping. Although very robust to topology changes, delay limits can not be guaranteed. [9] presents an alternative in the form of a MAC protocol supporting mobility in Wireless Sensor Networks (WSNs), which does not support the typical requirements of a BAN.

This work considers the Loose association Implicit reservation Protocols for Mobile BANs (LIMB) proposed in [10], [11], which apply a divide-and-conquer approach, where the nodes are divided in static Full Function Devices (FFDs) and mobile Reduced Function Devices (RFDs). The FFDs form a static backbone, connected by an existing BAN protocol. Each RFD connects to this backbone using the LIMB protocols, with a TDMA based scheme consisting of a LIMB phase, a backbone phase and an acknowledgement phase. During the LIMB phase, the RFDs perform a form of association and transmit their data, which is forwarded by the backbone nodes during the backbone phase. An aggregated acknowledgement of all received data is then generated, which is transmitted during the acknowledgement phase.

Three different protocol variants were outlined, each with a different association mechanism. LIMB-Just In Time Association (LIMB-JITA) performs associations right before data is transmitted, i.e., it wakes up the receiving FFDs right before sending data. In the LIMB-Early Association (LIMB-EA) variant the RFDs perform association during a separate association period which precedes the LIMB phase. The LIMB-No Association

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(LIMB-NA) variants performs no association, all FFDs only listen for data packets during a mini slot and then sleep if no data packet is received. Due to space constraints, for a full protocol description we refer to the work cited above.

An initial performance analysis was already presented in [11]. The main research contribution of this work is to extend the initial research, by analyzing two requirements to support mobility in BANs. The remainder of this work is organized as follows: section II outlines two requirements to support mobility in BANs, followed by a simulation study in section III. Section IV concludes this work and presents future research directions.

II. Mobility Support Requirements

A. Location Independence

A typical TDMA protocol consists of three phases: association, data transmission and acknowledgement. Typically these phases are tightly coupled. I.e., the node receiving the association will also receive the data and send the acknowledgement. The first requirement analyzed in this work argues that the three TDMA phases should be decoupled.

The LIMB protocols broadcast data packets to increase reception probabilities under mobility. This work argues that location independent acknowledgements are required to support mobility in BANs. More specifically, in order to support acknowledging transmissions from mobile nodes in a BAN, acknowledgements should not be bound to the location of one or more receivers of the transmission. In the LIMB protocols, this requirement can be implemented by having all FFDs transmit acknowledgements, instead of only a subset. (Translated to the protocol specification, this comes down to increasing the size of the acknowledgment phase.)

B. Clock Drifting Resilience

When mobile nodes are present in the BAN and random mobility is assumed, a single mobile node can appear anywhere in the network at any given moment. As such, the protocol timing becomes even more critical and protocol clock drifting resiliency should be added or increased.

For an implementation of this requirement in the LIMB protocols, consider the association mechanisms. To enable successful data transmissions, the first step is successful reception of RFD associations by the FFDs. Those associations are transmitted during short mini slots, which are more sensitive to clock drifting. To study the impact of clock drifting resiliency on the protocol, the FFDs are configured to listen for associations during longer periods of time than just a single mini slot.

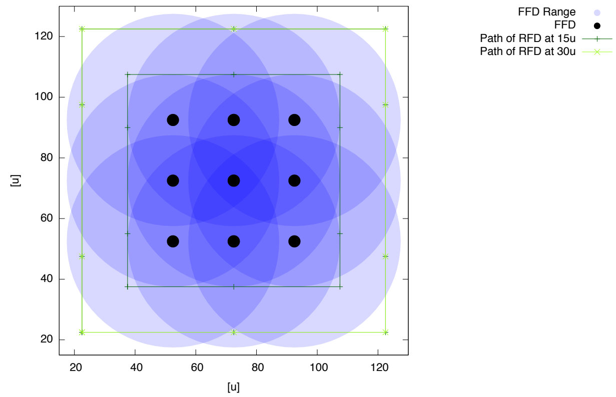


Fig. 1. Example line scenario topology, RFDs at 15u and 30u.

