Position Estimation in IR-UWB Autonomous Wireless Sensor Networks

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Abstract—**This paper presents positioning results determined by a multi-layer, packet based OMNet++ simulator for communication and positioning in an autonomous wireless sensor network. The simulator includes an IR-UWB physical layer model considering the impact of multi-user interference, a highly flexible MAC layer which performs physical layer adaptations to optimize the total link performance, and a ranging and positioning module.**
We will give an estimation of the positioning accuracy of the system by considering ideal, LOS and NLOS channel conditions.

Index Terms—**Autonomous sensor networks, IR-UWB, positioning, ranging.**

I. Introduction

The concept of autonomous UWB wireless sensor networks has been introduced in [1] and serves as a basis for the investigations presented in this paper. An autonomous wireless communication system describes groups of UWB devices organizing their communication independently of other UWB devices operating in the same area and react in an uncoordinated manner. This demand requires a highly flexible MAC layer which controls the transmissions of individual UWB nodes such that an optimal network performance is assured by allowing each node to come to a self-optimizing decision. This kind of medium access control has been introduced in [2] and is part of the simulation framework. The demonstration system to be developed within the PULSERS II project (Working Package 3b) is supposed to operate in harsh industrial environments with electro-magnetic and narrowband interference from primary users of the UWB spectrum and the interference coming from other UWB devices due to the uncoordinated multi-user operation. It comprises two major functions namely versatile communication and ranging/positioning. Hence, each UWB node provides communication and two way ranging based positioning capabilities. By means of aided inertial navigation, position accuracy can be further improved, especially in situations where the UWB link signal quality is deteriorated. However, the impact of an inertial measurement unit on the positioning accuracy has not been considered within the scope of these investigations.

In this paper, we will determine the 3-D position accuracy in view of a high level, packet oriented simulation framework which considers the impact of all system layers on the positioning accuracy. The impact of multi-user interference is considered within the physical layer model of the simulator in an abstract manner by evaluation of probabilistics of pulse collisions and the flexible medium access control algorithm performing physical layer adaptations has been implemented. Localization is done via anchor nodes to which each mobile performs ranging measurements which are used by a positioning algorithm based on multilateration.

The reminder of this article is as follows. We briefly describe the UWB node architecture, especially the positioning subsystem, and introduce the air interface and the ranging concept in Section II. In Section III, the simulation scenario is described and the results are presented. Finally, a conclusion and an outlook are given in Section IV.

II. UWB Node Architecture

A UWB node is the basic network element in the system and consists of functions for communication and positioning. The functional system architecture of a UWB node is depicted in Fig. 1 and is divided into three subsystems namely the UWB, the communication, and the positioning/ranging subsystem communicating via data and control interfaces with each other. The communication subsystem comprises data link control (DLC), networking and transport functionalities and can configure the UWB subsystem for joint communication and positioning. The positioning/ranging subsystem enables the UWB subsystem to obtain ranging measurement data and in return receive range-related raw measurement data and quality metrics for position calculation. The positioning subsystem consists of three main modules. First, the range management module which is responsible for the gathering of all data which are needed to process ranges/positions. This implies the management of the own position as well as the neighbour positions and the treatment of system clock values by forwarding the ranging clock values and their reliability to the range calculation unit. Besides, it initiates ranging measurements and assists the route management of the routing algorithm.

The second module is the range calculation which has the task to calculate ranges and range reliability from the system's clock information. All range information together with the fix anchor node positions are sent to the position calculation module which consists of a positioning algorithm based on multilateration to calculate the mobile nodes position.

The calculated position can be send to other UWB nodes or to the application subsystem running on a conventional PC for monitoring purposes. In order to serve both services

