A Hybrid MAC Layer for Localization and Data Communication in Ultra Wide Band Based Wireless Sensor Networks

Manuel Janssen, Andreas Busboom, Udo Schoon, Carsten Koch, Gerd von Cölln
Hochschule Emden/Leer
University of Applied Sciences, Germany
Department of Informatics and Electronics
Email: {Carsten.Koch, Gerd.von.Coelln}@hs-emden-leer.de

Abstract—**This paper presents a hybrid MAC layer design for UWB based sensor networks to handle multiple access with the ability to combine localization and data communication. UWB networks allow high precision ranging and robust data communication in harsh environmental conditions and for this are well suited for typical automation applications. To minimize localization errors in this applications, e. g. by moving sensor nodes, rangings have strong realtime requirements and must be done in a distinct pre-defined order. This can not be guaranteed in common MAC layer implementations, which are typically based on the IEEE 802.15.3 standard with contention access (CSMA/CA) and contention free access part (TDMA). The MAC scheme proposed in this paper overcomes this limitations as the contention access part is replaced by a TDMA/CDMA scheme. Evaluation results presented in this paper show that this novel approach outperforms existing schemes and fulfils the requirement for realtime ranging and communication.**

I. Introduction

Wireless Sensor Networks (WSNs) are becoming more and more important. Due to their flexibility, they are used in many types of applications, especially for sensing predefined parameters of a surrounding area. In addition to communication for sensor data exchange, localization and tracking functionality is of high interest. This offers new monitoring options which can be helpful for example in safety critical applications.

A. Motivation

With the massive expansion of offshore wind farms, there is an increasing need to perform offshore operations as efficiently and safely as possible. The research project SOOP focuses on this topic. SOOP stands for Safe-Offshore-Operations and is promoted by the European Regional Development Fund (ERDF). The main goals of SOOP are to increase personnel safety, to improve the environmental protection, to enhance process reliability and to reduce overall cost through increased efficiency. One objective of SOOP is to realize a sensor-based assistance system [1], [2], which is explained in detail in [3]. Affected by harsh environmental conditions and the demand of a highly precise localization and communication scheme, Ultra Wide Band (UWB) was selected as a suitable radio technology. This radio technology allows robust simultaneous rangings and communication in moderate ranges with low energy consumption (depending on the usage of an optimized transceiver ASIC). The contribution of this paper is to present a novel proposal about a centralized hybrid MAC layer design for UWB based WSNs. Based on the IEEE 802.15.3 MAC, the main property of this MAC Layer is to combine the usage of CDMA and TDMA which increases the throughput of the network and brings advantages in consideration of ranging measurements and their critical time behaviour for position calculation.

B. Related Work

Design and implementation of new MAC layer protocols optimized for UWB is object of current research [4]. MAC layer protocols can be classified in contention free or contention based protocols or a combination of both. Another distinction can be made by centralized or decentralized (distributed) MAC protocols [5]. One candidate for contention free protocols is the Time Division Multiple Access (TDMA) protocol [6]. In the class of contention based protocols, CSMA/CA and ALOHA based protocols are well known solutions to handle multiple access [6]. One disadvantage of contention free protocols like TDMA is that they are not flexible against changes in the network topology, due to the fact that they have to organize the slot assignment within the network for each user. As a result of the slot assignment, it is possible to switch client nodes into sleep mode during inactive or unused time slots to decrease idle listening, which leads to a lower power consumption [7]. However, contention access like CSMA/CA shows good benefits relating to changes in the network topology, but is not suitable for UWB based networks, due to the *listen before talk* mechanism, which requires sensing the medium. Sensing the medium presents a difficult task in coherent UWB based WSNs, due to the fact that transmissions of other users in the network will be perceived as noise, if signal coding is unknown [8]. A commonly used MAC protocol is the IEEE 802.15.3 MAC, which is designed to support additional physical layers such as UWB [9]. The IEEE 802.15.3 MAC is a centralized beacon enabled protocol. That means, several wireless devices can form a piconet in which one of them is the so called piconet coordinator (PNC). The main task of the PNC is to coordinate peer-to-peer communication between devices. Timing defined in IEEE 802.15.3 MAC is based on the time-slotted superframe structure, as shown in figure 1 and [10], [11].

