Maximizing Throughput in Deterministic and Low Latency Intra-Spacecraft UWB Sensor Networks

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***Abstract*—Sensor networks based on Impulse-Radio Ultra Wideband (IR-UWB) technology have gained traction in fields where precise localization and robust communication links are required. In spacecraft and launchers these networks can be used to connect sensors to a central on board computer or to provide a communication link between the different subsystems. This contributes to a reduced cable harness, a key driver in overall spacecraft mass and design complexity. A problem in low power wireless sensor networks is the low data throughput. This paper presents a high data throughput extension to an 802.15.4 standard compliant MAC layer for Ultra Wideband to accommodate for e.g. payload data acquisition or software update distribution to the different subsystems. Where the previous protocol allowed for a mere 3 kB/s of throughput in a typical configuration, the augmented MAC layer now is able to achieve up to 341 kB/s.**

***Index Terms*—intra-spacecraft, satellites, wireless sensor networks, wireless communications, IR-UWB, MAC layer**

I. 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 (WSN) can 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: (1) mitigating risks of breaking cables or connector problems, (2) easier accommodation and handling and (3) 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], [2], [3]). 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 subsystems. The most challenging one in this regard 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, which was presented in [6] with the inspaWSN network stack. 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 enclosures, in which the RF components will be operated. This results in interferences due to multi path fading effects when using traditional narrowband RF systems. The protocol stack used for the high throughput operation mode mitigates these issues by introducing impulse-radio ultra wideband (IR-UWB) in the physical layer of the stack.

Wireless sensor networks, especially when compliant to the IEEE 802.15.4 standard are optimized for low power operation on constrained devices and employ physical (PHY) and medium access control (MAC) layers with low data throughput. The network architecture in [6], compliant with the 802.15.4, is only able to deliver a maximum transmission rate of 3.31 kB/s for a single node in a typical network consisting of four nodes.

To fully utilize the mass of such a network system and avoid additional cable or even wireless systems needed for the transmission of higher rate data the achievable throughput needs to be increased. The work presented in this paper focuses on an extension to an existing low latency TDMA MAC. In contrast to previous work ([5]), our approach provides consecutive time slots for point-to-point connections in a separate phase of the TDMA protocol it is able to provide a high speed stream connection. This in turn increases the overall throughput of the sensor network while maintaining the low and deterministic latency properties.

The remainder of this paper is organized as follows. An analysis of the timing and throughput behavior of the given medium access scheme is given in Section II. Implementation details on how the raw throughput can be optimized are also discussed. Section III describes the integration of the optimized implementation into the existing low latency and deterministic network stack. In Section IV the results and possible data rates when employing different configurations are discussed.

II. Data Rate Considerations

In contrast to most conventional wireless sensor networks, which utilize channel hopping schemes with scheduled link pairs to maximize throughput and reduce interference susceptibility, the low latency and deterministic network (LLDN) MAC chosen for our networks employs a simple TDMA scheme. This medium access scheme was chosen to reduce the overhead of managing a channel hopping MAC which in turn reduces the latency in the network. But also because channel hopping in ultra wideband systems with channel widths of up to 1 GHz would require broadband antennas with high bandwidth which are more susceptible to interference [8].

In TDMA based medium access schemes the nodes which are participating in the network are assigned to timeslots by a coordinating instance. Though advantageous for certain use cases this access method poses multiple problems for systems that need to transmit a large amount of data. Due to the constant synchronization necessary to mitigate clock skew between the different nodes, a time overhead is introduced. This could only be minimized with lower drift oscillators, which consume significantly more power. Guard times between the different slots cause additional overhead. The main cause of low throughput in a single channel TDMA network however arises from the fixed slot length assigned to each node. If a node does not use its slot fully or at all, airtime is wasted for other nodes in need of transmission capacity.

The following tests have been conducted using the Decawave DW1000 UWB transceiver integrated circuit (IC), an off-the-shelf component that offers different data rates of up to 6.8 Mb/s.

