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# Supporting Mobility in Wireless Body Area Networks: an Analysis

*(Invited Paper)*

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***Abstract*—In a world with a growing elderly population, Wireless Body Area Networks (WBANs) are considered an opportunity to supply healthcare to a growing number of patients requiring continuous medical care. A large number of WBAN sensors, radios, medium access and routing protocols has already been developed and is actively being developed. Together with an increasing number of applications and field trials, this illustrates how promising WBANs are, both to academia and industry.**

**Currently, WBANs are almost always assumed to have a single-hop topology, where all nodes on the body are in range of the central sink device. However, to conserve energy and to limit exposure of the human body to radiation, research indicates the need to support multi-hop topologies. In those small-scale topologies, a small body movement can cause a complete topology reorganization or more general node mobility.**

**This work analyzes three algorithm variants to support these mobile WBANs, with respect to channel utilization and energy efficiency, in both a static and a mobile scenario.**

## I. Introduction

A Wireless Body Area Network (WBAN) is a network formed on the human body, consisting of wireless sensor nodes which monitor one or more body parameters[1]. The data gathered by the devices is transmitted to a central device or sink, which can process and/or upload the result. WBANs form an important development towards achieving ambulant patient monitoring, which can be considered a key technology to improve support of a growing elderly population. However, possible use of WBANs goes beyond healthcare and person monitoring in general, as WBANs are a perfect candidate for advanced Human-Computer Interaction[2].

Research on WBANs is mainly focused on physical layer solutions, where WBAN-specific radios and monitoring sensors are developed[3], [4]. This work will focus on Medium Access Control (MAC) protocols, an important area because of the specific application context of WBANs. Most WBAN MAC protocol research currently focuses on single-hop or star topology networks with slotted, Time Division Multiple Access (TDMA) medium access[5], [6], [7]. While more straightforward to control medium access, single-hop topologies are not always viable. The main cause is the high path loss around the human body, especially compared to the classical values in free space[8], [9]. As a solution, a number multi-hop WBANs protocols have been proposed in [10], [11], [12].

Given the deteriorated channel conditions and a moving human body, the sensor nodes attached to this moving body can be considered mobile, from a MAC point of view. This paper specifically focuses on WBANs with mobile nodes. To this extent an analysis of three variants of a MAC protocol for mobile WBANs is presented.

The remainder of this paper is organized as follows. Section II describes related work on mobility in WBANs followed by section III which presents the studied protocol and its variants. These are analyzed and simulated in section IV. Section V finishes with conclusions and future work.

## II. Related Work

The research on mobile WBAN support is very limited, usually mobility is not considered when designing MAC protocols for WBANs.

A good illustration is the IEEE 802.15 Task Group 6, formed by the IEEE in November 2007. The main goal of this group is the definition of a WBAN MAC protocol standard. Two years after its start, the group issued a call for protocol proposals, soliciting input from academia and industry on possible WBAN MAC protocols. None of the responses described any form of support for mobile WBAN nodes. Only patient mobility, where the entire WBAN moves, was covered by some proposals[13]. This work wants to tackle mobility of individual nodes rather than mobility of the entire network, which is the case when patient mobility is analyzed.

Coping with mobility is usually performed at the routing layer in e.g., ad hoc networks. However, the degree of mobility supported by the different ad hoc routing protocols varies strongly. The limiting factor is the time required for the distributed routing table to converge. This is typically in the order of seconds, which does not match with body movements speed. Moreover, almost ad hoc network solutions usually suppose an (almost) always-on radio interface, which is in sharp contrast with the energy efficiency requirements of a WBAN.

Wireless Sensor Networks (WSNs) research is heavily focused on energy efficiency; numerous energy efficient communication protocols have been proposed. As certain characteristics are shared with WBANs, this could have been an

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interesting source of inspiration. Research on mobile WSNs is very limited however, as mobility has a large impact on the network performance. Again, the standard protocol IEEE 802.15.4[14], has no explicit support for mobility and is shown to perform poorly under mobility[15], [16], [17]. MMAC is one of the few MAC protocols for WSNs, however it does not support the typically higher delay and throughput requirements of a WBAN.

