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 non synchronized 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. 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. 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 pre-defined ranging order can be ensured to minimize the position error. 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 (cf. [1]) which is described by T. Wehs in [2]. Due to this constrains, a wireless sensor network with the following requirements is needed:

- 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 task 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 allows robust rangings, combined with data communication across moderate ranges with low energy consumption as described in [2] and [3]. To realize a suitable network protocol for SOOP, the key topic of this paper is to propose a novel centralized hybrid MAC layer implementation for non synchronized UWB based WSNs. 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 has been used. Due to the contention free access, the MOIN protocol provides good real-time performance by executing rangings in a pre-defined sequential order which has been generated by an adaptive slot assignment method. This is necessary because the network in SOOP has non-synchronized anchor nodes and the calculation of a position is performed by the sensor nodes at runtime.

B. Related Work

New concepts about MAC layer implementations optimized for UWB based WSNs including localization functionality are part of several research activities [4]. Existing MAC layer solutions 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 they are not flexible enough for dynamic network structures where the network configuration can be altered at runtime due to the fact that they have to organize the slot assignment within the network for each user. 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 enables a lower power consumption [7]. However, contention based protocols like CSMA/CA have good benefits relating to changes within the network, 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 are defined in 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 in which one of them takes the responsibility of a piconet coordinator (PNC). This PNC has to coordinate peer-to-peer communications between devices based on a time-slotted superframe structure as shown in Figure 1 in case of the IEEE 802.15.3 MAC standard [9], [10].

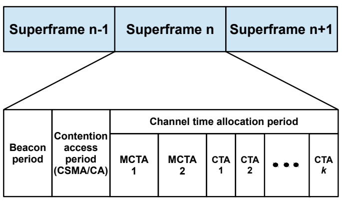


Fig. 1: The IEEE 802.15.3 MAC superframe structure

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. Bucaillein in [11]. The motivation of that MAC protocol is described as followed (cf. [11], [12]):

- 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).

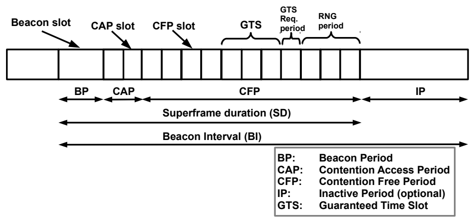


Fig. 2: PULSERS MAC frame structure [11]

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, an efficient ranging is made 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 into a longer superframe duration depending on the number of sensor nodes which have to be located.

For the sensor network of project SOOP, the main focus is put on the implementation of a Real-Time Locating System (RTLS) which combines data communication and localization. Currently there is no need for peer-to-peer communication. As mentioned before, the CSMA/CA approach as used in PUSLERS MAC or IEEE 802.15.3/4 MAC is not well suited for our system. Therefore, a custom MAC solution had to be assigned - the MOIN protocol as described in section II - which matches the requirements of SOOP and overcomes the limitations of the related MAC implementations described above by the following core features of MOIN:

- 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
- Supporting 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 proposed. 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 by two-way time-of-flight (TW-TOF) and have to be installed at fixed, known positions.

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 as well for Ethernet communication between MOIN-Coordinators and the MOIN-Master. Currently, anchor nodes only consist of an UWB transceiver module.

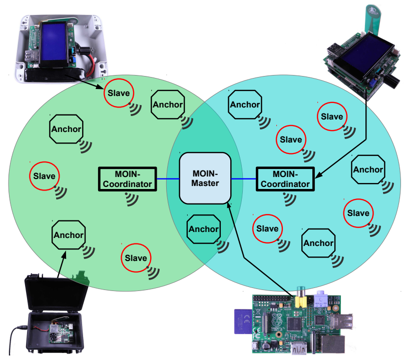


Fig. 3: MOIN network topology

B. MOIN Protocol Description

The MOIN protocol is based on the IEEE 802.15.3 standard as well as PULSERS MAC, but with some significant modifications. The main idea was to exchange the contention access period which has been 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. This yields into a modified superframe structure shown in Fig. 4.

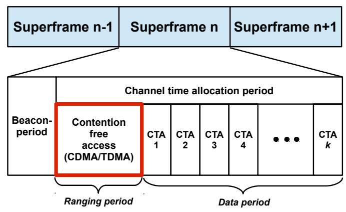


Fig. 4: Modified MAC superframe structure

The hybrid channel access method is part of our previous work which is detailed in [13] and now takes place within MOIN which enables to support multiple sensor domains with an adaptive slot assignment method to improve the range and throughput of the network. To sum up, it should be clarified that our proposed protocol works with three periods within each superframe. 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 our currently used 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. The code channels are limited by the used radio hardware but can increase by manufacturer.

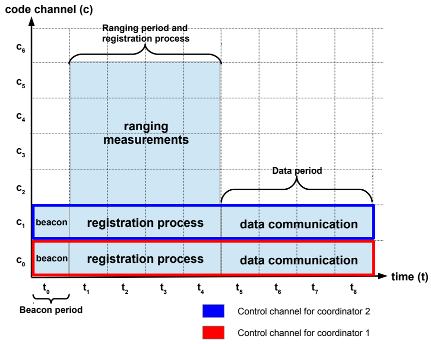


Fig. 5: Representation of the slot configuration in MOIN

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 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 our 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 Figure 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-Coordinator from the MOIN-Master in response of a *MM_MSG_DISCOVERY_RESPONSE* message (see Fig. 6).