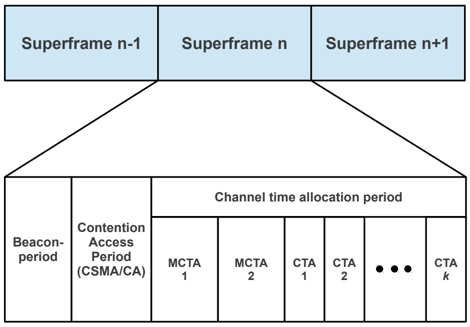

Fig. 1: The IEEE 802.15.3 MAC frame structure

In each superframe, the PNC sends a beacon to all other devices in his piconet for synchronization, channel-time allocation and management-information distribution. During the contention access period, all devices will be sharing the channel by the use of CSMA/CA. Also the IEEE 802.15.3 provides quality of service (QoS) for isochronous traffic. Therefore the PNC assigns channel-time allocations (CTAs) to devices over TDMA for contention free data transmission in the CTA period (CTAP). Combining asynchronous CSMA/CA-based random access and scheduling-based guaranteed access, the IEEE 802.15.3 MAC has a high flexibility, efficiency and QoS [12]. Due to the centralized network topology, a single-point-of-failure problem can possibly occur. So it is necessary to ensure, that the central device (PNC) is available for the most of the time or to provide multiple central devices as backup, which increases the complexity of the network management. Another big challenge is to handle inter-piconet interferences, because it is much more difficult to manage and decrease the network performance significantly. [9], [10]. Another example of a promising MAC protocol is the Complementary Code-CDMA-Based MAC Protocol for UWB which is described by J. Zhu and A. O. Fapojuwo in [9]. It is also a hybrid centralized beacon enabled MAC protocol. The basic idea compared to the IEEE 802.15.3 MAC is, that the contention access period (CSMA/CA) was exchanged by a CDMA based access period. As a result of contention free CDMA, packet collision is completely avoided, which leads to a higher throughput of an UWB system. Also it is possible to save energy by turning off some hardware components -like the radio module to prevent idle listening- inside unused slots. [9]. To sum up, the listed approaches for UWB MAC show good properties on handling multiple access in WSNs for data communication but do not address the challenge to extend localization functionality, including time critical ranging measurements. Therefore in section II we will propose a novel solution, supporting high precise ranging measurements for localization functionality inside the network. In section III we will present evaluation results on the multiple access behaviour in context of communication and localization in WSNs. In relation to existing protocols presented in section I-B a more detailed view is given. Finally we will conclude our work according to the results and will give an outlook for improvements which will be addressed by future work.

II. Solution

A. System Overview

The overall system architecture of our current wireless locating sensor network is shown in figure 2. It consists of four stationary nodes acting as anchor nodes for rangings, some mobile nodes (slaves) and a master which appears as coordinator. The master is responsible for coordination and management of the network. Each slave, has the capability to calculate

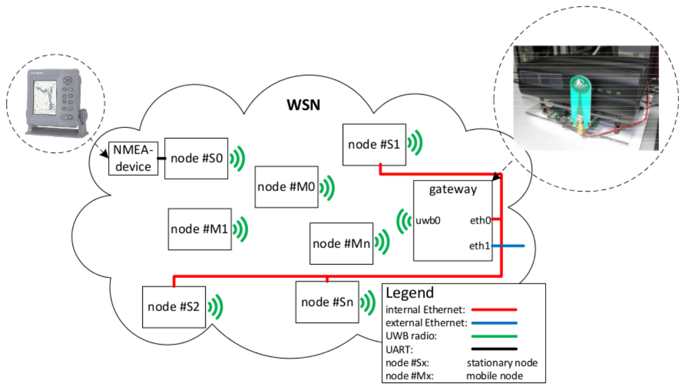

Fig. 2: Ad-hoc network topology consisting of mobile nodes (slaves), stationary anchors and a master (gateway)

