

A Mobile Open Infrastructure Network Protocol (MOIN) for Localization and Data Communication in UWB Based Wireless Sensor Networks

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Abstract—In this paper, a novel network protocol (MOIN - Mobile Open Infrastructure Network Protocol) for non synchronized UWB based wireless sensor networks is presented. Applications of classical protocols for such networks, where anchor nodes are not synchronized for ranging and communication purposes, typically are not effective for simultaneous ranging and communication tasks. The proposed MOIN protocol overcomes these shortcomings by using an optimized scheduling scheme for rangings. Dynamic domain selection and adaptive slot assignment depending on the number of network participants at runtime are key features to reduce the delay between each ranging procedure which minimizes motion artefacts. A sequential predefined ranging order can be ensured to minimize the position error. The channel access is realized by a centralized hybrid MAC layer which uses TDMA and CDMA. In addition, the MOIN protocol supports multiple sensor domains to achieve a higher network range. Another advantage of the adaptive slot assignment is the minimization of time slots in each superframe. This leads to a shorter superframe duration and significantly increases network throughput and update frequency rates.

I. INTRODUCTION

Today, wireless sensor networks (WSNs) are becoming more and more important due to their increasing use in many types of applications e.g. industrial, health care or area monitoring. In addition to the basic use case of gathering and transmitting sensor data, localization and tracking functionality are offering new monitoring options which are useful for many applications in which tracking of mobile agents has to be performed, e.g. in monitoring of safety critical operations such as installation and maintenance of offshore wind energy plants.

A. Motivation

Due to the ecologically motivated switching from fossil to renewable energy sources, a massive expansion of offshore wind energy farms is planned and conducted across the German coastlines. For this reason, there is an increasing need to perform offshore operations as efficiently and safely as possible. The goal is to reduce costs during the construction of those offshore wind energy plants and to improve the operational safety. The research project SOOP (Safe-Offshore-Operations) focuses on this topic. One objective of SOOP is the implementation of a sensor-based assistance system

and an underlying wireless sensor network with the following requirements [1], [2]:

- High precise ranging measurements for a Real-Time Locating System (RTLS) to enable tracking functionality of the crew and other objects on a vessel.
- Data communication for exchange and aggregation of collected sensor data.
- Dealing with harsh environments which lead to shadowing effects and reflections by the signal propagation.
- Implementation of a network protocol to coordinate ranging and communication tasks within a non synchronized UWB network with independent rangings.

To fulfill these requirements, Ultra Wide Band (IR-UWB) was selected as a well suited radio technology. UWB allow robust rangings, combined with data communication across moderate ranges with low energy consumption as described in [2] and [3]. This paper proposes a novel centralized hybrid MAC layer implementation for non synchronized UWB based WSNs with self locating sensor nodes, as used within the SOOP project. Compared to existing MAC implementations for UWB, the main characteristic of the MOIN protocol is to combine the usage of CDMA and TDMA for a fully contention free and simultaneous channel access in multiple sensor domains. This overcomes the limitations of existing MAC layers where contention access is used. Due to the contention free access and an optimized and adaptive scheduling scheme for rangings, the MOIN protocol provides good real-time performance.

B. Related Work

MAC layer optimization for UWB based WSNs including localization functionality is part of several research activities [4]. Existing MAC layers can be classified in contention based and contention free protocols or a combination of both. Another categorization can be made by centralized or decentralized (distributed) MAC protocols [5]. As a well known contention free protocol the Time Division Multiple Access (TDMA) protocol exists [6]. The most popular contention based protocols are the Carrier Sense Multiple Access