## III. Mobility Support Protocols

This section will describe the Loose association Implicit reservation Protocols for Mobile WBANs (LIMB) as proposed in [18], [19], based on a number of assumptions outlined in the following section. Afterwards, nodes are classified into two node types and the protocol frame structure is defined. Finally, the association mechanisms are outlined.

### A. Assumptions

WBANs are small scale networks with large channel quality variation caused by the human body. Because of the scale, any node movement could completely reorganize the network topology. As a consequence, the MAC protocol should support high node mobility.

The path described by the mobile nodes is assumed to be random, i.e., not deterministic. Human body movement is not predictable. Moreover, the longer the human body remains in the same position, the larger the probability of movement. This means that given the highly dynamic nature of the resulting topology, a priori optimization for certain movement patterns is not considered to be feasible.

The network is assumed to be connected with only temporarily disconnected nodes. I.e., it is assumed a node always has one or more nearby nodes, a node will never be completely isolated for a prolonged period of time. Note that channel variations play an important role, a neighboring node can be in range while channel conditions are poor.

### B. Node Types

To support mobility, the LIMB protocols classify nodes into two node types, similar to the nomenclature of IEEE 802.15.4.

The Reduced Function Devices (RFDs) are mobile nodes, requiring mobility support. Each RFD is assumed to be identified by a lightweight addressing scheme, which is deemed feasible in a typically small WBAN.

Full Function Devices (FFDs) are the more static nodes, which also run an existing WBAN protocol to connect to a WBAN. As such, FFDs run both a LIMB protocol and the protocol of the existing backbone network. As a consequence, the LIMB protocol forms an extension to existing protocols, extending their range to mobile nodes. Note that no addressing scheme is required for the FFDs.

To differentiate between mobile and static nodes, between the RFDs and the FFDs, it is assumed nodes can be identified as requiring mobility support. E.g., a node attached to a limb can be manually labeled RFDs, while a node mounted on the chest can be considered an FFD.

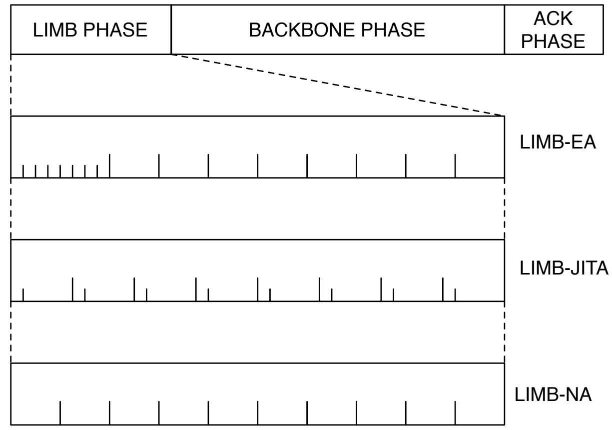


Fig. 1. LIMB frame structures

To support the LIMB protocols, the backbone protocol must be able to handle duplicate packets and support acknowledgement processing with a maximum delay of one TDMA frame. More general, it should be possible to consider the backbone network as a one hop network, LIMB protocols can function in a classical single-hop network.

### C. Frame Structure

The LIMB protocols have a fixed frame structure with three phases, as shown in figure 1. In those phases where an RFD transmits, slot allocation is *implicit* because of the addressing scheme.

In the first phase, the *mobile phase*, each RFD is assigned a dedicated slot, based on its address, to transmit data. Only if an association with this RFD exists, one or more FFDs listen in this slot.

The second phase, the *backbone phase* is used by the FFDs to exchange data with the backbone network over the existing WBAN protocol. Time is explicitly reserved for this exchange, as the received acknowledgements will be transmitted in the next phase.

