An Empirical Study of the Performance of IEEE 802.15.4e TSCH for Wireless Body Area Networks

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***Abstract*—Wireless Body Area Networks (WBANs) have made their way into many smart and ubiquitous healthcare and wellness applications. A low-power, efficient, and reliable communication protocol is of paramount importance for the success of WBANs in satisfying the requirements of the health applications. The IEEE 802.15.4 standard is always one of the main options due to its efficiency and low-complexity. However, it suffers from the impact of other wireless technologies using the same frequency band such as WiFi and Bluetooth. Time Slotted Channel Hoping (TSCH) is an operational mode of the IEEE 802.15.4e standard, which is originally developed for reliable industrial wireless networks. TSCH has Time Division Multiple Access (TDMA) and frequency hopping features, which increase the network robustness against effects such as noise, interference, and multi-path fading. This paper proposes to exploit TSCH for communications in WBANs, and studies its performance. The features of TSCH like power efficiency, TDMA-based operation, and heterogeneity support fit very well with the requirements of many health monitoring applications. The performance of the TSCH standard for WBAN communications is investigated through real-world experiments in various conditions. The results show that TSCH outperforms the basic IEEE 802.15.4 standard in terms of communication reliability against interferences from coexisting wireless devices.**

I. Introduction

Advances in the design of ultra low-power sensors, wireless transceivers, and embedded processors allow the realization of wearable and implantable bio-sensor devices. In a Wireless Body Area Network (WBAN), several low-power wireless sensors are deployed on/in a human body to measure the biological symptoms such as temperature, heart signals, blood pressure, and oxygen saturation. The sensory data is then sent to a border device to be further communicated to a health monitoring center for processing, storage, and necessary actions. The use of these networks reduces the medical costs, and increases the quality of life for patients under supervision.

WBANs have specific characteristics such as constraint in energy consumption due to small size of device, high mobility, and low radio transmission power. These specifications make the use of an efficient and low-power communication protocol very important. In particular, three standard communication technologies are considered for WBAN communications: IEEE 802.15.6 [1], Bluetooth Low Energy (BLE) [2], and IEEE 802.15.4 [3]. The IEEE 802.15.6 Task Group developed a communication standard optimized for ultra low-power devices operating around the human body. It defines a Medium Access Control (MAC) layer that supports heterogeneity in WBANs. Although this standard is especially designed for WBANs, there are no commercial implementations for experimental testing. BLE is a low-power and short-range communication technology developed by bluetooth SIG. It uses 40 frequency channels in the 2.4 GHz ISM frequency band. The main reason for using this technology in WBANs is that it is available in almost all mobile phone devices. The IEEE 802.15.4 standard is one of the most widely used standard in human healthcare applications. It defines the physical and MAC layers for Low-Rate Wireless Personal Area Networks (LR-WPANs). Physical layer of this standard uses the direct sequence spread spectrum (DSSS) technique for more tolerance against noise and interference. This protocol is of lower complexity and support various network topologies (e.g., star, peer-to-peer, and multi-hop tree).

Many wireless devices including WBAN sensors operate in the unlicensed 2.4 GHz ISM band. This causes communications of WBANs to be affected by other technologies which are operating in the same frequency band. WiFi, Bluetooth, and ZigBee are the main items [4]. For two reasons, WiFi is more important and can have more influence on WBAN communications. First, many WiFi devices (e.g., WiFi access points, laptops, and smart phones) may be present in the environments where WBANs exist. Second, WiFi uses larger packet size and higher transmission power compared to the other technologies operating in the same frequency band [5].

Due to the sensitivity of data generated by body sensors, the technology used in these networks must be highly robust against interferences. Among the technologies mentioned above, BLE performs well against multi-path fading effects and external interferences, thanks to its channel hopping feature. Time-Slotted Channel Hopping (TSCH) is an operational mode of the IEEE 802.15.4 standard for supporting industrial applications. TSCH used Time Division Multiple Access (TDMA) medium access mechanism with channel hopping. Thus it can be a promising option for communications in WBANs for several reasons: 1) TDMA-based operation of TSCH provides predictability and reliability for vital health related data delivery, by avoiding internal collisions; 2) frequency hopping feature reduces the impact of multi-path fading and interference; 3) TSCH provides the possibility of parallel transmissions leading to increased network bandwidth;

4) The DSSS technique increases the robustness in physical layer against noise; 5) TSCH inherits simplicity and flexibility of the base IEEE 802.15.4 protocol standard making it very efficient for computation/memory/energy constraint body sensor devices.