with Collision Avoidance (CSMA/CA) and the ALOHA approach [6]. Contention free protocols such as TDMA have the disadvantage that dynamic reconfiguration is not supported, which is necessary if the number of networks nodes is changing, for example. On the other side, the slot assignment enables sensor nodes to switch into a sleep mode during inactive or unused timeslots. This decreases idle listening and power consumption [7]. However, contention based protocols like CSMA/CA support dynamic network reconfiguration, but are not suitable for UWB based networks, due to the listen before talk mechanism, which requires sensing the medium. Also the carrier sense approach presents a difficult task in coherent UWB based WSNs, because transmissions of other users will be perceived as noise if the signal coding is unknown [8]. On a closer look to existing works, commonly used MAC protocols in the area of UWB WSNs usually are based on the IEEE 802.15.3/4 standards. These standards implement a centralized beacon enabled protocol. The network structure consists of several network devices which form a so-called piconet including one piconet coordinator (PNC). This PNC has to coordinate peer-to-peer communications between devices based on a time-slotted superframe structure as shown in Fig. 1 in case of the IEEE 802.15.3 MAC standard [9], [10].

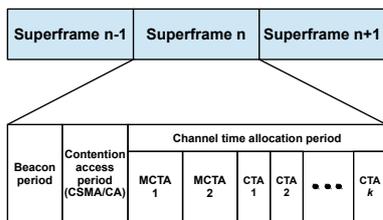


Fig. 1: The IEEE 802.15.3 MAC superframe structure

This superframe structure is divided into three main parts: First, there is the beacon period, where the PNC sends out a beacon to all connected network devices within its piconet. The beacon contains channel-time allocation and management information for the piconet and takes care about synchronization. The second part of each superframe is the contention access period where all network devices share the channel by using the CSMA/CA approach to communicate with each other. In the third part there is the channel time allocation period (contention free period). Here, the PNC assigns channel time allocations (CTAs) to network devices by using TDMA. That enables quality of service (QoS) functionality. In summary, it must be emphasised that the IEEE 802.15.3/4 standards are well suited for WSNs where communication has the main focus, but ranging or localization functionality is not supported directly.

Another interesting MAC layer solution is given by the PULSERS project as described by I. Bucaille et al in [11], [12]. The motivation of that MAC protocol is described as followed:

- Peer-to-peer communication is needed for applications such as warehouse tracking or home automation.

- Fulfill guaranteed requests with low latency.
- Ranging functionality with low power consumption.

PULSERS MAC is based on the IEEE 802.15.4 standard and its superframe structure is very similar to that (see Fig. 2).

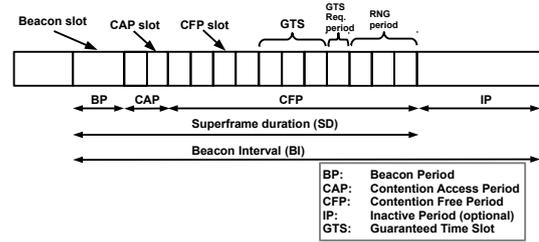


Fig. 2: PULSERS MAC frame structure [11]

The main differences between PULSERS MAC and the IEEE 802.15.4 MAC are, that PULSERS MAC supports higher QoS for real-time services by embedding a Guaranteed Time Slot (GTS) period within the contention free part. In addition to the GTS period, a GTS request period was added. This allows a sensor node, which requires GTS for data transmissions, to send a GTS request frame in any case. Furthermore, efficient ranging is possible by the use of an additional contention free ranging (RNG) period [11]. To sum up, it can be said that PULSERS MAC brings good benefits for peer-to-peer communication with strong requirements for QoS and real-time capabilities. Regarding localization, one key feature of PULSERS MAC is the implementation of ranging functionality within a separate ranging period. A problem within the ranging period could be that it is based on a pure TDMA scheme which may lead to long superframe durations depending on the number of sensor nodes which have to be located.