During the final phase, the *acknowledgement phase*, a number of FFDs broadcast acknowledgements in mini-slots, indicating packet reception success for all data packets transmitted by the RFDs. An RFD will sleep after receiving any acknowledgement, as all FFDs transmit the same acknowledgement set. Note how the broadcast acknowledgements are location and association independent.

An example is given in figure 2, where multiple FFDs are involved in a successful end-to-end transmission of a data packet. In the figure, the the data packet transmitted by the RFD is received by two FFDs. The acknowledgement is transmitted by a third FFD, illustrating the association location independence.

### D. Association Mechanisms

To define which FFDs listen to an RFD, three *loose association* mechanisms are defined, with different radio and timing requirements.

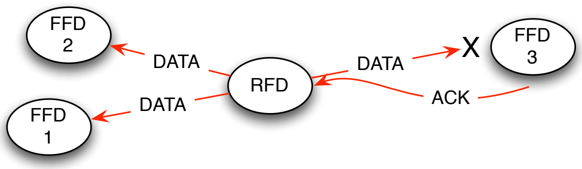


Fig. 2. A data packet is received by two FFDs and acknowledged by a third.

LIMB-Early Association (LIMB-EA) starts the mobile phase with a slotted *association phase*. Ordered by their identifier, the RFDs have a dedicated mini-slot to transmit an association. All FFDs listens for associations during this association phase.

LIMB-Just In Time Association (LIMB-JITA) defines an association mini-slot at the beginning of each data slot to allow the RFD to send an association. Again, all FFDs listen for these associations.

LIMB-No Association (LIMB-NA) defines no association mini-slot, instead the RFD immediately transmits a data packet at the beginning of its slot. FFDs listen at the start of each slot.

Figure 1 illustrates the frame structure of the three association variants.

## IV. Performance Analysis

### A. Simulation Setup and Considered Metrics

In order to evaluate protocol performance, simulations were performed with Castalia[20], a network simulator specifically designed for sensor and body area networks. The simulation was configured as follows. Nodes have Castalia standard CC2420 radios, powered by two AA batteries. Sensor data is generated by a temperature sensor at two samples per second. The Castalia default realistic interference wireless channel is used to simulate connectivity.

Both RFDs and FFDs run only the LIMB protocol. To simulate a backbone network between the FFDs, data packets received by FFDs are immediately passed to the sink in software. This means there is no transmission over a simulated backbone network, to have a view on only LIMB performance as opposed to the impact of different backbone protocols on LIMB.

The FFDs synchronize their clocks on the sink by means of a beacon transmitted every frame. The RFDs synchronize on all LIMB packets.

In total 23 RFD addresses are available and frames consist of 33 out of 100 slots allocated to the LIMB protocols. Slot length is set to 5 ms while mini-slot length is $5/7$ ms. Five acknowledgements are transmitted during one acknowledgement slot.

All simulations are performed with 200 different random number seeds, variance was calculated for all experiments and is mentioned when it is large. All scenarios ran for 120 seconds or 240 frames.

Two metrics are considered in this work: energy efficiency and channel utilization.

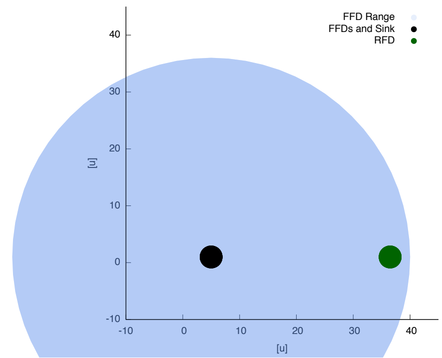


Fig. 3. Example topology for the cloud scenarios, with four FFDs and five RFDs.

Energy efficiency is included as it is crucial to the feasibility of WBANs. Only the energy consumed by the radio is taken into account, as reported by Castalia.