This paper proposes to use the TSCH protocol for communications in WBANs, and investigates its performance via extensive real-world experiments in various environments and conditions. We adapted and configured the TSCH implementation in the Contiki [6] operating system. Several wireless devices are installed on a human body and communications between them are logged in different environmental conditions, transmission powers, and postures. Also, all experiments are repeated in the same conditions using the basic IEEE 802.15.4 protocol for comparison. The results shows TSCH's considerably improved reliability compared to the base IEEE 802.15.4. This superiority is better visible, when lower transmission power is used by the body nodes. Moreover, even in the interference-free experiments, the TSCH performance is still better than IEEE 802.15.4, which can be explained by its ability to reduce the impact of multi-path fading and noises.

This paper is organized as follows. Section II reviews the standard technologies used for WBAN communications in literature. In Section III, a background about the TSCH mode of the IEEE 802.15.4 standard is presented. Section IV discusses the use of TSCH for WBANs. The experimental setups and the analysis of the achieved results are presented in Section V and VI, respectively. Section VII concludes.

II. Related Work

This section reviews the use of different standard wireless technologies in WBANs. The most important technology standards suitable for communications in WBANs are the IEEE 802.15.4, BLE, and IEEE 802.15.6. Each of these standard technologies has features and constraints, the performance of which for WBANs under different conditions is investigated in the literature.

Bluetooth Low Energy (BLE): This technology is developed for short-range low-power communication. [7] reports an experimental study on BLE-based WBANs, and investigates the coexistence capabilities of BLE in the vicinity of WiFi and IEEE 802.15.4 in a dense environment. [8] evaluates the suitability of BLE for WBANs with several slave nodes and high data rate traffic. Their study shows the BLE can be a good option for WBANs since its performance is not seriously affected by interference from other coexisting wireless technologies. Moreover, the availability of BLE radio transceivers in daily life smart devices (e.g., mobile phones and tablets) is a boosting factor in wide spreading usage of this technology in wearable devices. However, there are several drawbacks for using this technology in WBANs. The complexity of the standard specifications and its implementation, scalability and limited number of slaves, and the lack of multi-hop communication support are negative points about BLE for WBAN communications.

In order to achieve ultra low-power operation of WBANs, sensor nodes need to use very low transmission power. Considering sever influence of human body on wave propagation around/through the body, it is very likely that some nodes are not able to send their data packets directly to the gateway on the body [9]. In these situations, it is necessary for these nodes to possibly use multi-hop routes to deliver their data to the gateway [10]. Therefore, the protocol used in these networks should be able to support multi-hop communication.

IEEE 802.15.6: This standard is specially developed for WBANs, and many of the constraints of these networks are addressed in this standard. It includes several mediums such as Radio Frequency (RF) as well as Human Body Communications (HBC) at the physical layer. Also, this standard has a proper support of heterogeneity in the MAC layer, and supports up to two hops data forwarding. [11] uses analytical methods to evaluate the performance of IEEE 802.15.6 networks under non-saturation conditions. An evaluation of the performance of IEEE 802.15.6-based WBANs in terms of power consumption, throughput, and energy efficiency in unsaturated conditions is presented in [12]. In [13], the delay and throughput of these networks are evaluated via computer simulations. Although there are a few published implementations of IEEE 802.15.6 radio transceivers (e.g., [14]), the main problem of this technology is the lack of commercial radio chips. Moreover, single channel behavior of this standard in the RF versions make it vulnerable to external interferences from coexisting wireless devices.