its position from rangings to the stationary nodes by multilateration. Combined with the position information, the stationary nodes and slaves are able to sense their environment using attached on-board sensors such as temperature, acceleration or NMEA [13] devices. After a slave has calculated its position, it builds up a data packet including other sensor data and sends it back to the master. The data format of this packet is defined by the Sensor Configuration, Aggregation and Interchange (SCAI) protocol, a XML-based protocol designed to utilize and configure a heterogeneous sensor network [14], [15]. Currently we have developed a slave prototype to test the functionality (see figure 3) of our network. The hardware consists of a transceiver module for communication and a baseboard, which is responsible for the nodes components. It consists of a 32 bit ARM Cortex M3 micro-controller clocked at 100 MHz running the real time operating system (RTOS) FreeRTOS, required for the calculations, self-localization, gathering and processing of sensor data and for network communication. The implemented protocols ensure aspects like routing of data, energy efficiency, self organization and fault tolerance.

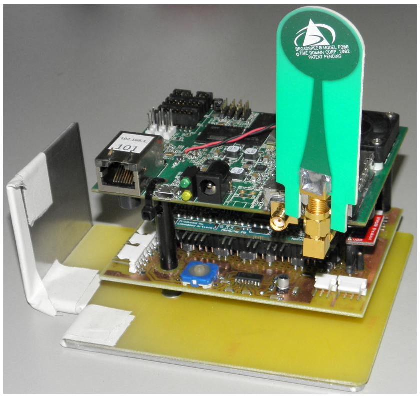

Fig. 3: Picture of the current evaluation model, showing a custom baseboard and off the shelf UWB transceiver modul.

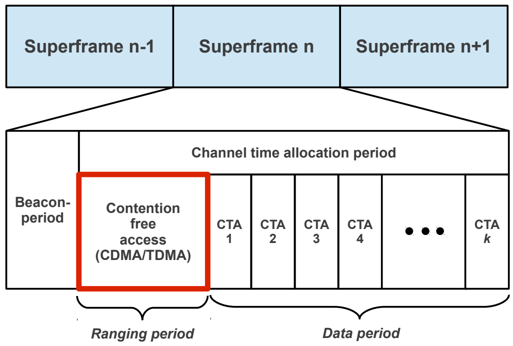

Fig. 4: Modified MAC superframe structure

In this approach, UWB technology is used in form of an off the shelf radio transceiver module to get started rapidly [16]. This transceiver module is connected to the baseboard via UART and packets generated on the baseboard are forwarded to the radio module for transmission. Incoming transmissions are likewise forwarded to the baseboard for processing. A more detailed overview about our system architecture is given in [17].

B. Hybrid CDMA/TDMA based MAC Protocol

As mentioned before, many MAC layer protocols are based on the IEEE 802.15.3 MAC, as well as our solution. The main idea of our protocol is to exchange the contention access period by a contention free period where the assignment is depending on time (TDMA) and different available code channels (CDMA). This entirely eliminates collisions within the network and disposes disadvantages of the CSMA/CA approach by sensing the medium, because it could be a difficult task in UWB based networks as described above. Furthermore, CSMA/CA is a non deterministic protocol and therefore unsuitable for time critical applications, such as the ranging measurements in our network, which have to be accomplished in the right order and with a smallest possible delay between each ranging process of a slave. Otherwise the position error will increase, due to any movements of the slave‘s set of directly linked rangings. Our proposed MAC superframe structure is shown in figure 4, which is similar to the IEEE 802.15.3 MAC, except the contention access period, which is replaced by a contention free period (TDMA/CDMA).