Considering the SOOP project, one main requirement is the implementation of a Real-Time Locating System (RTLs) which efficiently combines data communication and localization. As existing CSMA/CA approaches as used in PULSERS MAC or IEEE 802.15.3/4 MAC do not fulfill this requirement, this paper proposes an optimized protocol scheme for non synchronized networks where no peer to per communication is required. Core features are:

- High precise rangings and data communication.
- Fully contention free channel access with good real-time performance for ranging and communication.
- A modified superframe structure with hybrid channel access which increases network bandwidth and enables simultaneous rangings.
- Support of non synchronized networks, due to the fact that the synchronization is done by MOIN.
- An adaptive slot assignment to optimize the superframe duration depending on the number of nodes and with respect to the constrain about the sequential ranging order to minimize the position error caused by motion artefacts.
- Providing sensor domains with a kind of handover functionality to extend the network range.

II. MOIN PROTOCOL

In this section, the MOIN protocol will be described in detail. First, an overview on the network architecture is given. After that, the channel access strategy and interaction of all network components will be discussed. Finally, an adaptive selection method for an optimal slot assignment is shown.

A. MOIN Topology Overview

The overall network structure of our system is shown in Fig. 3. It consists of a MOIN-Master, MOIN-Coordinator(s), several anchor nodes and slaves. These components can be described as follows:

The **MOIN-Master** is responsible for coordination of the whole network. It uses the MOIN-Coordinators which are connected via Ethernet to extend the network range and overcome the well known problem of the Single Point of Failure. Furthermore, the MOIN-Master receives sensor data from all slaves as received by the MOIN-Coordinators. This allows the MOIN-Master to have an overview of the network state at any time. In our test environment the implementation is realized as a Python application and can be executed on devices providing an integrated Python interpreter such as every PC or an embedded device. A **MOIN-Coordinator** has to supply the associated sensor domain and its connected slaves with network management information received by the MOIN-Master. In addition, the MOIN-Coordinators are responsible for forwarding received data from the slaves to the MOIN-Master. The communication between MOIN-Coordinators and the slaves is realized by UWB. The **Slaves** have the capability to estimate their positions from rangings to fixed anchor nodes employing multilateration. After a slave has calculated its position, it assembles a data packet including other sensor data (e.g. acceleration, temperature and NMEA data packages need for maritime data [2]) and sends it back to the MOIN-Master via UWB to its associated MOIN-Coordinator. **Anchor nodes** are required to provide ranging functionality for the slaves and have to be installed at fixed, known positions.

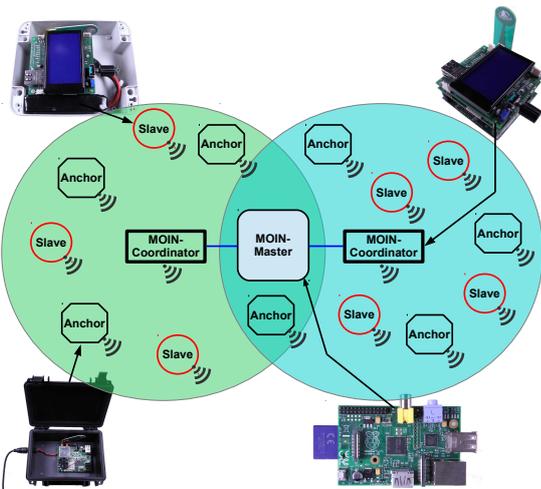


Fig. 3: MOIN network topology

The hardware of a MOIN-Coordinator or slave consists of an UWB transceiver module for communication and a baseboard, which is responsible for the nodes components. Our implementation consists of a micro-controller with 32 bit ARM Cortex M3 architecture, clocked at 100 MHz running the real-time operating system FreeRTOS, required for calculations, self-localization, gathering and processing of sensor data. Furthermore, an IP stack was implemented for Ethernet communication between MOIN-Coordinators and the MOIN-Master. Currently, anchor nodes only consist of an UWB transceiver module.

B. MOIN Protocol Description

The MOIN protocol is based on the IEEE 802.15.3 standard and considers the PULSERS MAC, but with some significant modifications. The main idea is to exchange the contention access period which is replaced 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 as mentioned before. Fig. 4 shows the modified superframe structure.