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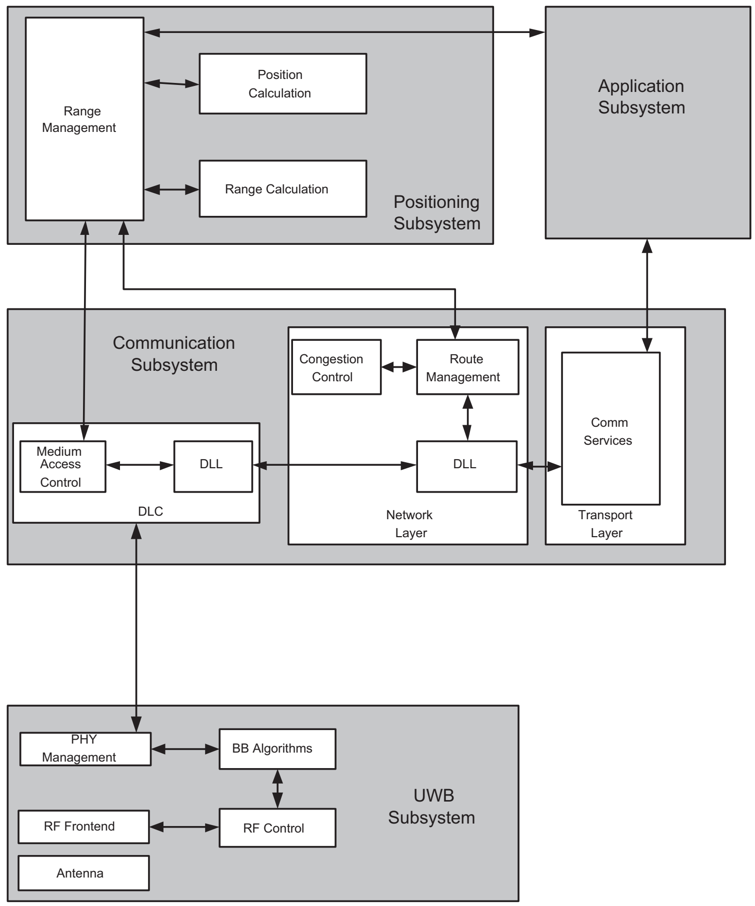

Fig. 1. UWB node architecture and application subsystem

namely communication and positioning in parallel, a common air interface format is needed. Hence, common and private communication channels are provided by the system.

A. Air Interface Format

The common channel will be transmitted in so-called beacon slots using a default set of PHY parameters like time hopping (TH) codes, modulation and forward error correction (FEC) allowing low data rate transmission but highly robust communication. It usually carries broadcasting and handshaking messages but also short information such as sensor data. The communication on the common channel is always unidirectional implying that any data transmitted on the common channel will not be acknowledged.
On so-called TH channels large volume information is transmitted on private communication channels which are always bi-directional as each packet has to be acknowledged by the destination node. The PHY parameters of the TH frames are dynamically set as the destination node can inform the transmitter about the link quality. This kind of medium access control has the goal to maximize the cumulative communication performance and was first introduced in [2] and enhanced in [3].

B. Ranging and Positioning

For the ranging and positioning purpose we only consider the beacon frames sent on the common channel. Fig. 2 shows the air interface frame structure with its beacon and TH frames. Each beacon frame splits into three beacon slots which are

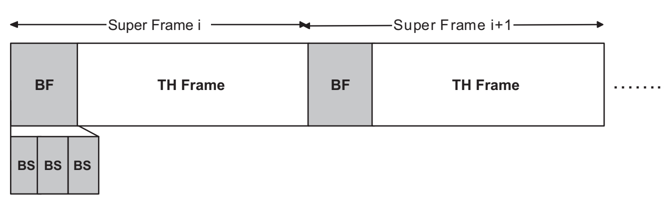

Fig. 2. Air interface frame structure

used for synchronization, protocol handshake elements, very low data broadcast, and for ranging requests and ranging answers.
Ranging is initiated by a UWB node sending a ranging request (RR) to a selected destination node which usually is an anchor node answering with a ranging answer (RA) back to the initiating node. As the ranging operation needs a strict timing between the request (RR) and the answer (RA), the third beacon slot is always reserved for the ranging answer

after a ranging request occurred. Thus, three beacon slots are gathered in one beacon frame. The second beacon slot can be alternatively used by any other node to send control information or to broadcast common data channel information. The duration of a whole superframe structure is 3.5 ms where the beacon frame has a duration of $3 \times 50\mu s$. This implies that one range measurement for one mobile can be done within one superframe transmission in order to fulfill the requirements of a range update time of 10 ms. In order to carry out position calculation multiple ranging procedures to different anchor nodes are needed. Fig. 3 shows the principle of positioning with two-way ranging where the initiating mobile node successively addresses three neigbour anchor nodes as an example.

Since a single ranging measurement can be done within one

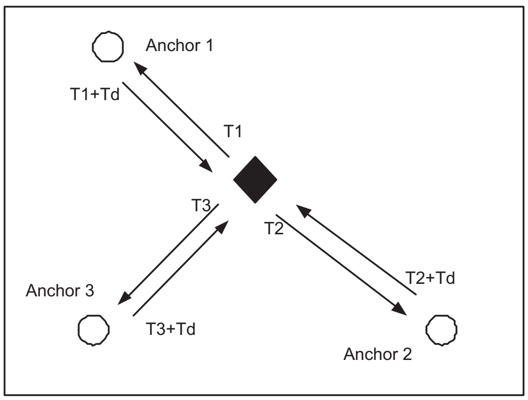

Fig. 3. Positioning principle using two-way ranging

beacon frame, the mobile node reserves the first slots of N successive beacon frames in order to minimize the latency, see Fig. 4. For each two-way ranging measurement the time in between the transmission of RR and RA has to be corrected by the internal delay to obtain the round trip time which can be directly translated into a distance between mobile and anchor node.