A good metric for the impact of channel quality and protocol robustness on the protocols is the channel utilization. It is defined from an application level point of view, as the ratio of the number of unique packets which have arrived at the sink, over the number of unique transmitted packets at each node.

### B. Scenario Definition

To evaluate protocol performance in the mobile WBANs, two scenarios are discussed in this work, the cloud and the random scenarios.

Although the LIMB protocols focus on mobile WBANs, protocol performance under static conditions is also considered, because mobility does not permanently occur, sometimes a quasi static topology can be observed. Moreover, a number of parameters can more easily be studied in a static scenario, especially the influence of scale. To this extent, cloud topologies as shown by the example in figure 3 are generated. The number of FFDs varies from two (only the sink and one node) to ten, the number of RFDs varies from one to ten. The distance between the RFDs and FFDs varies between 5u and 30u, in steps of 5u. This unit $u$ is an abstraction of real simulation scales, mapped to maintain correctness of the simulation models. The sink is placed very nearby the FFDs, avoiding an extra hop. Overall, the cloud scenarios focus only on the number of nodes in the network, by trying to cancel channel differences between different RFDs or FFDs.

As opposed to the structured cloud scenarios, random scenarios are also generated. The number of FFDs is again varied from two to ten, while the number of RFDs is varied from one to ten. In the random scenario, a backbone network of FFDs will connect mobile RFDs traversing a path along the FFDs.

The random scenario is generated in three passes. In the first pass, as shown in an example in figure 4, the connected FFD backbone network is generated by generating random points and checking whether the FFDs form a connected network. In the second pass, as shown in the example of figure 5, the starting position of the RFDs is defined, again by generating random points and checking connectivity to one or more FFDs.

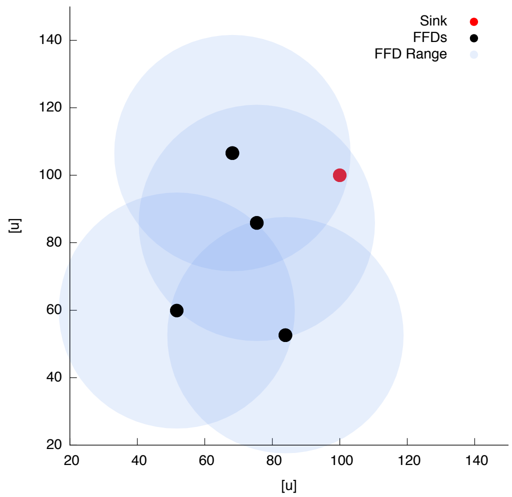


Fig. 4. First step in random scenario generation: FFD locations are generated.

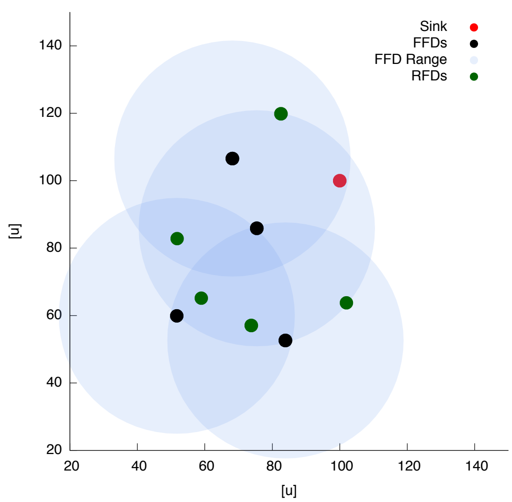


Fig. 5. Second step in random scenario generation: initial RFD locations are generated.

In the third pass, for each required stop, a next stop will be generated for each RFD, again in range of one or more FFDs. The RFDs will move from stop to stop. To add to the random nature of the scenarios, the RFD speed is randomized as well.

After the three passes, the results are filtered for unwanted mobility side-effects. As RFDs may still be out of range of all FFDs on parts of their paths, all RFD positions are checked to be in range of one or more FFDs.