The contention free period is used for ranging measurements of all slaves. Furthermore, in this period a registration process is provided to add more flexibility by handling joining mobile nodes (slaves) or be able to react on corrupt response messages dynamically. Based on that, the slot assignment can be easily adjusted. A dynamic channel switch mechanism is required, to take advantage of selecting different code channels at runtime to allow concurrent transmissions. Our current prototype provides seven code channels and as an option, the number of code channels can easily be increased [16]. Figure 5 presents a more detailed view of our currently used frame configuration in relation to the utilization of code channel and time assignments by assuming four slave nodes and four anchor nodes within the network. At least four anchor nodes are used, due to the need of four rangings for multilateration in 3D.

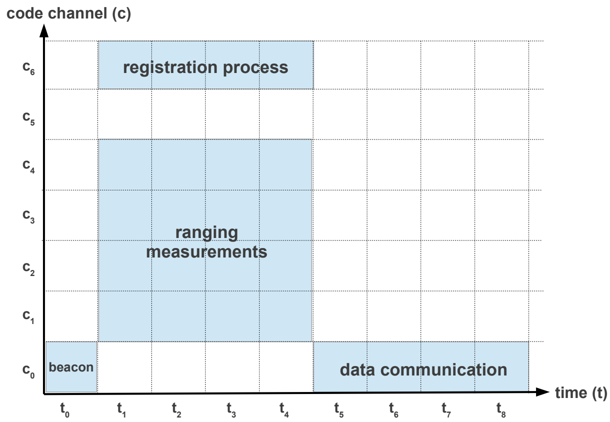

Fig. 5: Detailed view of slot configuration by code channel and time assignment

Time slot t_0 represents the beacon period, which is transmitted by the master via broadcast message on code channel c_0. Next, time slots t_1 to t_4 on code channels c_0 to c_6 build the hybrid contention free access period with CDMA/TDMA. This period includes the ranging measurements (code channel c_1 to c_4) and the registration process on code channel c_6. Finally the data period is assigned by t_5 to t_8 on code channel c_0, so each slave gets a time slot to send its data back to the master, including position information and sensor data. By increasing the number of slaves, the amount of time slots will be increased, too. For example, by a number of ten slaves, the hybrid contention free access period grows up from four to ten time slots. In the same way, the data period will increased by ten time slots. The duration of each time slot for ranging measurements is 40 ms limited by our UWB transceiver. In worst case, the duration of each time slot in the data period is 60 ms, but it is depending on the size of data which has to be transmitted. Furthermore, the timing is limited by the current radio hardware. One improvement could be, to increase the number of available code channels to reduce the number of time slots which are needed for ranging measurements. As a result, the throughput of the network will be increased and the overall cycle time will be reduced. Another enhancement could be, that by more than four slaves, after the fourth time slot of the ranging period, in each slot a different slave will be ready to send its data back to the master switching to another code channel. This would save time inside the data period (see figure 7). Figure 6 shows the scheduling of the ranging period, if there are more than four slaves (in this example there are six slaves assumed) available with four anchor nodes.

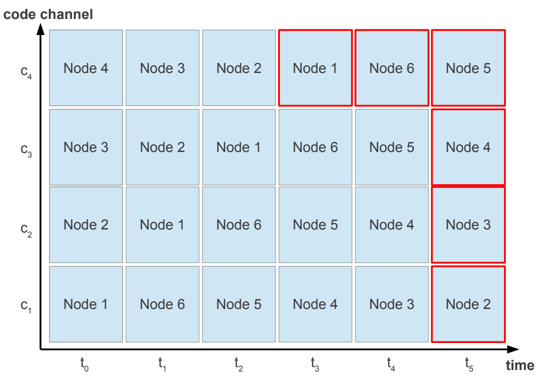

Fig. 6: Scheduling of slave nodes inside the ranging period with 6 slave nodes

As you can see, in time slot t_3 node 1 has completed its ranging measurements. In t_4 node 6 has done, and finally in t_5 all others have finished. Another feature addressed by future work, is the realization of Peer-to-Peer communication within the network. Therefore the data period must be extended by the number of time slots and also we have the possibility to utilize code channels, which are currently not in use. The total time t_{sf} of each superframe is composed by:

