Wireless intra-spacecraft communication with inspaWSN protocol stack based on IR-UWB

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Abstract: In recent years, many attempts were made to replace wired connections with wireless communication networks in spacecraft and launchers. The benefits include a simplification of the harness design and routing as well as a reduction of harness cables and thus mass in space systems. However, commonly used wireless communication techniques are less reliable compared to their wired counterparts. Moreover, they are sensitive to RF interferences and multipath fading, which is an important design driver in a spacecraft environment with highly reflective enclosures. This paper presents a novel wireless protocol architecture for intra-spacecraft wireless sensor networks (inspaWSN), which makes use of the impulse-radio ultra wideband (IR-UWB) PHY according to IEEE 802.15.4-2011 and an optimized low latency and deterministic network protocol (LLDN) in order to achieve the strict requirements on existing spacecraft networks, e.g. low and deterministic latency behavior for the attitude and orbit control system (AOCS). The implementation and evaluation of the proposed protocol stack is performed on an STM32 microcontroller network consisting of 3 nodes. The results in this paper show that it is able to fulfill the strict timing requirements in order to accomplish deterministic communication with a latency of 10 ms and less in a typical AOCS configuration.

1. INTRODUCTION

Data exchange among spacecraft subsystems is usually achieved by employing field bus systems like SpaceWire. The necessary cable harness for these connections, however, is a significant cost driver in development and construction of these systems. In addition, the harness contributes up to 10% to the dry mass of a satellite and leads to additional launch costs.

Low power wireless sensor networks could be employed to reduce the design and integration cost of these wired systems and have proven their robustness on earth e.g. in industrial control applications. Benefits include: Mitigating risks of breaking cables or connector problems; easier accommodation and handling and faster setup of assembly, integration and test (AIT) tasks. Recent studies have already shown wireless sensor network operation in space is a viable approach ([1] and [2]).

The typical setup of such a wireless sensor network (WSN) aboard a spacecraft consists of a central coordinating unit that is directly connected to the on board computer and numerous sensor nodes distributed throughout the satellite structure providing the data connection for the different sensors and actuators of the subsystems. The most challenging one is the attitude and orbit control system (AOCS) comprised of e.g. sun sensors, magnetic field sensors, star trackers and reaction wheels or magnetic torquers as actuators. In order to guarantee the correct operation of the AOCS control algorithms, its latency and reliability requirements must be strictly adhered to.

Hence, a wireless data link needs to provide a reliable, deterministic and low latency connection for these sensors and actuators. This is achieved by employing a modified alternative time division multiple access (TDMA) medium access control (MAC) layer from the 802.15.4-2015 standard originally designed for low latency industrial automation systems. Another problem arises from the highly reflective enclosure, in which the RF components will be operated. This results in interferences due to multipath fading effects when using traditional narrowband RF systems. The proposed protocol stack mitigates these issues by introducing impulse-radio ultra wideband (IR-UWB) in the physical layer of the stack.

2. SPACECRAFT SENSOR OVERVIEW

Satellite systems contain a considerable amount of sensors to monitor and control mission-critical functions. Various types of sensors track the in-orbit performance, but they are also used in AIT activities to support the qualification of the satellite in different test campaigns. The sensors are usually assigned to the related subsystems of a satellite. The *thermal subsystem* sensors monitor temperatures and have a typical sampling rate of 10s-30s with no specific latency requirements. The *mechanical subsystem* uses sensors to check mechanisms in orbit (e.g. for solar panel deployment). Sensors in the *electrical subsystem* track currents and voltages. They are highly integrated into the different components and are an example of sensors not suitable for a WSN deployment. The *AOCS subsystem* finally is comprised of several sensors and actuators controlling the spacecraft attitude. It needs a reliable connection with low and deterministic latency with high sampling rates of up to 100 Hz.

The requirements for the wireless network architecture presented in this paper are derived from the DLR satellite Eu:CROPIS, demanding a deterministic latency under 10 ms.

3. PROTOCOL ARCHITECTURE

This work considers the first two layers of a typical network stack, the physical and the MAC layer, that are needed to provide the functionality outlined above. The upper layers can either use a traditional internet protocol stack, e.g. utilizing 6LoWPAN as a base for typical IoT networks or make use of the CCSDS [6] protocols specified for space applications.