IEEE 802.15.4: The main features of this standard are low-complexity, low-cost, and low-power operation as well as its ability to support various network topologies such as star, tree, and mesh. [15] uses computer simulations to evaluate the performance of the various access schemes of the base IEEE 802.15.4 standard in a WBAN with several nodes. [16] analyzes the performance of an IEEE 802.15.4-based WBAN with a star topology with a maximum of 10 nodes. [17] performs an experimental study, with two nodes, to investigate the effect of WiFi network on the IEEE 802.15.4 WBAN links. [18] investigates the impact of the number of network nodes, sampling rates, and transmission periods on the performance of an IEEE 802.15.4 network for ECG data delivery. IEEE 802.15.4 has shown to be a good choice for WBANs due features such as low-power and multi-hop communication. However, Although it exploits physical layer techniques like DSSS to improve resilience against noise, this technology is heavily influenced by coexisting technologies operating in the same frequency band.

TSCH inherits the low-complexity and low-cost features of IEEE 802.15.4 while it adds interesting features in the MAC layer like TDMA-based channel access and frequency hopping. Such features lead to better channel efficiency, higher level of predictability, and more resilience against interference from coexisting wireless devices. To the best of our knowledge, this is the first attempt to use this standard for WBANs. We implement a real-world TSCH-based WBAN, and study its performance under different conditions.

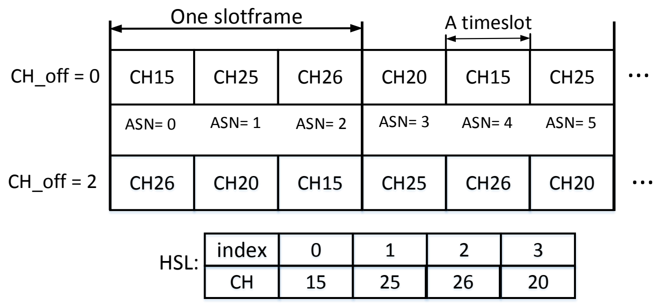


Fig. 1. TSCH slotframes structure illustrating two parallel slotframes

III. TSCH BACKGROUND

TSCH is an operational mode of the IEEE 802.15.4 standard which is developed for industrial applications. The physical layer of this standard is the same as the base IEEE 802.15.4 physical layer. Thus the same IEEE 802.15.4-compliant radio transceiver chip can be used for TSCH implementation in the firmware stack. The 2.4 GHz frequency band using O-QPSK+DSSS modulation scheme is the most widely used physical layer for this standard. There are 16 channels (channel 11 till channel 26) available in this frequency band, each with 2 MHz bandwith and channel spacing of 5 MHz.

The main features of the TSCH MAC layer mode are the TDMA-based medium access layer, and channel hopping. The TDMA mechanism provides a collision-free method for accessing the shared medium, which leads to efficient channel access and more reliability and predictability of the network. In TSCH, time is divided into equal length timeslots. Each timeslot is long enough for the exchange of a packet and its (optional) acknowledgment between a pair of nodes. A number of timeslots is called a slotframe which repeats over time. Fig. 1 illustrates the structure of a slotframe containing three timeslots. Wireless nodes align the boundaries of their timeslots using a synchronization mechanism specified by the standard. Moreover, there is a guard time in the beginning of each timeslot to compensate small misalignments caused by clock drifts. A timeslot may be dedicated to a node in a neighborhood for its collision-free transmission, or it may be shared between nodes to use a CSMA/CA mechanism for accessing the channel. The TSCH standard does not provides any scheduling mechanism for assigning timeslots for packet transmissions by nodes in the network; this task is left for the upper layers in the protocol stack.

Besides the TDMA mechanism, TSCH implements a channel hopping technique aiming at reducing the impact of multi-path fading and interference. In the 2.4 GHz frequency band, nodes jump to different frequency channel from the 16 available channels in this band. Thus, nodes do not stay in a single channel for their communications. The index of the channel in each timeslot is obtained from Eqn. 1.

$$CH = HSL\left[(ASN + CH\_Off)\% \; |HSL| \;\right] \tag{1}$$

where CH represents the channel number from a Hopping Sequence List (HSL). HSL is a especially ordered subset of sixteen frequency channels in the 2.4 GHz ISM frequency band, and $|HSL|$ denotes the number of channels in HSL. Absolute Sequence Number (ASN) is a global variable synchronized in the whole TSCH network, which counts the timeslots. TSCH provides the possibility of parallel communication in the network by using different channel offset (CH_Off). Given the number of available channels, it is possible to create up to sixteen parallel transmissions in a timeslot. Fig. 1 illustrates the channel hopping mechanism in a network using two channel offsets.