III. Performance Analysis

A. Simulation Setup

To evaluate the performance impact of the outlined requirements, a simulation study was performed. This work is based on the assumptions of [10]: the BAN is considered to be a small-scale, connected network where only temporarily disconnected node subsets are possible. Two types of simulation scenarios are considered: line scenarios and random scenarios.

The line scenarios focus on the impact of mobility. As such, scenarios as shown by the example in figure 1 are generated. The nodes around the sink node in the center are FFDs, with one to ten RFDs moving around them. In the presented results, the distance of the RFDs to the FFDs was fixed to 15u for reasons of brevity. It was observed that for larger distances, the poor channel has more impact on performance, while for smaller distances the channel variations are very limited.

Random scenarios were also considered, to avoid dependencies on highly structured topologies. The scenarios are generated as follows: a backbone network of FFDs is generated first, followed by a path for the mobile RFDs which traverses multiple stops. The scenario is generated in three passes, each covering a different aspect of the simulation.

In the first pass, the connected FFD backbone network is generated: the FFDs will always be in range of at least one other FFD. Stated differently, it would be perfectly possible to connect all FFDs with an existing multi-hop protocol. In the second pass, the starting position of the RFDs will be generated. This will involve once again generating random points, and checking whether they are in range of one or more FFDs. In the third pass, for each required stop, a new position will be generated for each RFD, again in range of one or more FFDs. The RFDs will move from stop to stop, generating repetitive movement over the random path. To add to the random nature of the scenarios, the RFD speed is random too. The obtained scenarios are then filtered for unwanted

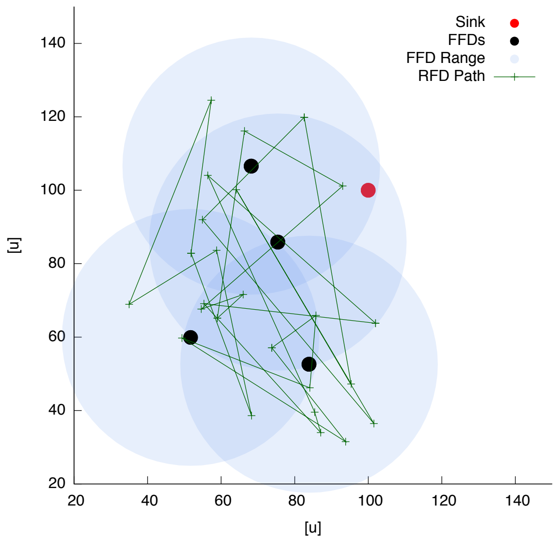


Fig. 2. Example random scenario after third step.

TABLE I
OVERVIEW OF LIMB PARAMETERS.

Property	Value
Mini slots in one slot	5
Slot size	5ms
Mini slot size	5 ms $\times \frac{5}{7}$
First ACK slot	33
Number of association slots	6

mobility side-effects, where parts of the paths between the different stops may be out of range of all FFDs. Figure 2 shows example paths generated in the final step of the algorithm.

To maintain randomness, four different scenarios were generated for each number of FFDs and RFDs. While four is a small number, this already allows studying the protocol behavior under the random scenarios. Because of the large number of combinations of RFDs and FFDs, increasing the number of considered random scenarios would substantially increase the number of simulations to run.

Simulations were performed with the Castalia simulator[12], with runs of 120 seconds simulation time and 200 different seeds per scenario. Frame size was set to 100 slots with a LIMB phase of 34 slots, other simulation parameters were configured as described in table I.

To study performance, two metrics were considered: channel utilization and energy consumption. Channel utilization is measured as the amount of unique packets which have arrived at the sink over the total amount of transmitted packets by each node, while energy consumption is obtained directly from Castalia measurements. Note that by its definition, channel utilization will reflect both efficiency and reliability.