3.1 IR-UWB PHY

The base of the implemented network stack is built upon an IR-UWB PHY that conforms to the IEEE 802.15.4-2011 [4] extension of the standard. Ultra Wideband possesses a low power spectral density avoiding interference with other RF sensitive systems. The transmission is also resilient against multipath fading effects, which is common for the metal enclosures of spacecraft or launchers.

IR-UWB can be operated on several channels in the range of 3.5 GHz to 6.5 GHz. Common narrowband technologies like Wi-Fi, Bluetooth or ZigBee cause interference with other systems operating in the same frequency spectrum. IR-UWB on the other hand generates short pulses (< 2 ns) to transmit the data. This short pulse duration thus spreads the spectrum to approx. 500 MHz using the same power output, which leads to a very low power spectral density. Due to the low signal level for any given frequency, UWB can easily coexist with other RF applications operated in the same frequency spectrum [5].

The pulse duration also allows UWB to be nearly immune against the multipath fading effects experienced within the highly reflective metal enclosures of a spacecraft structure [6]. Compared to other available PHYs for WSNs like ZigBee, WirelessHART or ISA100.11a, it provides a much higher data rate (up to 27.1 Mbps) and in turn allows to achieve the low latency required for the proposed application [1].

3.2 LLDN based MAC

The robust UWB physical transmission scheme is combined with a modified version of the low latency deterministic network (LLDN) MAC layer specification proposed in the IEEE 802.15.4e [7] extension, which ultimately was not included in the current 802.15.4 revision of the standard.

The additional MAC Layers of the 802.15.4 extension usually try to add robustness to the transmission over the traditional narrowband PHYs, e.g. by employing a channel hopping scheme. LLDN, however, is a simple TDMA approach with fixed timeslots and reduced header information. It only allows a star topology and thus deterministic and low latency for our desired application.

An LLDN network divides the time into superframes, which in turn are divided into equally-sized time-slots. A detailed chronogram of the operations that take place within one slot is shown in Fig. 1. A network coordinator takes care of assigning these slots to the nodes in a separate configuration phase and will send out beacon frames to synchronize the network. Since the slots for the nodes are configured beforehand, overhead for addressing is not needed as these can be inferred from the slot number. Another feature to shrink the header size are group acknowledgements (GACK), which allow the omission of separate ACK frames in most cases, as the coordinator will give out ACK information with the beacon transmission.

Although, from the same standard the LLDN scheme is not compatible with the UWB PHY layer, since some features like carrier sensing are not possible on a UWB Network and thus need to be implemented differently. A standard LLDN network uses longer slot times that include a contention based access time period for all nodes of the network and a time period for the coordinator in addition to the exclusive time period for the node the slot is assigned to. This mechanism prolongs the superframe and additional ACK frames and a CCA mechanism are needed. Using the bidirectional timeslots of the standard allows the same use cases with reduced need for a CCA scheme. However, during the non-time-critical management phases of the network this is not possible and a simple ALOHA scheme is used instead.

In addition management frames sent out by the coordinator allow to flexibly reconfigure the network to e.g. utilize a higher data rate compared to a typical WSN to transmit bigger blocks of data like firmware updates or payload data.