IV. TSCH FOR WBAN COMMUNICATIONS

We propose to use the TSCH standard technology for WBANs. It is expected to be a promising solution because of its TDMA-based channel access as well as the channel hopping mechanism, next to the other benefits of the base IEEE 8021.15.4 standard such as low complexity/cost/power, noise-resilient physical layer, and support of various topologies. This section discusses the suitability of TSCH for WBANs with respect to the WBANs' characteristic specifications.

The TDMA mechanism provides a collision-free communication for body sensors leading to reduced packet losses of vital body data, and less retransmissions required by the energy constraint body sensors. It also make the network predictable which is a requirement for many health applications. The number of wireless sensors in a typical WBAN is limited and thus scalability is usually not an issue. On the other hand, due to posture changes and movements, all nodes may be in the communication range of each other. Therefore, timeslot scheduling, which is a complex task in TDMA-based mechanisms, is not an issue in WBANs since a simple unique timeslot assignment to sensors with periodic data sampling works well. Moreover, TSCH mechanism allows shared use of timeslots. Shared timeslots can be exploited for transmissions of body sensors with sporadic or event-based data sampling. Thus, TSCH implementation for WBANs does not have the complexities involved in the large-scale WSNs.

WBANs are deployed on humans' body which are nowadays surrounded by many other wireless devices (e.g., WiFi access points) operating in the same 2.4 GHz frequency band. Using a single frequency channel has the risk of continuous interference from a coexisting wireless device which can lead to long disconnections of vital body sensors; it can lead to the failure of the whole healthcare application. Even if the interference does not completely block the medium, it increases the packet losses in WBAN which in turn translates to higher data delivery latency and higher energy consumption due to more number of packet retransmissions. The channel hopping mechanism of TSCH greatly addresses this risk by using different channels over time for WBAN communications. Thus if the WBAN is facing interference in some channels, it does not stick to those channels, and try all channels for its communications.

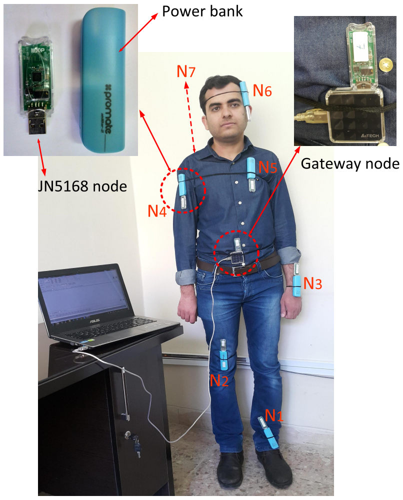


Fig. 2. WBAN node deployment in the conducted experiments.

V. Experimental Setup

We implemented our TSCH-based WBAN by adapting and configuring the TSCH implementation existing in the Contiki [6] operating system. This allows us to directly run the protocol stack on real wireless nodes. We use the NXP JN5168 [19] dongles which is supported by Contiki. JN5168 is a low-power SOC containing a 32-bit RISC embedded processor as well as an IEEE 802.15.4 transceiver. It provides a receiver sensitivity of -95 dBm, and several transmission power levels of up to 2.5 dBm. During the experiments, each dongle is equipped by a power bank as its energy source.