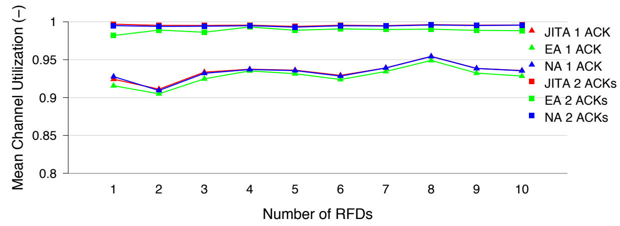
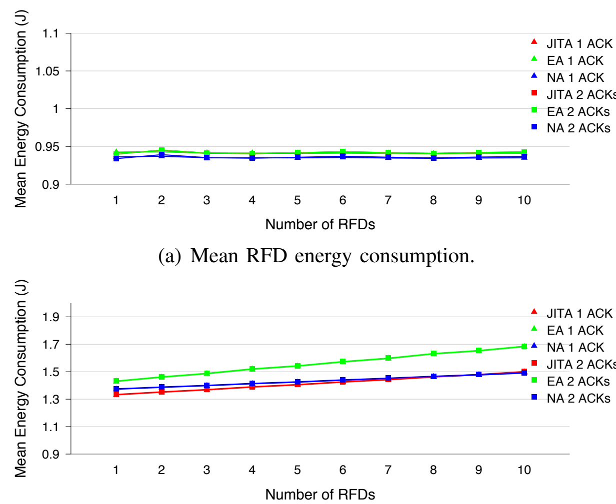


Fig. 3. Mean channel utilization in line scenarios with 1,2 ACK slots.



(a) Mean RFD energy consumption.

(b) Mean FFD energy consumption.

Fig. 4. Mean energy consumption in line scenarios with 1,2 ACK slots.

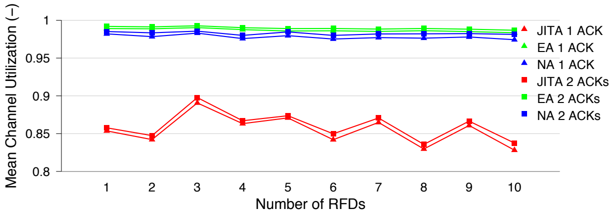
B. *Increased Acknowledgements*

To study the impact of an increased amount of acknowledging FFDs, the simulation was configured with one and two acknowledgement slots, denoted as 1 ACK and 2 ACKs in the plots.

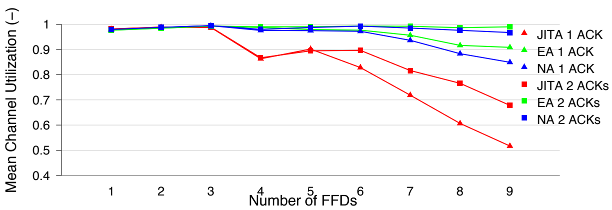
Figure 3 shows the impact of the number of acknowledgements on the channel utilization in the line scenarios, while figure 4 shows the impact on energy efficiency. It can be observed that the number of RFDs has no impact on the channel utilization in case of an increased number of acknowledgements, which is a good property of the protocol[1]. Moreover, the RFD energy consumption is not influenced by the number of RFDs in the network because of the slot assignment, the RFDs can be considered as isolated. The FFD energy consumption increases linearly, as expected. Clearly, increasing the number of acknowledgements increases channel utilization by up to 10%, while the energy consumption increase is very limited.

For the random scenarios, figure 5 shows a similar increase in channel utilization for an increased number

[1]For a limited number of acknowledgements, the channel utilization does not show smooth behavior because of missed acknowledgements. Depending on the RFD speeds which are closely related to the number of RFDs, strong fluctuations can be observed.



(a) Channel utilization for 5 FFDs and varying number of RFDs.



(b) Channel utilization for 5 RFDs and varying number of FFDs.