To maintain randomness while limiting the number of simulations, four different scenarios were generated for each number of FFDs and RFDs. Figure 6 shows the paths generated in the final step of the algorithm with four FFDs. As all paths remain within range of the FFDs, indicated by the blue discs, the scenario is not filtered out.

### C. Simulation Results

Figure 7 shows the mean channel utilization in the cloud scenarios, for the three protocol variants and a varying distance between the FFDs and FFDs. The number of RFDs is varied,

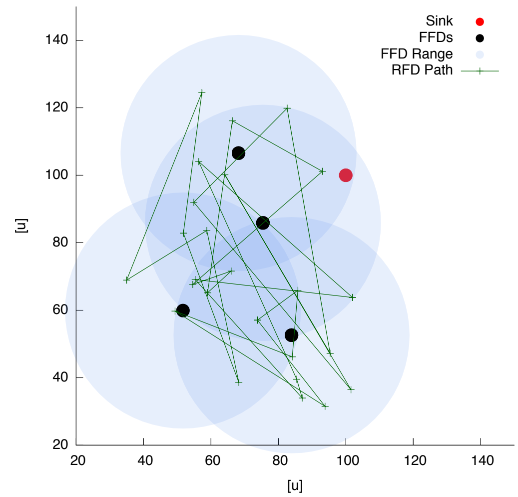


Fig. 6. Third step in random scenario generation: RFD paths are generated.

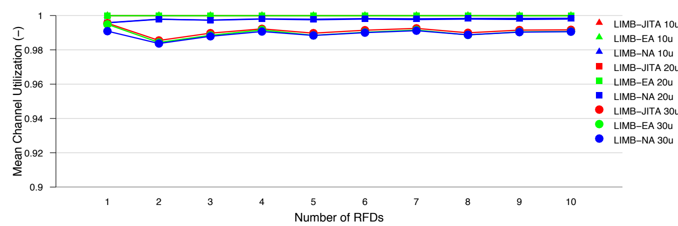


Fig. 7. Mean channel utilization in cloud scenario with RFDs at 10u, 20u and 30u from FFDs, for five FFDs and varying number of RFDs.

with five FFDs. The figure shows that the channel utilization is almost completely independent of the number of RFDs, given a sufficient number of FFDs, sufficient association slots and slots in the LIMB phase. Distance between the FFDs and the RFDs plays a very small role, only a small influence can be observed.

Figure 8 shows the mean channel utilization for five RFDs and a varying number of FFDs, for the same distances and variants. A larger influence of the distance between the RFDs and the FFDs can be observed. An increasing number of FFDs is required to benefit from the loose association, more specifically from the broadcast communication. LIMB-EA performs worse for a larger distance between nodes, with a lower channel utilization.

RFDs will consume significantly less energy than the FFDs, as a consequence the energy consumption of both node types

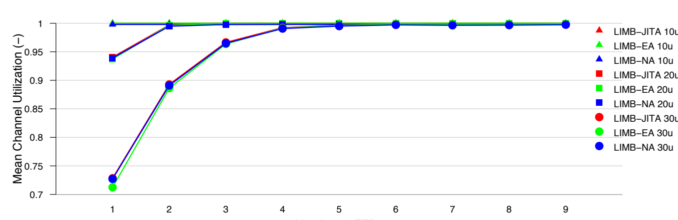


Fig. 8. Mean channel utilization in cloud scenario with FFDs at 10u, 20u and 30u from RFDs, for five RFDs and varying number of FFDs.

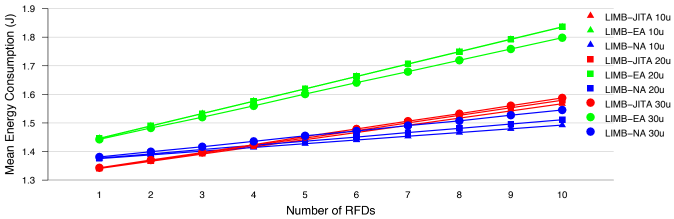


Fig. 9. Mean energy consumption of the FFDs in cloud scenario with RFDs at 10u, 20u and 30u from FFDs, for five FFDs and varying number of RFDs.