Eight nodes are installed on a person's body with height of 170 cm, and weight of 65 kg, as shown in Fig. 2. We use slotframes with 9 timeslots of length 10 ms. The first timeslot is assigned to the gateway node (the TSCH coordinator) for sending Enhanced Beacon (EB) packets that are used for synchronization and control data exchanges. All wireless nodes in the WBAN listen in this timeslot in every slotframe. The rest of the timeslots in the slotframe are exclusively dedicated to wireless nodes. After receiving the EB packet from the coordinator and connecting to the network, each node starts broadcasting one packet per slotframe in its own timeslot. To measure the link quality between all pairs of nodes, every node (including the gateway) listens to the channel in all timeslots (except its own transmission timeslot), and logs the packet reception status from all nodes in its memory. Each experiment runs for 1000 slotframes, which means 1000 packet transmissions by each node. Acknowledgement is disabled to avoid any packet retransmission, so that the quality of links in the physical layer is observed. After finishing each experiment, the gateway performs a process for gathering the logged data from all nodes. It then transfers the logged data to a computer.

Three postures are examined during each experiment, as *stand*, *sit*, and *lie down*. Moreover, wireless nodes use two different transmission powers ($0\ dBm$ and $-6\ dBm$). Thus there are six combinations of postures and transmission powers. Each combination for experiments is repeated in three different environment conditions (all indoor) resulting in 12

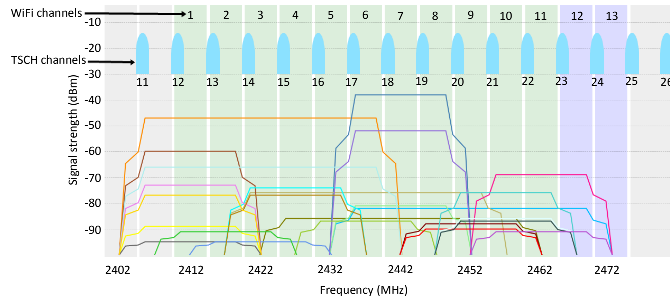
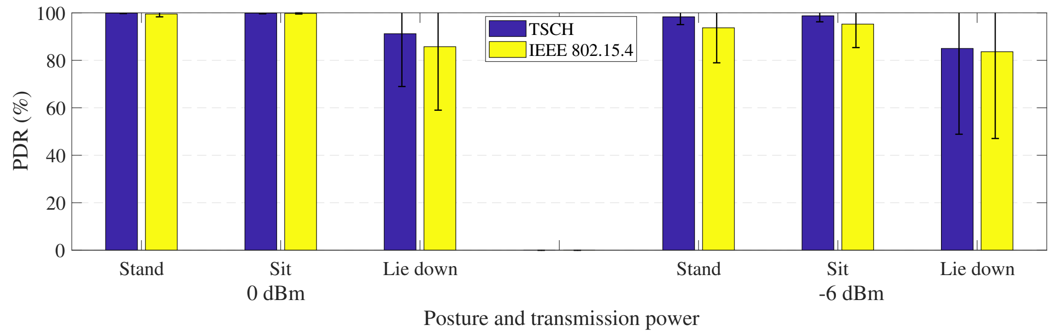


Fig. 3. The status of the 2.4 GHz spectrum in office experiments

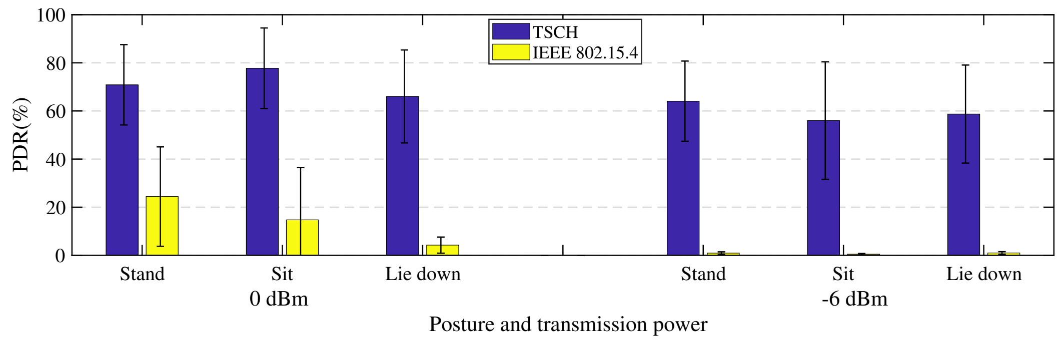
experimental setups. The first one is an interference-free condition in which we do not expect any other wireless device to coexist with our WBAN. The second condition includes controlled interference made by a WiFi modem (TP-LINK model TDW8901N) operating in the WiFi channel number 6 with 20 MHz bandwidth, and the maximum transmit power, transferring a big file to a mobile phone devices. The third condition is an office environment to represent a typical environment that a WBAN may experience. Based on our observations, this office is usually in the range of around twenty WiFi access points with different signal powers. Fig. 3 depicts the status of the 2.4GHz spectrum (derived from a WiFi analyzer application), while performing the office experiments.