Fig. 5. Mean channel utilization in the random scenarios with 1,2 ACK slots.

of acknowledgements. Notice how the plots are not as smooth as the line scenario plots, as the randomly generated topologies are not correlated. Again, channel utilization is not influenced by the number of RFDs in the network, although the channel utilization decreases with an increasing number of FFDs. The energy consumption, not shown because of space constraints, behaves similar to the observations in the line scenarios.

It should be noted that in both scenarios, the variance (not shown) drastically reduced with an increased number of acknowledgements.

Overall, it can be concluded that more acknowledgement slots improve channel utilization with a very limited impact on energy efficiency. Moreover, the number of acknowledgement slots should correspond to the number of FFDs in the network. I.e., every FFD should transmit an acknowledgement, as illustrated by figure 5(b). Only then will the protocols become location independent. However, a decreasing channel utilization can still be observed in figure 5(b), even with two acknowledgement slots. This will be improved by the next requirement.

C. *Prolonged Association Listening*

To analyze the impact of prolonged association listening, the FFDs were configured to listen for associations during one and one and half mini slots in the LIMB-JITA and LIMB-NA variants, denoted as listening 1.0 and listening 1.5 in the plots. Because of the separate association period, no prolonged association listening was possible in the LIMB-EA variant.

For the line scenarios, figure 6 gives the channel utilization for the different association listening durations, showing almost no improvement. Figure 7 gives the FFD energy consumption for the association duration lengths, which shows a clearly increased energy consumption.

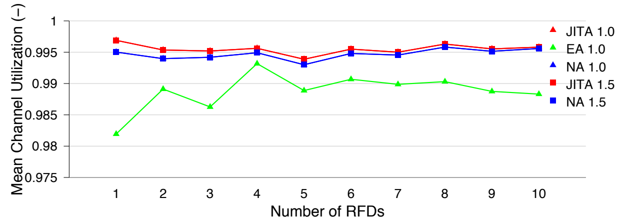


Fig. 6. Mean channel utilization in line scenarios with 1 and 1.5 association slots.

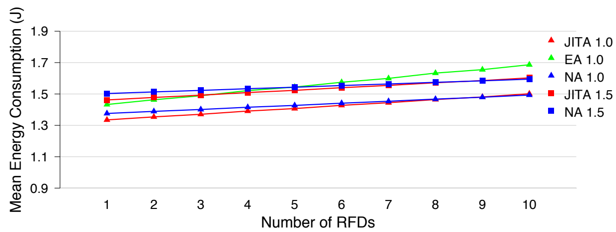
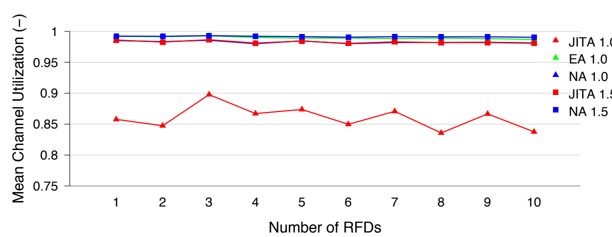


Fig. 7. Mean FFD energy consumption in line scenarios with 1 and 1.5 association slots.

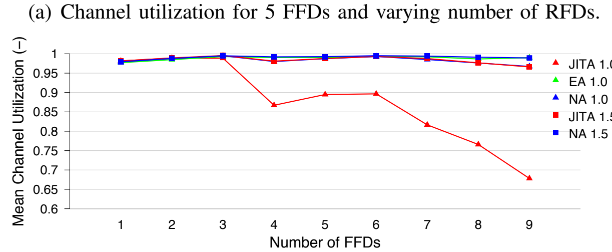
The energy consumed by the RFDs, not shown because of space constraints, remained unchanged.

However for the random scenarios, figures 8(a) and 8(b) illustrate the increased channel utilization, especially for LIMB-JITA more than 30% is gained. Figures 9 and 10 illustrate how this significant improvement comes at the expense of FFD energy efficiency.