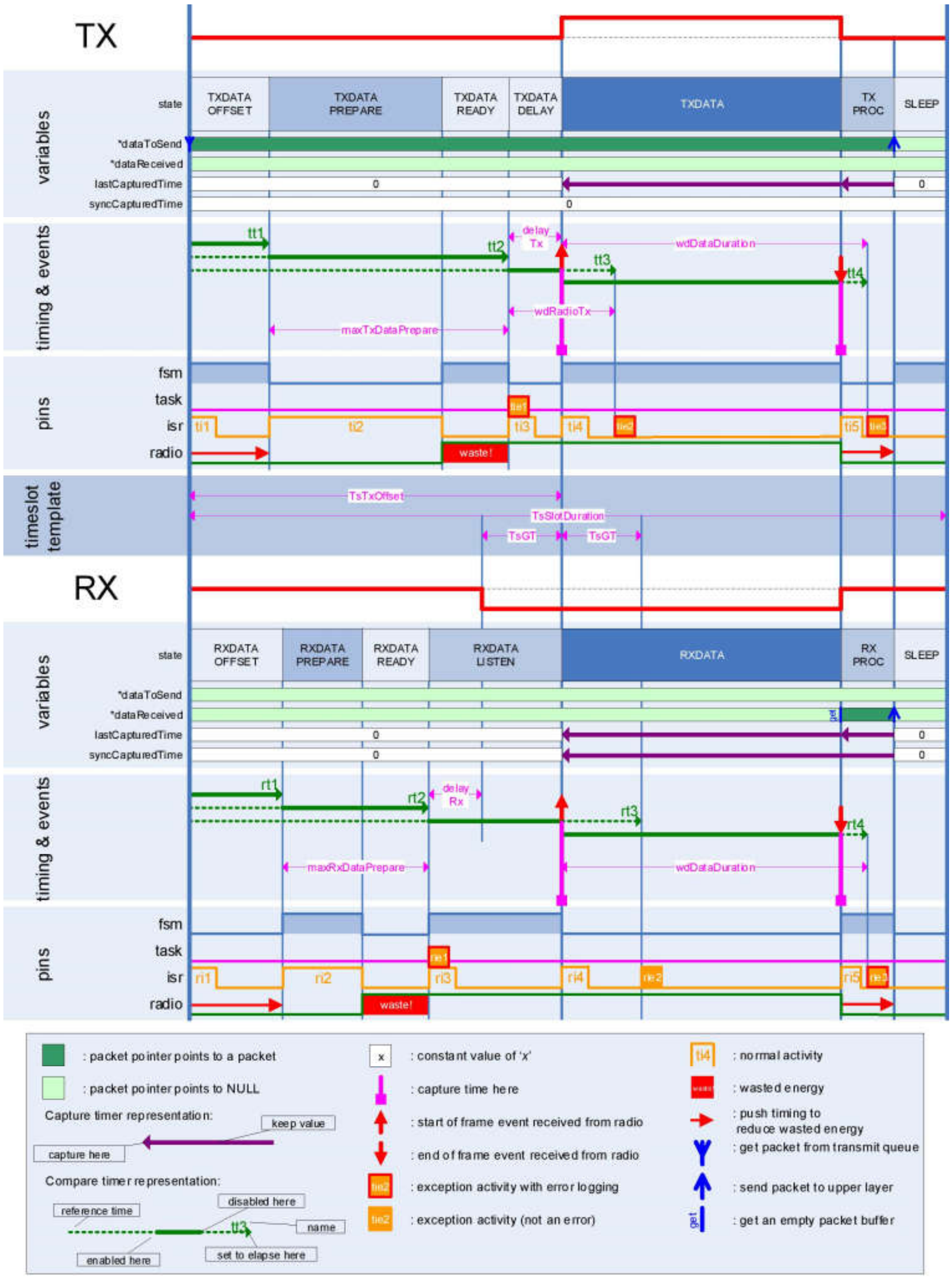

Figure 1: Chronogram of the LLDN MAC A single LLDN Slot is comprised of different phases the RX and TX node have to go through. In the first interrupts the node is prepared for the upcoming transmission in order to minimize the time needed during the actual event. This is done to reduce the time the receiving node stays in the RXDATA LISTEN phase, where the receiver draws a significant amount of power. Offsets from the precalculated reception time to the actual time are caused by clock drift and used to reconfigure the timers so the nodes stay synchronized.

4. EVALUATION

The proposed system architecture has been implemented on an STML151 Cortex M3 low power micro controller combined with a Decawave DW1000 UWB transceiver and integrated into an existing RTOS System. In a test network of three nodes an average minimum latency of 3.4 ms was achieved.

Two separate tests were conducted. In the first one the uplink processing was synchronized to the respective slot, which is possible because LLDN uses a fixed slot plan. This allows the minimum latency of 3.4 ms between generation of e.G. sensor data and its processing on the receiving node. Due to the fixed arrangement of the slots after they have been configured in the configuration phase of the LLDN protocol, this latency is also deterministic.