A. Timing Analysis

Another reason for low throughput arises from the fact that the radio transceiver cannot fully utilize its full physical transmission capability due to the fact that a constant bus communication with a micro controller needs to take place. This includes actually loading the necessary payload data into the transceiver buffers but also round trips for status checks or clearing of interrupts. In addition, each physical frame is preceded by a preamble for receiver synchronization and necessary start and end of frame indications.

Thus, a single frame transmission not only consists of the physical frame representation of the payload data that needs to be transmitted but is producing a significant amount of overhead, which is illustrated in Fig. 1.

The figure shows a simplified abstraction of the time necessary for a single frame transmission. Not taking into account the numerous bus round trips that need to take place e.g. for status checks, the frame is comprised of 4 different parts which make up the majority of the frame transmission time. The serial peripheral interface (SPI) transfer time refers to the serial interface used to connect to the transceiver IC. The majority of this time is dedicated to transferring the frame contents into the transceivers transmit buffer. Similarly, when receiving a frame, the same time is needed to transfer the received frame

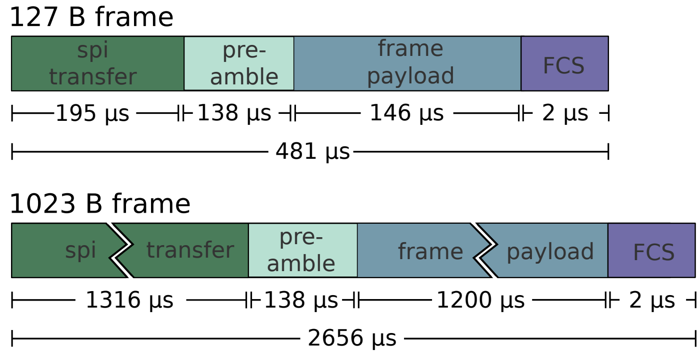

Fig. 1. Timing of a single slot in different frame length configurations for a transmitted frame in a 6.8 Mb/s IR-UWB PHY link

from the transceiver to the host micro controller. Only then the system is able to prepare another frame for transmission.

SPI transfer and the actual frame transmission by the transceiver are variable with the length of the frame to be transmitted. Another, rather large influence on overall transmission time is caused by the preamble, which for IR-UWB systems is much longer than for narrow band PHYs. Larger frames can be beneficial in channels with a high SNR due to the omission of repeated preambles with the short 127 B packet size mandated by the 802.15.4 standard.

B. Implementation Details

To mitigate these inefficiencies inherent in the control of the chosen UWB transceiver, an updated radio driver module was implemented. The goal was to optimize for maximum throughput in a point to point connection first and integrate this operation mode into the MAC as a separate phase in order to still allow the use of the low overhead LLDN features when high throughput is not needed.

Like most transceiver ICs, the DW1000 supports some hardware assisted frame handling features to minimize the round trips between the host micro controller and the device. Since it is optimized for standard 802.15.4 frames, it does not support the short LLDN frames, so the full overhead of source and destination addresses, pan_id, and so on. has to be transmitted when using them. To still be able to use the LLDN frame format, the driver can be switched into different operation modes. The default mode allows the low overhead LLDN operation when needed for the low latency part of a superframe. In addition it is also possible to to switch to a maximum throughput mode where all automatic features of the transceiver are used to maximize throughput in a continuous phase for a high speed transfer. The integration into the superframe structure of the LLDN MAC is discussed in the next section.

A basic hardware feature used are automatic acknowledgments (ACK). In a typical point to point connection all transmitted data packets are acknowledged by the receiving node with another packet containing their respective sequence number. Auto ACK allows the host micro controller to save a round trip communicating with the transceiver, as it handles the ACK itself. The TX is configured so that it immediately turns on the receiver after transmitting the frame and the receiver will immediately send the ACK frame once the frame check is successful. This saves the SPI bus round trips to configure the transceiver and to read the data on the receiving side to confirm that the frame is "good". This procedure saves a significant amount of overhead time, however, it requires the use of standard 802.15.4 frames which are unsuitable for operation in combination with the LLDN MAC layer.