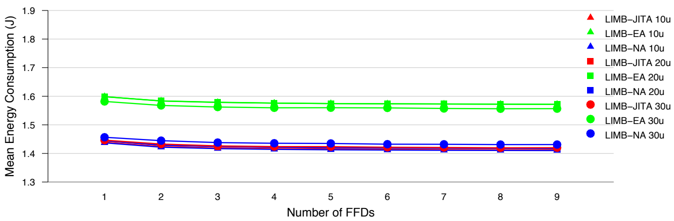


Fig. 10. Mean energy consumption of the FFDs in cloud scenario with FFDs at 10u, 20u and 30u from RFDs, for five RFDs and varying number of FFDs.

will be analyzed separately. Figures 9 and 10 consider the FFD energy consumption for respectively a varying number of RFDs and a varying number of FFDs. As expected, the former figure shows how an increasing number of RFDs increases the energy consumption of the FFDs. Because of the long association period, the LIMB-EA FFDs consume significantly more energy. For a varying number of FFDs, figure 10 shows the impact of the round-robin acknowledgment scheme. For more FFDs, each FFD has a lower acknowledgment transmission rate, leading to slightly decreasing energy consumption. The distance between the RFDs and FFDs plays a role in both FFDs energy consumption figures, especially for the LIMB-EA protocol. When the inter-node distance is larger, fewer associations are received by the FFDs, which sleep more and save more energy.

Figures 11 and 12 show the RFD energy consumption, for respectively a varying number of RFDs and FFDs. The figures illustrate how the energy consumption of the RFDs is independent of the number of RFDs. This illustrates how RFDs do not interfere with each other and how energy consumed by the RFDs is independent of the number of FFDs, given sufficient FFDs. An increase in energy consumption is only visible for a bad channel and a single FFD in the network.

The random scenarios focus on unstructured mobility scenarios and show different results. The channel utilization for a varying number of RFDs is shown in figure 13, for a varying number of FFDs in figure 14. It can immediately be observed that the performance of LIMB-JITA is poor, especially compared to the other LIMB variants. (This significant difference clearly motivates including the random scenarios.) This performance loss is considered to be caused by the FFD topology, as similar results were obtained when the distance between the FFDs was increased. This phenomenon will be studied in future work.

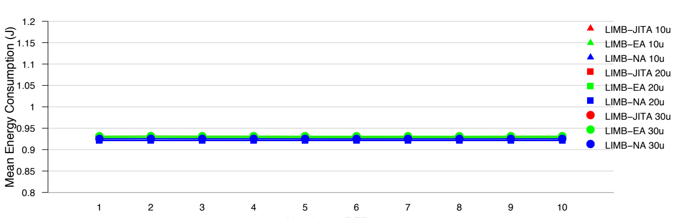


Fig. 11. Mean energy consumption of the RFDs in cloud scenario with RFDs at 10u, 20u and 30u from FFDs, for five FFDs and varying number of RFDs.

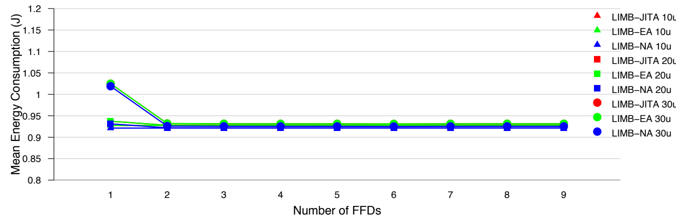


Fig. 12. Mean energy consumption of the RFDs in cloud scenario with FFDs at 10u, 20u and 30u from RFDs, for five RFDs and varying number of FFDs.