$$t_{sf} = B + R + D \tag{1}$$

Where B denotes for the beacon period, R the ranging period and D the data period. The duration of the beacon period is currently defined by 36 ms, limited by radio hardware and beacon size. The following equation describes the totaltime of each ranging period t_{rp} within a superframe:

$$t_{rp} = \begin{cases} 4 + (r-4) * t_{r_{slot}} & , 0 < m \leq 4, \\ \frac{r*m}{c} * t_{r_{slot}} & , m > 4 \end{cases} \tag{2}$$

Where m defines the number of slave nodes, r is the amount of rangings of each slave m, $t_{r_{slot}}$ defines the slot duration for one ranging and c stands for the number of available code channels. If the number of slaves is larger than 0 and less or equal then 4, the minimum amount of ranging slots must be 4, due to the need of four rangings for multilateration in 3D as stated before. Also, we assume that the number of rangings r is equal to the number of code channels c. This means, that every anchor node has its own code channel c. The duration of the data period t_{dp} can be calculated by:

$$t_{dp} = m * t_{d_{slot}} \tag{3}$$

Where m is also the number of slave nodes and $t_{d_{slot}}$ defines the duration of one data slot.

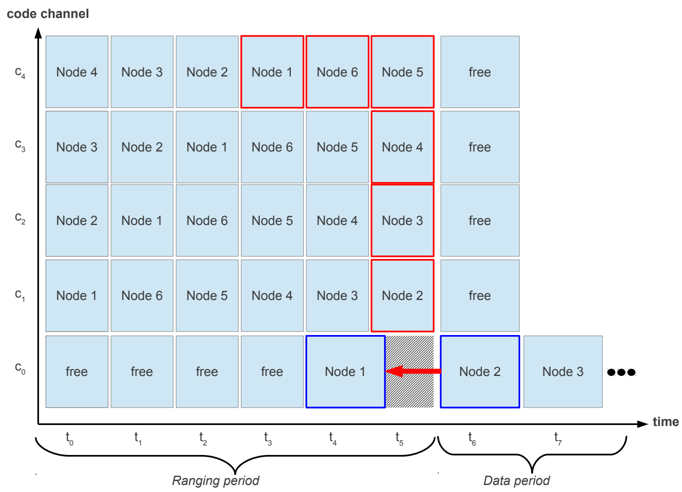

Fig. 7: Modified scheduling of 6 slave nodes

For a better understanding of the overall network, figure 8 shows a flow chart of the master and figure 9 of the slave nodes function.

The master starts building up a MAC frame including the beacon and slot assignment, based on available time, number of nodes and code channels. After that, the MAC frame will be transmitted via broadcast message to all other reachable nodes on code channel 0. In the next step, a timer will start the synchronizing with the receiving slaves. The master switches to code channel 6 and broadcasts an invitation message for the registration process of new slave nodes. Next, the master listens for invitation response messages until the end of the ranging period, to add new slave nodes to his node list. Finally the master listens on data response messages from the slaves and makes a comparison of the sender IDs according to his node list. By exceeding a time-out threshold for a sender ID, the related slave will be removed from the node list and the procedure repeats again by building up the next MAC frame. While a slave is unregistered, it will listen for invitation messages on code channel 6. After receiving an invitation message, the slave has to confirm this message and select code channel 0 to be able to listen for an incoming MAC frame in the next cycle. By receiving this MAC frame, the slave starts or resets its internal timer for synchronization among the slot assignment. Next, the slave checks the time slots to which it is

