UWB-TSCH : Time and Frequency Division Multiplexing for UWB Communications

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In this paper, we present UWB-TSCH, an adaptation of the Time Slotted Channel Hopping (TSCH) MAC layer design for IEEE 802.15.4 UWB PHY layer. This approach combines time division medium access with frequency hopping. It allows for UWB nodes to reach much higher channel occupancy than with ALOHA and to drastically reduce their energy consumption, allowing them to be used in low power wireless sensor networks. Moreover, we show that using multiple channels concurrently, localization schemes such as Time Difference of Arrival (TDoA) could reach in excess of 2400 localizations per second.

Keywords : UWB, ultra-wideband, TSCH, MAC, TDMA

1 Introduction

Ultra Wideband (UWB) is an RF communication technique that spreads the signal over a bandwidth larger than 500 MHz, typically by sending very short radio impulses. It allows precise estimation of *Time-of-Arrival* (ToA), making it a core component for centimeter-accurate positioning systems, especially indoors. Several approaches allow to perform UWB-based localization [A$^+$16] such as *Time Difference of Arrival* (TDoA), *Two Way ranging* (TWR), and *Angle of Arrival*.

To date, due to its inability to perform clear channel assessment, a feature required by CSMA, UWB is typically used with an ALOHA medium access scheme [Abr70]. Other medium access mechanisms have been discussed in the literature [M$^+$18, T$^+$07, GM07].

In this paper, we investigate the use of Time Slotted Channel Hopping (TSCH) as medium access mechanism. TSCH combines *time division multiplexing* and *channel hopping*, to achieve higher channel efficiency, more deterministic delays and increased robustness against RF interference. It has been standardized for specific PHY layers in a recent revision of the IEEE 802.15.4-2015 standard [IEE16].

However the standard does not provide any adaptation for its use with the UWB PHY layer. UWB-TSCH has been investigated by King et al. by choosing an UWB bitrate allowing to use the standard implementation of TSCH on OpenWSN [K$^+$17]. This paper goes further and discusses using TSCH with UWB, adapting from the current standard and the selection of UWB parameters. We support this discussion with a prototype implementation on an off-the-shelf embedded platform equipped with an UWB transceiver. The prototype allows DATA frames to be carried, possibly simultaneously, over multiple orthogonal channels. Finally, the prototype implementation is validated and its performance evaluated in a testbed with real nodes.

2 Timeslot

The operation of TSCH revolves around the communication *slot*, a precisely delineated interval of time during which a single transmission can occur. A TSCH slot is organized in 3 parts, as shown in Fig. 1. In the first part, the sender can optionally perform a *Clear Channel Assessment* (CCA) to assess if the channel is currently busy, for example due to an interfering source. In the second part, the sender transmits its DATA frame. Finally, in the third part, the receiver transmits an ACK frame, if requested by the sender.

The exact slot organization and duration depends on the PHY layer parameters. Among them, the most important is the PHY nominal bitrate as it impacts the DATA and ACK frame transmission times, hence the minimum achievable slot duration. The UWB PHY support 5 bitrates from 110 kbps to 27 Mbps. Another important parameter is the *Pulse Repetition Frequency* (PRF), a measure of how many pulses are sent on average per unit of time. Due to space limitations, we refer the reader to [C+16] for a more in-depth discussion of the UWB parameters and frame format. In Fig. 1, `MaxTx` and `MaxAck` correspond to the transmission times of the longest possible DATA frame and longest possible ACK frame respectively. The slot organization also depends on guard times that allow the nodes to slightly de-synchronize over time. The duration of those guard times depends on how much the clocks are allowed to drift from each other and the maximum interval of time between re-synchronizations.

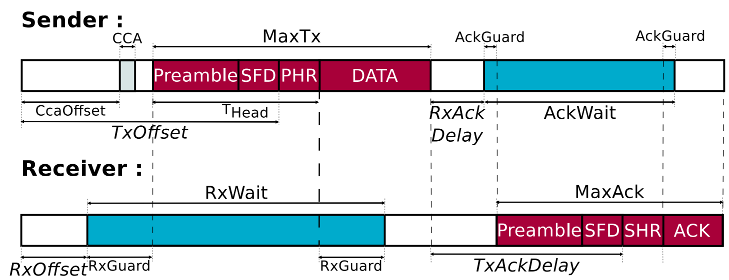

Fig. 1: Detailed view of a TSCH slot (this figure is not to scale).