Figures 15 and 16 show the energy consumption of the RFDs in a more dark color and the FFDs in a lighter color. The plot closely resembles this of the previous scenarios, again with the difference for LIMB-JITA. The energy consumption of FFDs with LIMB-JITA is lower, indicating that fewer associations succeed. As a result, the FFDs will expect fewer data packets and sleep more, leading to decreased energy consumption.

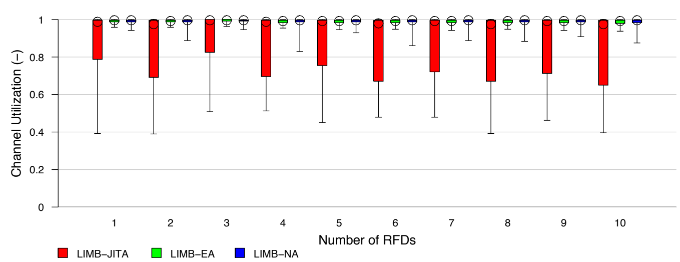


Fig. 13. Channel utilization in random scenario for five FFDs and varying number of RFDs.

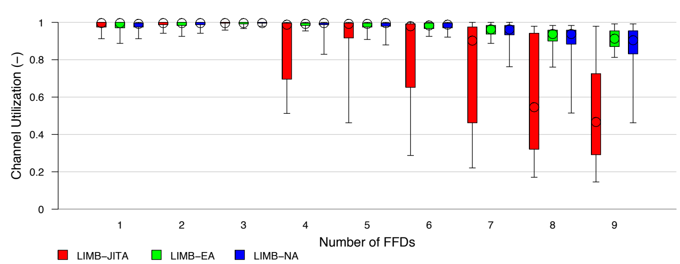


Fig. 14. Channel utilization in random scenario for five RFDs and varying number of FFDs.

## V. Conclusions and Future Work

This paper presented an extended simulation study of the LIMB protocols for mobile Wireless Body Area Networks.

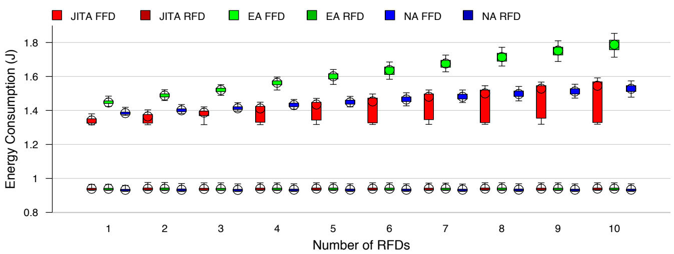


Fig. 15. Energy consumption of FFDs and RFDs in random scenario for five FFDs and varying number of RFDs.

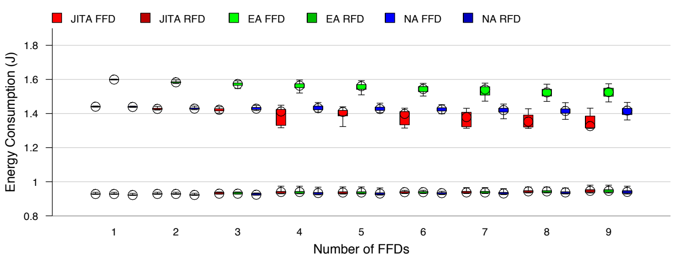


Fig. 16. Energy consumption of FFDs and RFDs in random scenario for five RFDs and varying number of FFDs.

It is shown that the protocols perform well, depending on the topology. More specifically, given a sufficient number of FFDs, the channel utilization and energy consumption of the RFDs is independent of the number of RFDs. The energy consumption of the FFDs depends on the number of RFDs to support and to a lesser extent on the number of FFDs.

Further analysis of the LIMB protocols will focus on the performance loss of LIMB-JITA in the case of the random scenarios, and the impact of the FFD topology in general. Moreover, assessing IEEE 802.15.6 integration is crucial to the general adoption of this work. Related, the impact of different backbone network protocols on the LIMB protocols will also be studied.

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