A second feature that was implemented allows the use of double buffering on the transmit side. In the normal operation mode the contents of transmit buffer need to be transferred via an IC interconnect bus (SPI in this case) before the actual transmit of the packet can take place. Since the transceiver employed allows the use of a larger non-standard 1024 B transmit packet. It is possible to split the corresponding buffer into two logical ones and use them in an alternating fashion. While the transceiver is ordered to transmit one half of the buffer, the micro controller can simultaneously load another frame into the second half. This way, the time for SPI bus transfer and PHY transmit is used concurrently, increasing the net transmission rate.

For the maximum possible throughput these two features can be combined. While one half of the TX buffer is transmitting the radio driver just has to manage the retransmit in case the automatic ACK signals a timeout in packet reception. Other than that it can take care of loading the next half buffer into the transceiver.

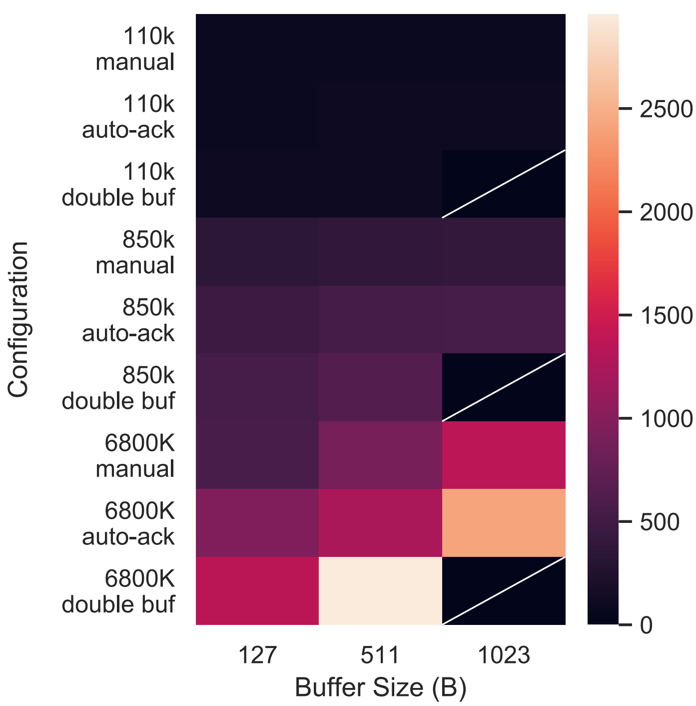

Fig. 2. Net data throughput in different configurations of PHY data rate and different driver modes

Fig. 2 shows the achievable net throughput in a point to point connection with different data rates and in the different driver modes implemented to support higher transmission speed. The DW1000 transceiver offers different PHY data rates of 110, 850 and 6810 kBit/s respectively. Measurements have been conducted for the different driver modes implemented for the high speed point to point transfer. The *manual* mode refers to the original radio driver, where no special handling of the transceiver and data is done. In *auto-ack* mode only automatic ACKs are used, whereas in *double buf* automatic ACKs as well as TX double buffering is employed.

Due to the nature of double buffering, the full transmit buffer of 1024 B cannot be used in this case and has to be divided into 2 equal buffers of 512 B each. Compared to the auto-ack operation mode, where the full 1024 B frames can be transmitted, the double buffering mode is still significantly faster due to the fact that the buffer loading and transmit time takes place simultaneously.

Little difference in throughput is seen with low PHY speeds as the overhead is small compared to the actual transmission time needed. The maximum data rate is achieved in the double buffering configuration with a 6.8M PHY rate at 2956 kb/s.

III. MAC Layer Integration

The implementation details discussed up to this point are merely referring to a point to point connection between two nodes and the maximum throughput that is achievable using low power UWB transceivers and micro controllers. The goal was to integrate a means of high throughput into our existing inspaWSN protocol stack with its low latency and deterministic MAC layer implementation [6] for the IR-UWB PHY.

This section will give a short overview of the existing PHY and MAC and how the high data rate point to point mode was integrated into the protocol stack.

A. PHY Overview

The foundation of the implemented network stack is built upon an IR-UWB PHY that conforms to the IEEE 802.15.4a [7] amendment of the standard which was introduced to specify alternate PHY layers of which IR-UWB should provide a precision ranging capability. In addition UWB possesses a low power spectral density avoiding interference with other RF sensitive systems. The transmission is also resilient against multi path fading effects, which are common for the metal enclosures of spacecraft or launchers.