The difference between the channel utilization increase in the line scenarios and the random scenarios can be explained as follows. In the line scenarios, all FFDs are in proximity of the sink node. As a consequence, their clock will drift very little, a beacon transmitted by the sink at the beginning of each cycle is almost always



(a) Channel utilization for 5 FFDs and varying number of RFDs.



(b) Channel utilization for 5 RFDs and varying number of FFDs.

Fig. 8. Mean channel utilization in the random scenarios with 1 and 1.5 association slots.

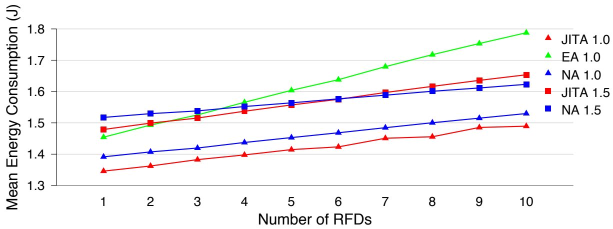


Fig. 9. Mean FFD energy consumption for 5 FFDs and varying number of RFDs in random scenarios with 1 and 1.5 association slots.

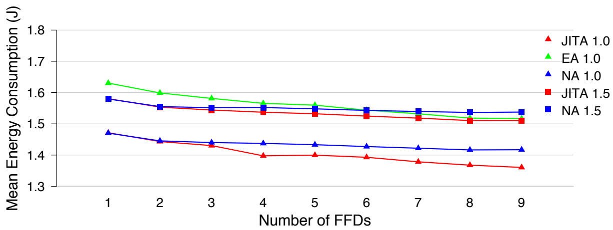


Fig. 10. Mean FFD energy consumption for 5 RFDs and varying number of FFDs in random scenarios with 1 and 1.5 association slots.

received. In the random scenarios however, a multi-hop topology is formed where clocks of FFDs are likely to drift more. As a consequence, in the random scenarios prolonged association listening and more general clock drifting resiliency will increase channel utilization.

When comparing the results for the line and the random scenarios, prolonged association listening and more general increased clock drift resiliency could be considered a tradeoff between energy consumption and channel utilization. However, the increased sensitivity to clock drifting only arises in larger backbone networks, and only for FFDs further away from the sink node. Exactly those FFDs will relay less data for RFDs, making more energy available for prolonged association listening. As such, there is no real tradeoff, prolonged association listening comes down to improving the situation for those FFDs susceptible to clock drifting.

IV. Conclusions

This work has analyzed two requirements to enable mobility support in mobile BANs: location independence and clock drifting resilience.

Location independence means that the different phases of a TDMA transmission should be decoupled, to avoid nodes having to remain in one location. In the LIMB protocols, this is reflected in the requirement to let all FFDs transmit acknowledgements rather than a subset of all FFDs. Doing so, an RFD does not have to remain near receiving FFDs for an acknowledgement. A simulation study shows the increased channel utilization and only slightly increased energy consumption when all FFDs transmit acknowledgements.

Clock drifting arises in larger, multi-hop networks. As a result, associations may be missed in the LIMB protocols, as this part of the protocol is the most sensitive to clock drifting. Because of the missed associations, channel utilization decreases. Therefore, prolonged association listening is introduced. It is shown by a simulation study that for the dense line scenarios the channel utilization does not improve, while energy consumption increases. In the larger, more sparse random networks, more clock drifting is present and the channel utilization increases. Therefore, depending on the network topology and the location of an FFD in this topology, prolonged association listening should be enabled to increase channel utilization.

Both requirements are applicable to other TDMA or hybrid TDMA-CSMA protocols where mobility should be supported, as similar effects are expected to arise. As such, the authors are working on an analysis of the IEEE 802.15.6 BAN standard with respect to mobility and the application of the mechanisms outlined in this work. Moreover, the results outlined in this work will have to be tested in real-world scenarios when deployed in BAN patient trials. As an intermediate step, the mobility model of [14] is considered for implementation in the simulator for a more realistic mobility simulation.

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