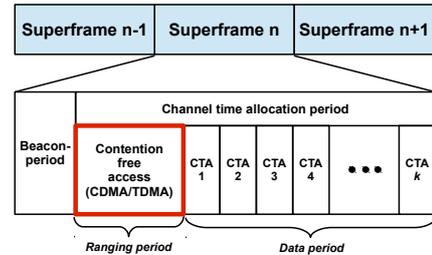


Fig. 4: Modified MAC superframe structure

The hybrid channel access method is part of our previous work which is detailedly described in [13]. The superframe consists of three periods. At first, there is the beacon period for synchronizing the whole network including important network information like a pre-defined slot assignment order for example. After that, the ranging period follows. It is used for ranging measurements of all slaves which are connected to the network. One key feature is the hybrid channel access method which enables simultaneous rangings. The third part of each superframe is the data period where all slaves can transmit collected sensor data including their calculated position information back to a centralized base station. Fig. 5 presents a more detailed view of a possible superframe configuration in relation to the utilization of code channel and time assignments by assuming one MOIN-Master, two MOIN-Coordinators, four slaves and four anchor nodes. It should be noted that at least four anchor nodes are needed for multilateration in 3D. Furthermore, each anchor node requires a pre-defined code channel to realize simultaneous rangings over CDMA.

Code channels c_0 and c_1 are presenting the control channels for the MOIN-Coordinators in order to supply the associated sensor domain. Time slot t_0 represents the beacon period, which is transmitted by the MOIN-Coordinators via broadcast

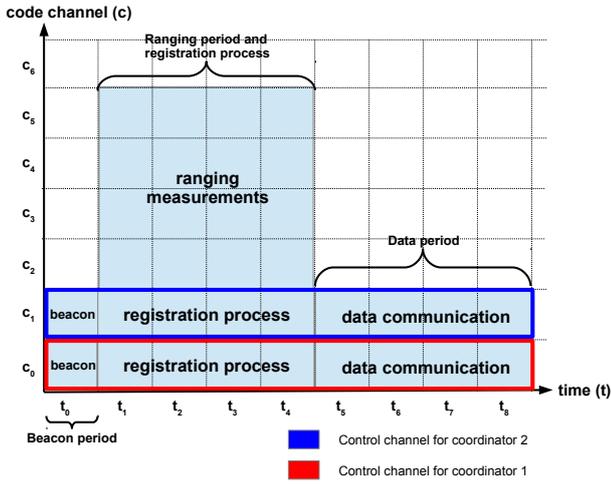


Fig. 5: Representation of the slot configuration in MOIN

message on the related control channel. The beacon itself is build up by the MOIN-Master and transmitted to the MOIN-Coordinators. Next, time slots t_1 to t_4 build the hybrid contention free access period with CDMA/TDMA. This period includes the ranging measurements (code channel c_2 to c_5) and the registration process on the control channels for each sensor domain (c_0 and c_1) to register new upcoming slaves. Finally, the data period is assigned by t_5 to t_8 on control channels c_0 and c_1 , so each slave gets a time slot to send its data back to the MOIN-Master forwarded by the related MOIN-Coordinators, including position information and sensor data. The duration of each time slot for ranging measurements is 40 ms limited by the used UWB transceiver [14]. In worst case, the duration of each time slot in the data period is 60 ms, depending on the size of data which has to be transmitted. The interaction of all MOIN components (except the anchor nodes) is realized by a so called MOIN Component Interaction Protocol (MOIN CIP) on a higher level then the MOIN MAC. This protocol has the task to ensure the communication of the whole network. The major task of the MOIN CIP is to control the communication between the MOIN-Master, the MOIN-Coordinators and the slaves. It is responsible for handling new upcoming or already connected MOIN-Coordinators. Furthermore, the forwarding mechanism of the MOIN-Coordinators between the Slaves and the MOIN-Master has been realized by the MOIN CIP. Therefore, the following message types were defined:

MM_MSG_COORD_SYNC:

This message will be send by the MOIN-Master to all MOIN-Coordinators periodically. Already connected MOIN-Coordinators, respond with message *MM_MSG_ALIVE* to propagate the MOIN-Master that they are still alive. MOIN-Coordinators which are not registered, respond with the message *MM_MSG_DISCOVERY_RESPONSE* to enter the network (see Fig. 6).