The IR-UWB transceivers used for this work 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 traditional 802.15.4 PHYs 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. 500–1000 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 [8], [4]. The pulse duration also allows UWB to be nearly immune against the multi path fading effects experienced within the highly reflective metal enclosures of a spacecraft structure [10]. Compared to other available PHYs for WSNs like the classic 802.15.4 ones, 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 application in critical sensor networks, where it is needed e.g. for the attitude and orbit control system [1].

B. LLDN MAC Overview

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 [11] extension, which ultimately was excluded in the current 802.15.4 revision of the standard.

The 802.15.4e extension proposes additional MAC layers in an attempt to add robustness to the transmission over the traditional narrowband PHYs, intended for industrial control applications. This is done e.g. by employing channel hopping schemes as in the popular time slotted channel hopping (TSCH) MAC. The low latency and deterministic network (LLDN) extension, 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 in control systems with strict timing requirements. It is implemented in our inspaWSN protocol stack for low power micro controllers [6].

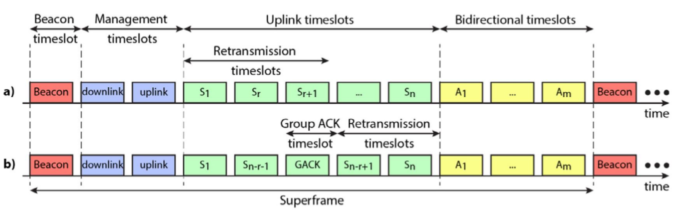

Fig. 3. Traditional LLDN superframe

An LLDN network divides the time into superframes (see Fig. 3, which in turn are divided into equally-sized time-slots. A central network coordinator node takes care of assigning these slots to the nodes in a separate configuration phase and will send out beacon frames in regular intervals to allow the nodes to synchronize to 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 acknowledgments (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 due to the missing carrier 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. Since this is not possible with the IR-UWB PHY, the approach up until now was to utilize the bidirectional timeslots for the transmission of larger data blocks. However, since the transmission direction (from-coordinator / to-coordinator) in this slot phase toggles with each superframe, the throughput is just half of what the data rate during the uplink slots provide.

Despite the fact that the ALOHA time hopping channel access method proves to be detrimental to overall throughput in UWB networks, it is used during the non-time-critical management phases of the network to provide a basic level of collision avoidance [9]. The management frames sent out by the coordinator during these phases allow to flexibly reconfigure the network to e.g. add new nodes to the network or reconfigure in case of a node failure.

The timing in a typical LLDN superframe can be seen in (Fig. 1). The worst case configuration is a superframe with the same amount of bidirectional and uplink timeslots. The resulting overall superframe time is given with n uplink slots with r retransmit slots. The slot time for retransmit is T_d and for regular transmit during uplink or bidirectional slots T_i. Since bidirectional slots need an additional turnaround delay T_{dly} and time for the ack (T_{ack}) they are factored in as well.

$$\tau = r \cdot T_d + \sum_{i=0}^{n} (2T_i + T_{dly} + T_{ack}) \qquad (1)$$

The modified LLDN and UWB prove to be an ideal combination: The rather simple TDMA MAC scheme with no channel hopping does not produce additional overhead to cope with robustness issues of the underlying PHY and thus is able to deliver lower latencies.

C. High Data Rate Subframe

As described in II there are additional radio driver modes available now to integrate a high speed transmission phase into the LLDN superframe. For the traditional, low latency operation mode of the MAC these can easily be configured on a per slot basis.

The main idea is to keep the superframe length τ the same as for the traditional LLDN operation mode. To achieve this, a high data rate (HDR) phase is inserted into the superframe at the expense of some of the bidirectional timeslots (see Fig. 4). As described in the last section, LLDN bidirectional slots are mainly used for large data block transmissions or for actuator control with the former use case now being replaced by the HDR phase. The original standard allows multiple nodes to be assigned to the remaining bidirectional slots. Frames sent from the coordinator in the bidirectional slots are using standard headers containing addresses, so nodes can distinguish if packets are intended for them. Only the original slot owner is allowed to uplink data frames in a bidirectional timeslot. Additional listening nodes are assigned only to be able to hand down information from the coordinator. As all the phases within the LLDN are configurable, the overall throughput is highly dependent on the configured length of the HDR phase in relation to the rest of the superframe.