As ranging requests (RR) can collide and detecion is impossible, collision resolution strategies have been implemented. The RR message is repeated with a certain propability several times.

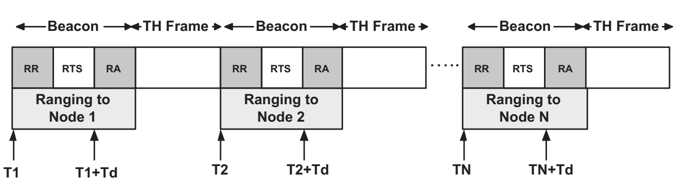

Fig. 4. Positioning estimation using N successive beacon frames

III. Simulations

A. Simulation Scenario

The simulation scenario is depicted in Fig. 5 and shows one mobile and eight anchor nodes placed in the corner of a $20 \times 20m$ room. The height of the room corresponds to $5m$. The mobile node moves by using a random way point model with dynamical speed of 0.5 - 3 m/s. The update interval of one new range calculation to a random anchor node is set to 10 ms. Hence, the algorithm calculates a new position every 10 ms with two new range information, the other ranges are the previous ones. The simulation parameters are shown in Table I.

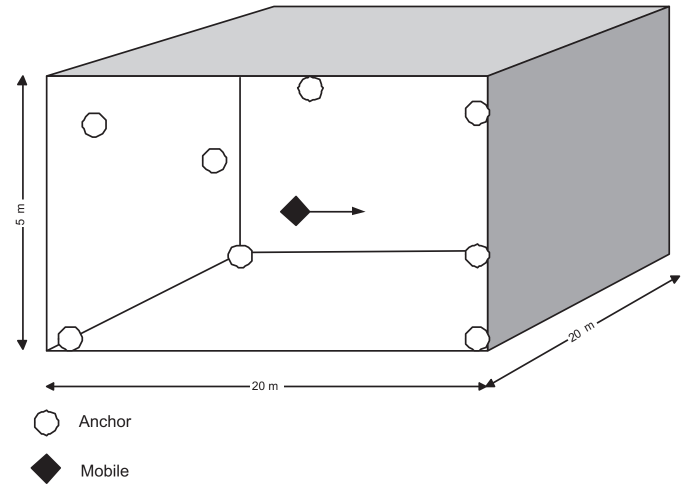

Fig. 5. Simulation scenario with one mobile and eight anchor nodes

TABLE I
Simulation paramters

Parameter	Value
Anchor Nodes	8
Mobile Nodes	1
Dimension	3
Mobile Speed	0.5 - 3m/s
Error Variance	0cm (ideal), 10cm (LOS, NLOS)
NLOS Offset	2 - 4m
Channel Characteristic	Ideal, LOS, NLOS

For the LOS and NLOS parameters we refer to [4], where the authors have determined the error variance σ^2 and the offset due to obstacles in NLOS cases for a IR-UWB localization system by practical indoor measurements.

B. Simulation Results

The simulation results for the different channel conditions are depicted in Fig. 6 (a)-(c). As a qualitiy parameter we determine the root mean squared error (see Table II).

In case of the ideal channel model the positioning error is only caused by the mobility of the mobile. The higher the speed of the mobility is, the lower is the resolution accuracy of the mobile's position, as the ranging module can only deliver a new range information every 3.5 ms. This is a MAC specific attitude and extremely influences the positioning accuracy. The positioning module calculates the position by using the new range information together with the previous ranges. Hence,

there is an offset of approximately 3cm for the x-axis.
Additionally to the errors caused by the mobility the noise in LOS situations deteriorates the positioning accuracy up to 30-75 cm and in NLOS cases, where time of arrival offsets occur due to obstacles in the environment, the position of the mobile can be estimated with an error of 2-4m. This indicates that NLOS detection methods are essential for accurate and robust indoor localization.
In all channel conditions the resolution of the y and z-axis is generally worse as the constellation of the anchor nodes plays an important role as shown in [5]. For a random anchor constellation the Vertical Dilution of Precision ratio $VDOP_{ratio}$ is worse as the Horizontal Dilution of Precision ratio $HDOP_{ratio}$. In order to yield better resolutions for the vertical axis the anchors must be arranged in a tetrahedron. However, we did not consider this effect in our simulations but this causes the higher resolution error of the y and z-axis.