MM_MSG_COORD_RESET:

This type of message will be send by the MOIN-

Master at start up, because the MOIN-Master could have failed within a previous run. In this case, the MOIN-Coordinators which were connected, are not be able to notice that. Previously connected MOIN-Coordinators respond with the message *MM_MSG_ALIVE*, so the MOIN-Master is able to correct his internal Coordinator list. Not registered MOIN-Coordinators respond with the message type *MM_MSG_DISCOVERY_RESPONSE* to enter the network.

MM_MSG_DISCOVERY_RESPONSE:

This message type is used by MOIN-Coordinators to enter the network as a response of a *MM_MSG_COORD_SYNC* or *MM_MSG_COORD_RESET* message (see Fig. 6).

MM_SET_COORD_CHANNEL:

This message assigns a control channel to an upcoming MOIN-Coodinator from the MOIN-Master in response of a *MM_MSG_DISCOVERY_RESPONSE* message (see Fig. 6).

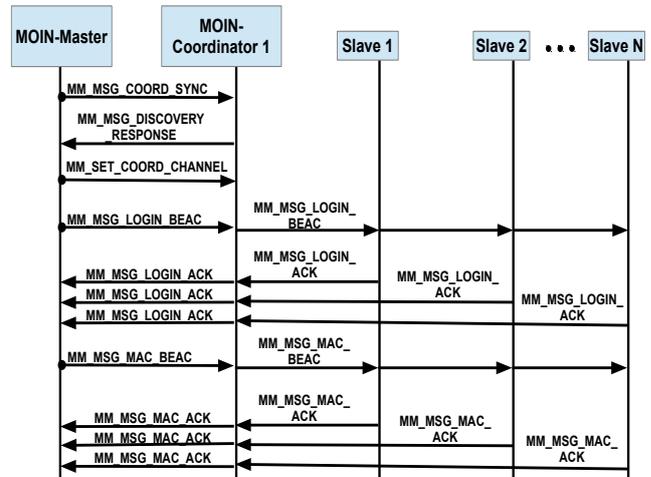


Fig. 6: Communication sequence realized by the MOIN Component Interaction Protocol

MM_MSG_ALIVE:

This type of message corresponds with the message types *MM_MSG_COORD_SYNC* and *MM_MSG_COORD_RESET* and will be received by the MOIN-Master from the MOIN-Coordinators periodically, so the MOIN-Master knows that the registered MOIN-Coordinators are still alive.

MM_MSG_LOGIN_BEAC:

This message will be send from the MOIN-Master to the MOIN-Coordinators which have to forward it to all slaves in range. Not registered slaves respond with *MM_MSG_LOGIN_ACK*.

MM_MSG_LOGIN_ACK:

See message type *MM_MSG_LOGIN_BEAC* which corresponds to this type of message.

MM_MSG_MAC_BEAC:

This type of message will be send from the MOIN-Master to the MOIN-Coordinators which have to forward it to all registered slaves. Attached to this message, there is the beacon which has important network information to coordinate the channel access including the slot assignment for ranging

and communication task of each connected slave. After a slave has calculated its position, it builds up a data packet including other sensor data. This data packet will be attached by responding with the message type *MM_MSG_MAC_ACK*.

MM_MSG_MAC_ACK:

See message type *MM_MSG_MAC_BEAC* which corresponds to this type of message.