Besides studying the performance of the TSCH-based WBAN, we aim at comparing its performance with the base IEEE 802.15.4 protocol. This standard has several modes of MAC configuration, and can perform a hybrid CSMA/CA and TDMA channel access mechanism. To have a fair comparison and exclude the effect of in-network collisions occurring due to CSMA/CA mechanism, we consider the beacon-enabled mode with communications in only Guaranteed Time Slots (GTS). Each experimental setup in the interference-free and controlled interference environments is tested once with the TSCH stack using all 16 channels in the 2.4 GHz for its channel hopping, and once with the IEEE 802.15.4 GTS mode operating in channel 17 (which overlaps with WiFi channel 6 that is being used in the controlled interference conditions). For the office experiments, three different experiments with the base IEEE 802.15.4 are conducted using three frequency channels (channels 12, 17, and 22 in the 2.4 GHz band).

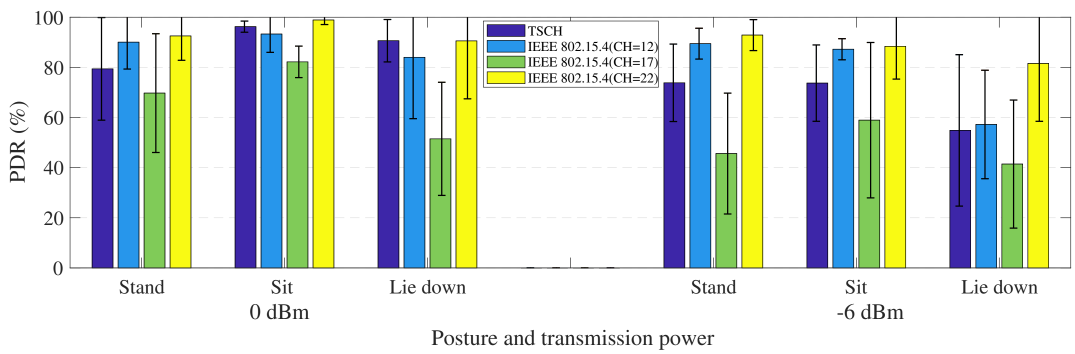
After performing the experiments, the logged data are processed to extract the Packet Delivery Ratio (PDR) for each link, which is the ratio of the delivered packets over the total transmitted packet in an experiment. This metric shows the reliability of the WBAN protocol in data delivery. In this paper, we present the average PDR over all links towards the gateway, and their standard deviations. Moreover, the maximum length of burst packet losses is measured and reported for each experiment. This metric shows the number of subsequent packet losses for the nodes, and reveals the ability of a protocol for providing continuous data delivery. The raw logged data is made available to the scientific community via www.es.ele.tue.nl/nes, in which we have link status from any node to all others.



(a) Interference-free environment



(b) Controlled WiFi interference environment



(c) Office environment

Fig. 4. Average PDR in different experiments performing in three environment conditions

VI. Result Analysis

Fig. 4(a) shows the achieved PDR in experiments performed in the interference-free environment. These experiments can show which part of the packet losses are due to other effects than external interference (e.g., signal attenuation through and around the body). Although, no PDR less than 80% is observed in both transmission powers, TSCH has performed slightly better than the base IEEE 802.15.4. This superiority can be explained by the impact of channel hopping of TSCH on multi-path fading effect. The effect of the transmission power is also visible in the lower PDR of experiments with transmission power of $-6\ dBm$. Regarding the posture, *lie down* is the worst case. The results of this case confirms the conclusions made in literature (e.g., [9], [10]) about the need for multi-hop communication in WBANs when very low transmission power levels are used.