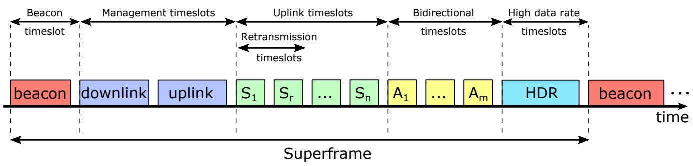

Fig. 4. High data rate (HDR) phase inserted into the original LLDN superframe

If a node needs to transmit larger amounts of data, it can request to send during the HDR section of the superframe using an LLDN MAC command frame with the newly added id `0x21` to indicate an HDR phase with the requested node. The coordinator will inform the target peer in its assigned bidirectional timeslot of the request so it is able to wake up its receiver to listen during the HDR phase of the superframe. Only then the coordinator will respond to the requesting node with a response command frame for the HDR section indicating a clear-to-send. It will also mark the HDR section of the frame as "in use" and deny further requests by other nodes to use the section until the original requesting node issues another HDR command frame indicating it finished its transmission or after a timeout, a maximum time after the initial clear-to-send, where all transmissions in the HDR section need to be stopped.

Since HDR transmissions mandate the use of full header data frames, even peer to peer connections are possible in the network, which is usually a problem in standard LLDN networks, as these connections are only possible during shared group timeslots which require a working CCA mechanism. As stated earlier, this is a problem with a UWB based system, since no reliable CCA can be performed here. In the implementation up until now, all information needed to be routed via the coordinator, which diminishes data throughput even further, when in need of a direct connection between different nodes in the network.

$$\tau = r \cdot T_d + \sum_{i=0}^{n}(T_i + \frac{T_i + T_{dly} + T_{ack}}{k}) + \sum_{j=0}^{k}(T_k) \quad (2)$$

In (2) the worst case superframe configuration for LLDN with HDR is given. Transmission within bidirectional and HDR phases of the frame is split according to factor k. Timeslots for T_k can also be shorter than for T_i slots, since using the time saving radio driver features within this phase reduces the time needed for a data and ACK roundtrip between two nodes. In addition within the T_k slots the nodes do not have to adhere to the slot plan but will rather transmit as fast as possible until a certain threshold before the end of the HDR phase is reached. This way the necessary guard times between the slots can be omitted and ideally more data is transferred. Thus it can be seen that overall superframe length stays the same or is even shorter than for the original LLDN superframe configuration.

IV. Evaluation

For the evaluation of the implemented LLDN MAC layer extension, a current German Aerospace Center (DLR) development board for UWB was used (Fig. 5). It is comprised of a sensor base board with RS422 transceiver and a COTS system on a chip with an STML151 ARM Cortex M3 low power micro controller connected to a DecaWave DW1000 IR-UWB transceiver with a matching broadband antenna.

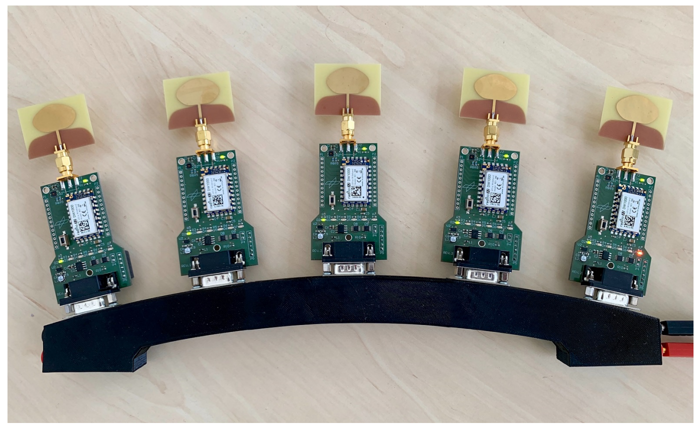

Fig. 5. Development boards used employing a Cortex M3 microcontroller in combination with a DW1000 UWB transceiver.