C. MOIN Timing

In the next step, the calculation of the superframe duration and the adaptive slot assignment mechanism will be described. The total time t_{sf} of each superframe is composed by:

$$t_{sf} = t_b + t_r + t_d \quad (1)$$

t_b denotes the time used for the beacon period, t_r by the ranging period and t_d by the data period. The duration of the beacon period is currently about 40 ms, limited by radio hardware and beacon size. The most significant period is the ranging period t_r . Many scheduling schemes are possible depending on the respective demands like prioritization or finding the minimum slot number. As an example, this paper presents an adaptive scheduling scheme, which meets the requirements to get the minimum slot number under the constrain of a sequential pre-defined ranging order related to connected sensor nodes during runtime. Based on this, the ranging period can be described as follows:

Assuming that the number of slaves m is greater than 0 (otherwise no slaves are connected) and the number of anchor nodes r has to be greater then or equal 4 (needed by multilateration in 3D) the minimum duration of the ranging period t_r can be calculated by:

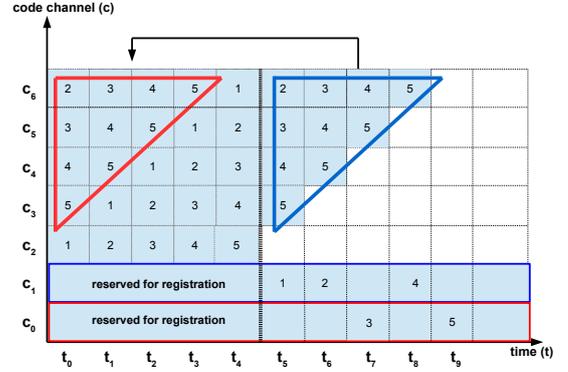
$$t_r = \begin{cases} ((m \text{ div } r) + 1) * r * t_{r_{slot}}, & m \neq r \\ \frac{m}{r} * r * t_{r_{slot}}, & (m \text{ mod } r) = 0 \end{cases} \quad (2)$$

Where m presents the number of slaves, r the number of anchor nodes and $t_{r_{slot}}$ the duration of one timeslot within the ranging period. Furthermore, it is assumed that each anchor node has its own code channel, so that the number of anchor nodes is limited by the number of code channels. The duration of the data period t_d can be calculated by:

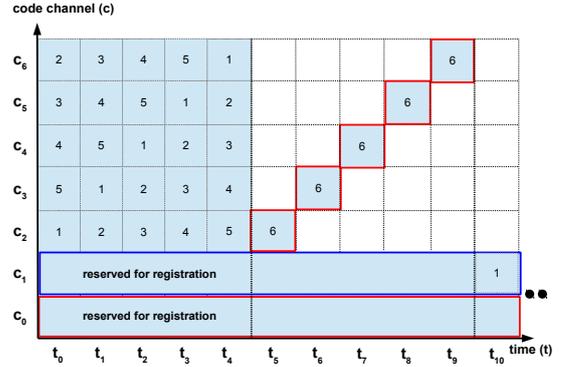
$$t_d = m * t_{d_{slot}}, \quad m > 0 \quad (3)$$

Where m defines the number of slaves and $t_{d_{slot}}$ defines the duration of one data slot. Fig. 7(a) shows an example of the adaptive slot assignment by assuming two MOIN-Coordinators, five slaves and five anchor nodes. Timeslots t_0 to t_4 present the ranging period on code channels c_2 to c_6 . Code channels c_0 and c_1 are presenting the control channels for the MOIN-Coordinators. In the first step the slaves will be piped into the ranging period. Relating to the number of slaves m and anchor nodes r the slot assignment can be optimized by shifting wasted ranging slots in front of free, unused ranging slots (see the blue triangle which has shifted to the red one) which decreases the number of overall ranging slots (from 9

to 5 in Fig. 7(a)) and safes time. If the number of slaves is greater then the number of anchor nodes ($m > r$), then a new slot frame will be appended within the ranging period to provide more ranging slots for additional slaves. The number of slaves which can take place into a slot frame is defined by the number of anchor nodes, corresponding to the number of code channels. An example is given in Fig. 7(b), where a new slot frame has opened for slave 6.