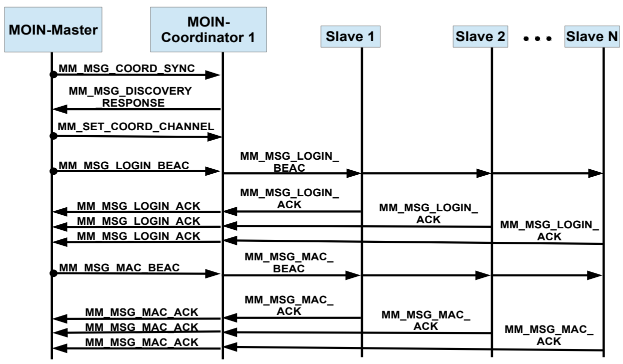


Fig. 6: Communication sequence realized by the MOIN Component Interaction Protocol

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:

$$t_{sf} = t_b + t_r + t_d \tag{1}$$

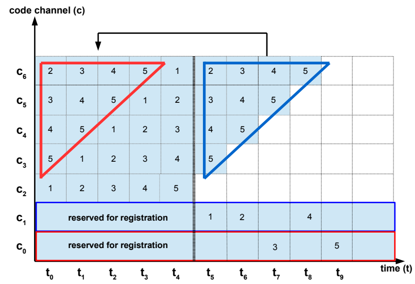
Where t_b denotes the time used by the beacon period, t_r by the ranging period and t_d by the data period. The duration of the beacon period is currently defined by $\approx$ 40 ms, limited by radio hardware and beacon size. The most important period is the ranging period t_r. Many scheduling schemes are possible depending on the respective demands like prioritization or finding the minimum slot number for 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:

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

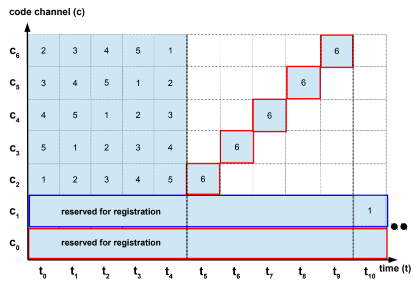
Where m presents the number of slaves, r the number of anchor nodes and $t_{r_{slot}}$ the duration of one timeslot within the ranging period. Furthermore, it would be assumed that each anchor node has its own code channel, so the number of anchor nodes is limited by the number of code channels. The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

$$t_d = m * t_{d_{slot}} \ , \ m > 0 \tag{3}$$

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 Figure 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 Figure 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. Also it should be noted that the number of slots can be decrease by reducing the ranging conversations of each slave to a minimum required number of four, which can under some circumstances lead to worse position results.

III. Performance Evaluation

For performance evaluation of MOIN, some experiments have been performed. The first experiment was realized by a network configuration consisting of one MOIN-Master, one MOIN-Coordinator, five slaves and four anchor nodes. Fig. 8 shows the time behaviour of a slave at runtime. 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 will be send back to the assigned MOIN-Coordinator which will forward it to the MOIN-Master.

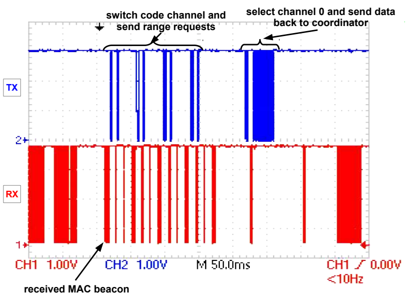


Fig. 8: Timing of a slave node with four ranging measurements

Furthermore, the duration of a superframe has simulated for a different number of slaves, to get a more detailed view about the time behaviour of MOIN (see Fig. 9). The result can be evaluated as follows: Up to a number of 10 slaves, MOIN reaches update rates of approximatively 1 Hz which is applicable for small sized scenarios where only a few number of objects have to be localized. By increasing the number of slaves, the update rates steadily increase, too. The main reason for that is, that the data period increases steadily by every new upcoming slave, due to the fact that the data period works in a sequential order like a pure TDMA scheme. To solve that problem, it may be possible to distribute the data packets to several MOIN-Coordinators or anchor nodes to get more parallelism within the data period.

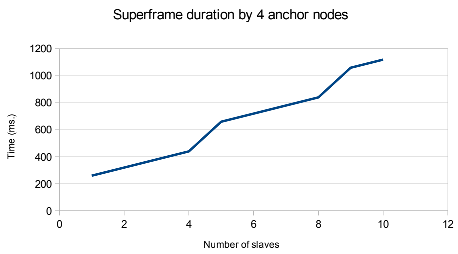


Fig. 9: Superframe duration with 4 anchors for localization

IV. Conclusion and Future Work

In this paper we have proposed the MOIN protocol for non synchronized UWB wireless sensor networks required for SOOP. The core feature of MOIN is to realize simultaneous ranging and communication tasks, where anchor nodes are not synchronized and classical protocols which have been discussed, are not effective. MOIN has included a fully contention free hybrid channel access mechanism which has good benefits for 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, it enables to pre-define a sequential ranging order for each connected slave by an adaptive slot assignment and improves 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 it could be helpful to modify anchor nodes so that they are equal to the slaves. This would allow to use the anchor nodes as additional data sinks and may reduce the data period. Furthermore, many other adaptive scheduling schemes are possible and will be analysed by future work.

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