In previous experiments (see [6]) the performance of the LLDN MAC was already assessed against the popular TSCH MAC by controlling for various configuration factors of both to ensure that a superframe of the same slot length with equal transmission opportunities for the different nodes is constructed (Tab. I). With an optimized superframe for the LLDNs increased timing efficiency the throughput was higher at 3.3 kB/s in a network consisting of 4 nodes, but still far below what is needed for larger amounts of data.

To keep the measurements comparable for the new HDR extension of LLDN, a similar superframe configuration compared to the previous tests was chosen. In addition to the coordinator, four nodes are added to the network. When using a slot time of 3325 μs, the slots needed are:

- a beacon slot
- two uplink slots for possible retransmits
- four regular uplink slots for the nodes
- one bidirectional slot for the coordinator to downlink data to the nodes and
- three HDR slots to be reserved for high speed data transmission phases

This results in a total superframe length of 36.575 ms, the same as for the previous tests comparing different MAC layers but now with the addition of the HDR phase.

When looking at just the transmissions possible in the HDR phase of the frame, the throughput between two nodes in the given superframe configuration can either be at around 157 or

TABLE I
THROUGHPUT FOR DIFFERENT MAC LAYERS IN A NETWORK OF 4 NODES

MAC Type	Superframe Length	Payload Length	Throughput
LLDN	60 ms	124 B	2.02 kB/s
TSCH	60 ms	120 B	1.95 kB/s
LLDN opt.	36.575 ms	124 B	3.31 kB/s

341 kB/s, depending on the frame size chosen (see Tab. II). When deducting the overhead of header and CRC in the frame check sequence, possible net payload sizes of 115 B and 500 B can be achieved per packet. The higher data rate of 341 kB/s can be reached, if the bigger non-standard packets are chosen. With the double TX buffering approach, a frame size of up to 512 B can be achieved.

TABLE II
THROUGHPUT FOR DIFFERENT HDR PAYLOAD LENGTHS

Net Payload Length	Full Frames / HDR	Throughput
115 B	14	157.22 kB/s
500 B	7	341.79 kB/s

Since the nodes operate in an unslotted mode during the HDR phase, there is the possibility of not being able to fully utilize it. If the end of the phase is closer than a full frame transmission and ack cycle, an internal flag is set so that no new transmission can take place to avoid running over the superframe boundary. In a worst case, almost a full frame cycle could stay unused. In very short HDR phases the possibility of this happening is higher and the use of 127 B frames might prove beneficial, since more of them can fit into the time frame.

V. CONCLUSION

Increasing the data throughput of nodes in wireless sensor networks allows them to be used for additional tasks that previously needed other methods of data transport. This is especially true for networks operating in harsh environments, where mass and energy constraints are key factors for designing such networks.

This paper presents an extension to a low latency and deterministic MAC layer for IR-UWB that is able to provide much higher data rates at 341 kB/s in a typical configuration compared to the unmodified MAC layer. Using an optimized radio driver in combination with unslotted phases within the defining superframe TDMA structure of the MAC it is able to establish streaming point to point connections between nodes in the network.

For the proposed application of intra spacecraft communication this means it is possible to not only transfer sensor data with low latency, but also to transmit e.g. science data from a payload or image data from on board cameras. But also in AIT scenarios, fast rate sensor readings that are not time critical can be transferred after buffering on the acquiring node.

Future work will include further optimizations to the MAC layer of inspaWSN. For the HDR feature specifically the possible dead time at the end of the phase needs to be addressed. In its current form, further transmissions are prohibited, if the HDR phase end is not sufficient to guarantee a full frame round trip. This could be optimized so that the remaining time is used to calculate a possible fragmentation of the frame to be sent and use the remainder of the high speed phase to transmit the first slice of the fragmented MAC payload. This way, the full airtime of the HDR phase could be used. The impact of interference during the large 1024 B frames that are used needs to be investigated as well. Small interference factors in the channel could significantly lower the overall data throughput if these large frames need frequent retransmission. In this case, an automatic switch to the 127 B standard operation mode could be discussed to improve robustness of the transmission while still delivering a reasonable data throughput.

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