(a) Scheduling of 5 slaves nodes inside the ranging period



(b) Scheduling of 6 slaves nodes inside the ranging period

Fig. 7: Examples of the adaptive slot assignment mechanism

It should be considered, that a smaller number of ranging slots is possible, but only without the restriction of a sequential ranging order.

III. EVALUATION

As our approach is based on a centralized MAC protocol, synchronization of sensor nodes is critical. Several timing measurements had been taken to verify synchronization for different network configurations. As an example, Fig. 8 shows the correct timing behaviour of a slave at runtime for a network with one MOIN-Master, one MOIN-Coordinator, five slaves and four anchor nodes. First the slave receives the MAC beacon from the assigned MOIN-Coordinator to get information about the order of slot assignment. Then, the slave starts the ranging task in the correct order, calculates the position and builds up a data packet including position information and other collected sensor data. Finally, the data

packet is send back to the assigned MOIN-Coordinator which forwards it to the MOIN-Master.

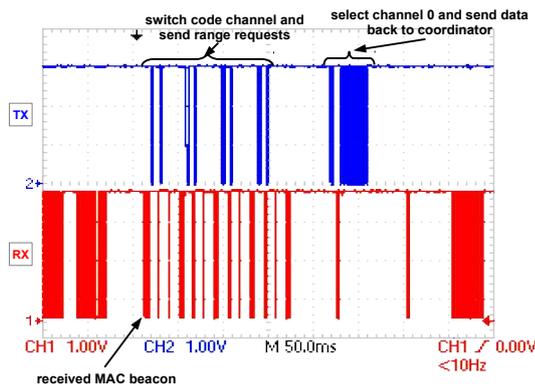


Fig. 8: Timing of a slave node with four ranging measurements

A second critical point is the update rate. Update rates have been simulated for a number of different slaves and network configurations. Fig. 9 exemplifies the results for a number of up to ten slaves in a network consisting of one MOIN-Master, one MOIN-Coordinator and four anchors. From Fig. 9 it comes clear that the superframe duration increases with the number of slaves nearly linear, due to the fact that the data period works in a sequential order like a pure TDMA scheme. Optimization is possible by distributing data packages to several MOIN-Coordinators or anchor nodes, i.e. that is to parallelize data transfer.

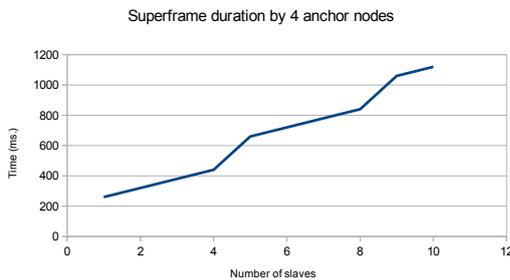


Fig. 9: Superframe duration with 4 anchors for localization

IV. CONCLUSION AND FUTURE WORK

In this paper we have proposed the MOIN protocol for non synchronized UWB wireless sensor networks, as used in the SOOP project. The core feature of MOIN is to realize simultaneous ranging and communication tasks, where anchor nodes are not synchronized and classical protocols are not effective, as discussed. MOIN has included a fully contention free hybrid channel access mechanism which allows efficient and simultaneous ranging and data communication. This overcomes the limitations of related protocols like the IEEE 802.15.3 or PULSERS MAC, where contention access is used. Furthermore, a pre-define sequential ranging order for each connected slave can be defined by an adaptive slot assignment and so helps to im-

proves the position accuracy by minimizing motion artefacts. Evaluation results have shown, that the performance of MOIN is well suited for small sized scenarios, where only a few objects should be localized. It has been mentioned, that one challenge addressed by future work, is to minimize the duration of the data period to improve the performance of MOIN. Therefore anchor nodes should be modified to allow direct data transmission to the MOIN-Master. Furthermore, many other adaptive scheduling schemes are possible and will be analysed by future work.

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