3 Channel hopping

The IEEE 802.15.4 standard defines 16 channels for the UWB PHY, ranging from 249.6 MHz to 10.16 GHz [IEE16, P.463]. Fig. 2 shows a subset of these channels available on off-the-shelf transceiver [Dec16]. Channels 1-3 and 5 have bandwidths of 500 MHz while channel 4 has a bandwidth of 1331.2 MHz and 1081.6 MHz for channel 7.

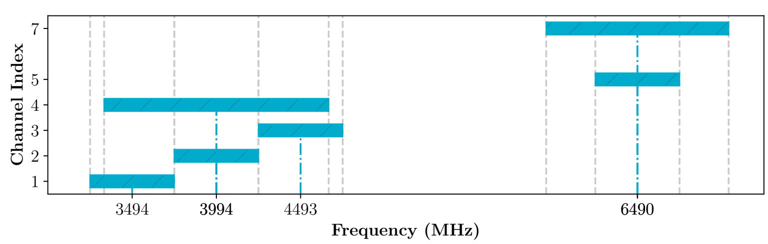

Fig. 2: Subset of the UWB channels defined by IEEE 802.15.4 [IEE16].

A clear observation from Fig. 2 is that some of the UWB channels overlap. However, TSCH does not mandate that channels be orthogonal for the operation of channel hopping. Still, when simultaneous use of different channels is required e.g. to increase the bandwidth, then only a subset of the UWB channels can be used. A more careful look of the Power Spectral Density (PSD) mask [IEE16] for each channel reveals that adjacent channels can also interfere with each other. For example, some overlapping still exists from channel 2 to channels 1 and 3. As a result, transmitting on channel 2 is likely to perturb channels 1 and 3 within a range of at least 10 meters [Dec17, P.7]. Thus, taking the PSD masks into account, only 3 out of 5 adjacent channels presented in Fig. 2 can be used simultaneously (i.e. channel 1, 3 and 5).

Different PRFs could allow to extend the number of available orthogonal channels. Concurrent communications on the same channel but with different PRFs should not interfere with each other [Dec17, P.5]. Using this approach, 3 concurrent communications can be performed simultaneously on the same channel using PRF of 4, 16 and 64 MHz.

4 Prototype and Validation

For our prototype implementation of UWB-TSCH, we rely on the Decawave DWM1000 UWB transceiver module and on the Zoul platform from Zolertia. On the software side, we use the TSCH implementation of ContikiOS. Our own radio-driver manages the UWB transceiver [C^{+}16] and we adapted the TSCH slot definition to the UWB PHY, as described in Section 2.

Timeslot parameters Table 1 shows the theoretical length, T_{Length}, of a timeslot for each UWB PHY parameter. We have validated our implementation using the 6.8 Mbps bitrate. The resulting slot is 2.5 ms long, that is four times shorter than a standard 2.4 GHz O-QPSK slot (10 ms). Due to the tighter time slot constraints of UWB-TSCH in comparison to the regular O-QPSK version, several adjustments were required in the ContikiOS TSCH implementation.

Tab. 1: Minimum T_{Length} (µs) as a function of PRF and bitrate.

PRF	**Bit rate (kbps)**				
(MHz)	**110**	**850**	**1700**	**6810**	**27240**
62.4	23981	5495	/	2196	1809
15.6	23781	5446	/	2189	1807
3.9	24154	4017	3172	2157	/
Max	24154	5495	3172	2196	1809

Channel hopping Extensive experiments were conducted to assess the performance of concurrent communications using all possible combinations of channels and PRF supported by the DW1000 transceiver. By virtual channel, we denote the association of a physical channel and a PRF. We used physical channels 1, 2, 3 and 5 with PRF 16 and 64 MHz. This leads to 8 distinct virtual channels, hence $\frac{8*(8-1)}{2} = 28$ possible combinations. In our experiments, we performed 40k simultaneous packets transmissions for each combination of two virtual channels. Figure 3 reports the loss rate measured during this experiment. On this figure, the x-axis shows the virtual channel. For example, x-axis "1-16" refers to physical channel 1 and PRF 16 MHz. The y-axis reports the loss rate obtained when a virtual channel is used simultaneously with either all other virtual channels (red bars) or all other virtual channels excluding physical channel 2 (blue bars). In all cases we observe that the loss rate stays well below 1%. We also observe that virtual channel combinations involving adjacent physical channels, e.g. (1, 2) and (2, 3), result in a slightly higher loss rate, thus corroborating the remarks about channel overlapping in Section 3.