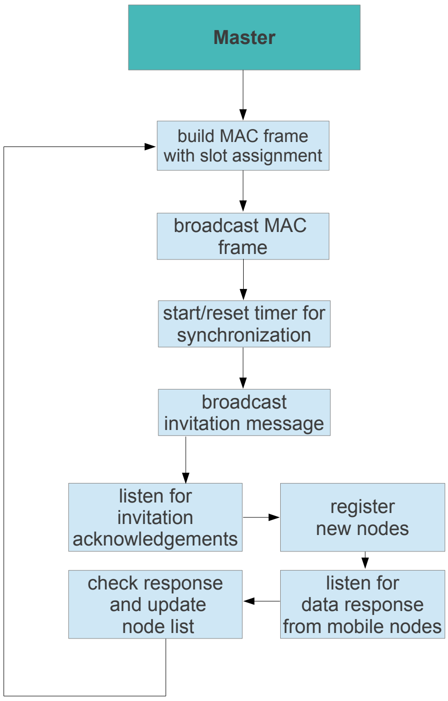

Fig. 8: Flow chart of the master

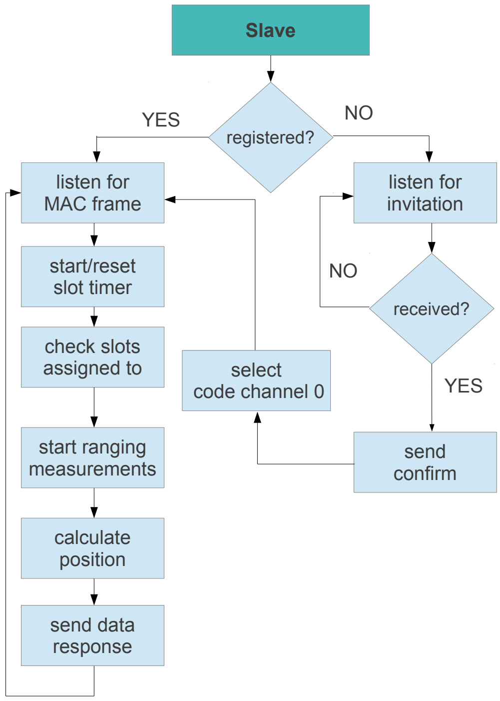

Fig. 9: Flow chart of a slave node

assigned to. Now the ranging procedure will start. Inside this stage, the slave selects dynamically the correct code channel which it is assigned to. As described before, an example of the scheduling is shown in figure 6.

If a slave has got all rangings from the anchor nodes, it will return to code channel 0, and it will calculate its position. Finally with this position information, a slave node builds up a data packet including collected sensor data and sends it back to the master. Once a slave does not get a MAC frame within a given time, a time-out will be occurred and the node has to change its code channel be able to listening for new invitation messages from the gateway.

III. Performance Evaluation

For performance evaluation of our proposed MAC layer protocol, some experiments have been performed, to measure and analyse the time behaviour. The initial state was a network scenario including one master node, one slave node and four anchor nodes without any MAC layer functionality. The slave node was responsible for rangings to one anchor node after another, followed by sending its position and sensor data back to the master in a static manner. The overall network time of this scenario consists of four rangings ($4*40$ ms) added by sending back the data packet to the master (60 ms). So each network cycle takes 220 ms. The execution time to calculate the position or to process sensor data is negligible compared to the timing conditions which are needed for communication. To enable more than one slave and to add a kind of MAC layer functionality, a simple centralized TDMA like approach was implemented. It was similar to the initial network scenario, but the slave nodes have been executed in a row, with a predefined order given by the master. The cycle time can be described as follows:

$$t_c = B + m * 220 \text{ ms} \tag{4}$$

Where B defines the duration (36 ms as mentioned before in section II) of the beacon frame transmitted by the master to all slave nodes via broadcast message and m presents the number of slaves. For example, by a number of five slaves, the duration of each cycle is 1136 ms (update frequency ≈ 0.9 Hz) of time. This approach is very easy to implement, but very inflexible against any changes inside the network topology (e.g. increase or decrease the number of slave nodes). Also the duration of the cycle time can be optimized as shown below. Due to the availability of different code channels, it is possible to execute the rangings simultaneously. This requires, that the number of code channels is equal to the number of anchor nodes, which have to be used for rangings. Furthermore, the slave nodes must be able to select dynamically a predefined code channel at runtime. Therefore we have implemented the proposed hybrid MAC layer including the CDMA/TDMA period and a required dynamic code channel switch mechanism. More flexibility was added by the mentioned registration process described in section II to overcome changes within the network. The evaluation of this approach has been performed by setting up a network configuration consisting one master, five slave nodes and four anchor nodes. In comparison to the static TDMA approach as mentioned before, figure 10 shows the time behaviour of the master and figure 11 presents the timing of a slave, by using our proposed hybrid MAC layer.