TABLE II
ROOT MEAN SQUARED ERROR [M]

	x_{mean}	y_{mean}	z_{mean}
Ideal	0.031	0.087	0.093
LOS	0.32	0.65	0.74
NLOS	2.21	3.92	4.45

IV. CONCLUSION

We have presented positioning results of an OMNet++ simulator for an autonomous multi-sensor wireless communication system which has beed developed in the PULSERS II project by considering different channel conditions. The simulator includes an abstract PHY layer considering the impact of multi-user interference, a flexible MAC layer which performs PHY layer adaptations, and a positioning and ranging module. In ideal channel conditions the resolution of the position estimation only depends on the speed of the mobile which has beed chosen randomly between 0.5 - 3 m/s, as the MAC algorithm allows new ranging measuerements every 3.5 ms due to the superframe structure.
In LOS and NLOS cases the position estimation is additionally influenced by the error variance and the time of arrival offsets due to obstacles and the accuracy is in the order of 30-80 cm in LOS situations and up to 2-4 m in NLOS cases. Hence, NLOS detection algorithms are essential for accurate positioning and must be added to the simulator.

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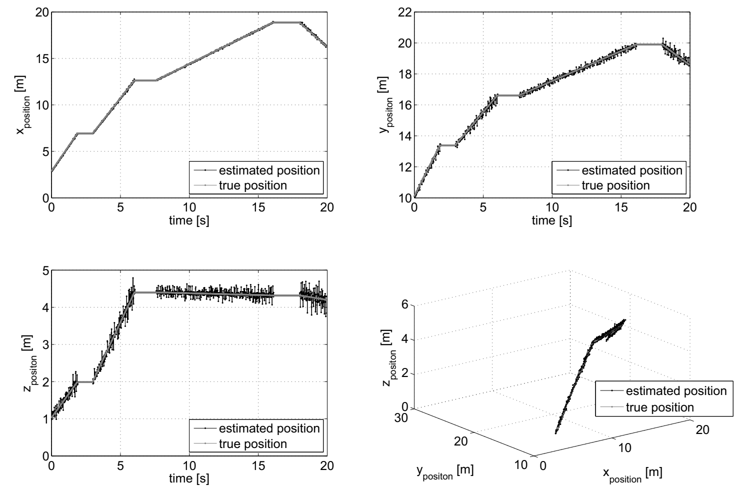
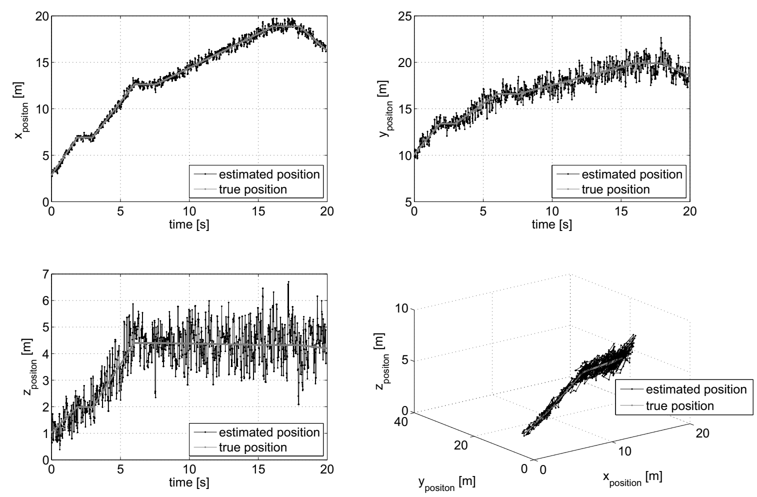
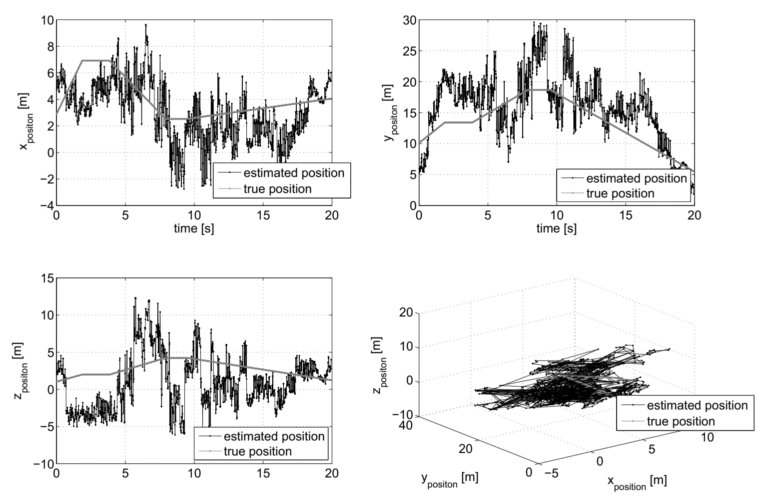


(a)



(b)



(c)

Fig. 6. Simulation results for ideal (a), LOS (b) and NLOS (c) channel conditions