Time synchronization To assess how well the implementation manages to keep the nodes synchronized to a source clock, we made an experiment with a linear topology composed of 5 nodes (4 hops) where node `N1` is the main source clock and the other nodes (`N2`-`N5`) stay synchronized. The experiment lasted 14 hours during which the delineations of more than 1 million slots per node were recorded using a logic analyzer. This allowed us to measure at every hop the difference of slot-start to the primary source clock (`N1`). Figure 4 shows the resulting error distribution. The synchronization error is close to zero for all nodes, meaning that the synchronization mechanism works well. The standard deviation of the error increases with the hop count. This is expected as the synchronization is performed hop-by-hop and errors accumulate along the path.

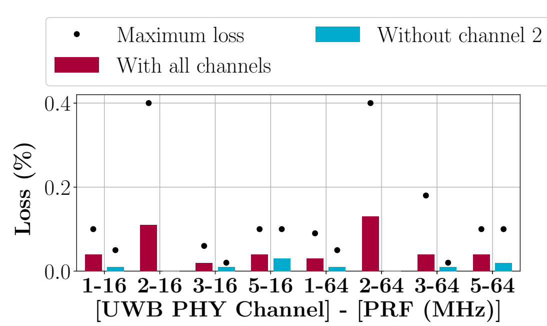

Fig. 3: Mean (bars) and max (dots) channel loss per channel/PRF combination.

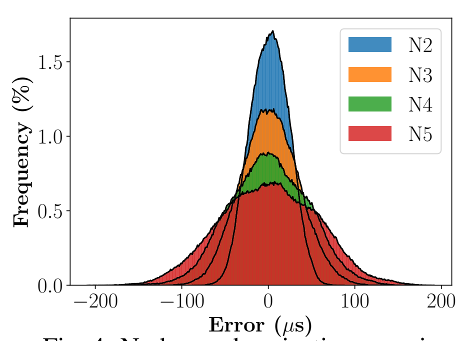

Fig. 4: Node synchronization error in µs.

5 Conclusion

This paper combines Ultra Wideband (UWB) communications, as defined by the IEEE 802.15.4 standard, with Time Slotted Channel Hopping (TSCH), a low power MAC layer that draws on time division multiplexing and channel hopping. We call the resulting protocol UWB-TSCH [C+19]. Compared to an ALOHA access scheme, UWB-TSCH allows more deterministic channel access and a higher channel occupancy. It also allows for the nodes to remain more frequently in a low-power state, saving substantial amounts of energy. To make UWB-TSCH possible, the time slot parameters are adapted to suit the UWB PHY. Moreover, the UWB channel diversity is investigated, especially with regards to nearby channels and the use of different Pulse-Repetition Frequencies (PRF).

To show the feasibility of our approach, we implement UWB-TSCH on an off-the-shelf platform to which we add an UWB transceiver. We implement our adaptations to the TSCH stack available in Contiki-OS. Although our implementation relies on the low-frequency real-time clock of the platform, we also make use of the high frequency timing capabilities of the UWB transceiver in order to meet some of the deadlines. We optimize the implementation to allow channels to change as fast as possible in order to keep the slot duration as short as possible. We perform extensive experiments to assess the ability for channel hopping and concurrent channel use with UWB. On this basis, we refine our selection of usable TSCH channels. Moreover, we measure the ability of the implementation to keep up with the stringent timing constraints of the timeslot. We show that the implementation is accurate enough to keep sender and receiver slot boundaries synchronized. This allows to reach a Packet Delivery Ratio higher than 99.999 % at a slot rate of 400 slots per second (time slot duration is 2.5 ms).

Acknowledgments

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