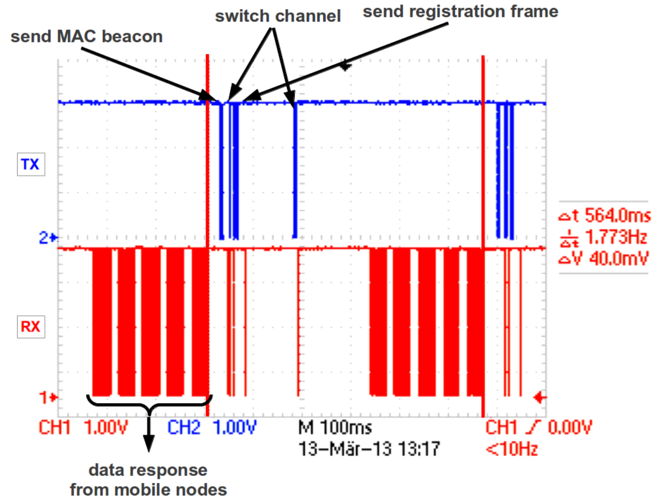

Fig. 10: Timing of the master with five slave nodes connected

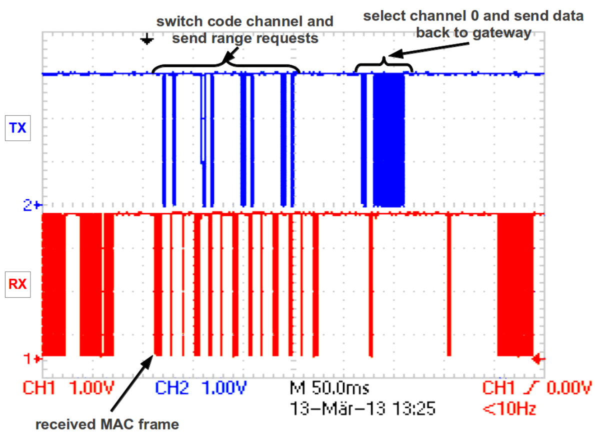

Fig. 11: Timing of a slave node with four ranging measurements

As you can see, the totaltime of one network cycle decreases to 564 ms (update frequency $\approx$ 1.8 Hz) by the same number of slaves and also the same number of rangings, due to the concurrent rangings from the slaves.

IV. Conclusion and Future Work

In this paper, we have proposed a new hybrid MAC layer approach for UWB based Wireless Sensor Networks, providing localization and data communication. Limitations of existing approaches, which are based on IEEE 802.15.3 MAC, have been discussed. It has been shown that existing protocols do not fulfil our requirements of safety and time critical applications. To overcome these limitations, the basic idea was to replace the CSMA/CA period of the IEEE 802.15.3a MAC by a CDMA/TDMA period optimizes for ranging and data communication. The concept of our protocol has been implemented prototypically. Evaluation results, confirmed that our approach fulfils the high realtime requirements for localization and data communication. Furthermore, the proposed approach supports low power consumption, due to the slot assignment architecture. Sleep modes can easily be extended and will be addressed by future work. Also, the utilization of time slots will be optimized as shown in figure 7. In addition, our proposed MAC layer will support an intelligent anchor node selection scheme, which will determinate in a corresponding anchor node optimization task.

Acknowledgment

The authors would like to thank the European Regional Development Fund (ERDF) for funding the project SOOP and to give us the opportunity to work on such an interesting and innovative topic.

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