In the controlled WiFi interference scenario, 4 channels of the 16 TSCH channels are affected by the interference. The results of this set of experiments are shown in Fig. 4(b). Note that the same WiFi interference patterns are generated in different experiments. As expected, TSCH shows considerably better performance than the base IEEE 802.15.4 because of the use of frequency hopping. The IEEE 802.15.4 is using channel 17 which overlaps with the used WiFi channel. Thus most of the WBAN packets are corrupted by strong WiFi signals. The situation gets worse when a lower transmission power is used.

An important point here is that, in these experiments, we have used the original TSCH network in which we have all 16 channels in the HSL. Thus, when four channels are blocked by an interference source, we loose around 25% of packets because we still use those channels in some timeslots. This shows the an adaptive channel blacklisting technique [20] is a necessary part of the TSCH mechanism to avoid using low-

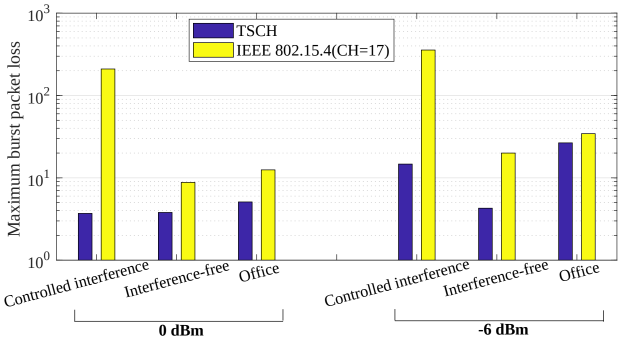


Fig. 5. Maximum burst packet losses averaged over all nodes and postures

quality channels. Such a mechanism continuously measures the quality of all channels, and accordingly adapt HSL at run-time to keep only good quality channels for channel hopping.

An office environment can represent the real situation in which a WBAN may operate. The interferences are not only from one source, and they may be dynamic over time. These tests were conducted in a 15 m^2 room. Fig. 4(c) shows the achieved PDR in the TSCH network as well as in the IEEE 802.15.4 experiments in three different channels. As the figure shows, when a channel with low interference is used for the IEEE 802.15.4 network, it performs well. But it can be the case that the used channel experiences a high level of interference leading to very poor link quality. This is while the TSCH network can continue to have acceptable link quality since it hops over all the available channels in this band.

An important feature of the TSCH protocol is that it helps the links to avoid getting disconnected for long periods of time due to interference or the multi-path fading effect. To evaluate the performance of the protocol in this regard, Fig. 5 (logarithmic) shows the maximum length of burst packet losses in the experiments averaged over all nodes and postures in each experiment. The IEEE 802.15.4 network experiences link disconnections for very long time, while TSCH can avoid such long disconnections. In the controlled interference scenario, the length of busts packet losses is orders of magnitude shorted in TSCH network compared to that in the base IEEE 802.15.4. This is because TSCH does not stick to a noisy channel all the time. Long disconnections can lead to application failure in many WBAN applications specially when it is about the health updates of the patients.

VII. Conclusion

This paper proposes to use Time Slotted Channel Hopping (TSCH), a medium access operational mode of the IEEE 802.15.4 protocol standard, for Wireless Body Area Networks (WBANs). The collision-free medium access together with channel hopping mechanism of TSCH make it a promising protocol for reliable, efficient, and predictable intra-WBAN communications. This paper investigates the performance of TSCH through real-world experiments in various conditions. Several wireless sensor devices are installed on a person's body and packet reception status of all linked are logged. The analysis of the logged data confirms the suitability of this protocol and its better robustness than that of the base IEEE 802.15.4, against interference from coexisting wireless devices. Also the results show that a channel blacklisting mechanism is a real necessity for the TSCH networks to provide the best performance.

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