Results showed that a significant portion of this time, however, is consumed by the processing of the packets on the node and network coordinator. Latency proved to be deterministic due to the strict network topology and MAC scheme with jitter of about 100 μs.

In a second test the parameters regarding slot length and number of slots in the superframe were chosen in a way that allowed the modified LLDN MAC to be comparable to the popular TSCH MAC. Test data was queued for transmission at random intervals to spread communication attempts over the duration of the superframe of 60 ms. Results in Fig. 2 show that the TSCH MAC produces outliers where packets where received in the next superframe. This is caused by the rescheduling of slots that is usually used to switch channels on narroband PHYs used with TSCH. Deterministic latency is thus not achievable utilizing TSCH in this configuration.

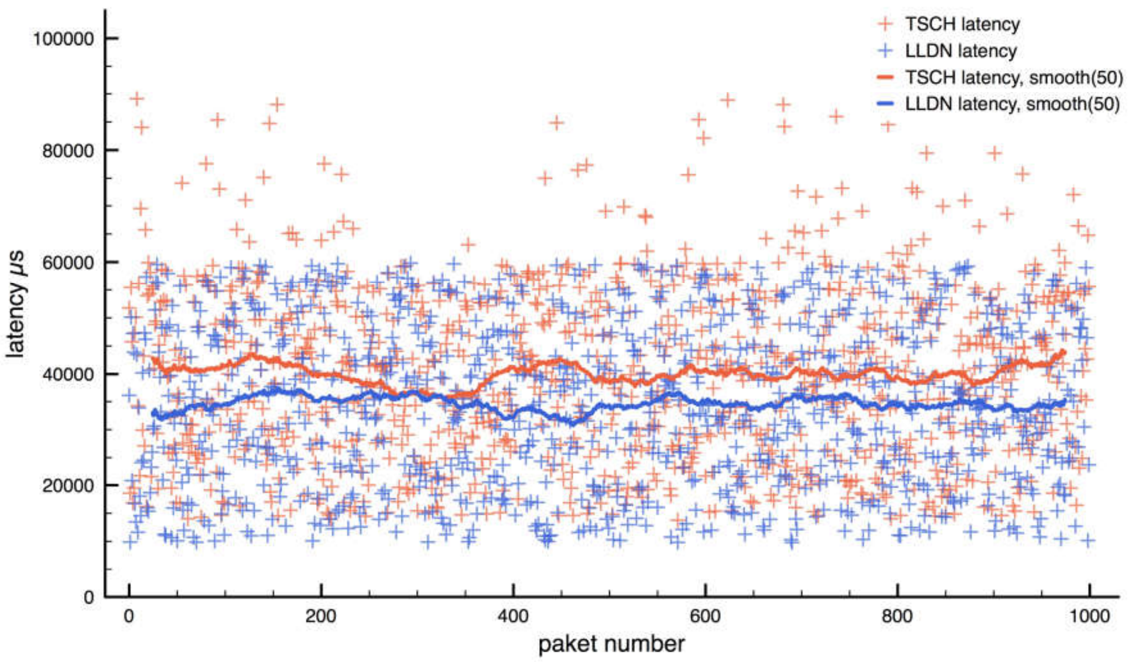

Figure 2: LLDN and TSCH mode latency comparison

Energy consumption is on par with other systems of this class with 3.63 mJ per packet for a standard wireless node. Deep sleep of a node is also possible and only requires a resynchronization to the network on wakeup, as LLDN does not keep track of the node state.

5. CONCLUSIONS

In this paper we presented inspaWSN, a novel wireless protocol architecture for intra-spacecraft wireless sensor networks. Key driver for its requirements were AOCS systems with their strict timing demands.

The required latency of 10 ms is easily met, but a usage of a more capable microcontroller with respect to computing power could further reduce the latency. The utilized IR-UWB PHY layer with the low overhead of the modified LLDN MAC proofs to be a robust combination. Future work will include further modification of the LLDN to optimize it for the specific requirements of intra-spacecraft communication. A second step will be the development of a low overhead transport layer to support applications developed for the platform.

It is planned to integrate inspaWSN into a future DLR satellite mission as a technology demonstrator payload in order to achieve a technology readiness level (TRL) of 8.

6. REFERENCES

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