MAC-layer Protocol for UWB-Based Single-Tag Indoor Localization System

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Abstract – **In this paper we present a MAC-layer protocol for UWB-based indoor localization system composed of a set of fixed anchor nodes and single mobile tag. The protocol we propose solves the problem of delivering ranging data from the mobile tag to the location server through the multi-hop sink-tree network of anchor nodes. The proposal regulates the process of network formation and employs a TDMA scheme wherein each anchor node is statically assigned a time slot for ranging and data forwarding, thereby avoiding collisions and improving system scalability.**

Keywords – **ultra-wide band, indoor localization, medium access control, sink-tree network.**

I. Introduction

Accurate location information is essential for the location-based services in many context-aware applications [1]. Among variety of localization technologies, the ultra-wide band (UWB) localization is considered to be the most promising radio-based localization technology available today, which offers the potential of achieving a centimetre level localization accuracy even in indoor multipath environments [2][3]. To modulate the information, the UWB uses ultra-short pulses with duration of less than 1 ns, which are transmitted over a large bandwidth in the frequency range from 3.1 GHz to 10.6 GHz [4][5]. The most important characteristic of UWB is large bandwidth in comparison with prevalent narrowband systems (e.g., Wi-Fi, and Bluetooth LE). Due to the inverse relationship between the time-of-flight (TOF) estimation error and signal bandwidth, the distance between two UWB transceivers can be measured with a high precision with excellent immunity against multipath fading [6].

In this paper, we consider a simple yet practical application scenario of single person localization in a multi-room indoor environment. The application setup includes a number of battery powered fixed anchor nodes distributed throughout the area of interest, a mobile tag node carried by a person to be localized, and a centralized location server. The tag periodically performs UWB ranging with surrounding anchors and sends the ranging data to the location server. Although UWB signal can penetrate one wall, it usually cannot propagate through multiple walls, so the full coverage of the entire localization space (e.g., typical residential apartment) is not possible. Therefore, the delivery of ranging data is the main problem with this set up because of limited range of UWB communication in the indoor environment. In order to solve this problem, we propose a MAClayer protocol that enables the tag to deliver ranging data to the location server through anchor nodes organized in a multi-hop sink-tree network.

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Regarding MAC design for UWB indoor localization systems, several proposals have been presented in the recent past. An analysis of scalability of different MAC schemes in terms of tag density was presented in [7]. In [8] a WiFi-UWB MAC protocol is presented, in which the time difference of arrival (TDoA) based UWB indoor localization system is deployed on top of a WiFi ad-hoc mesh network. In order to allow simultaneous localization of multiple tags, and avoid collisions between UWB messages, the protocol adopts a TDMA approach with on-demand slot assignment. In contrast to previous works, our proposal is a pure UWB MAC protocol adapted to time-of-flight (ToF) based UWB localization and highly optimized for single-tag application scenarios with low to moderate location update rate requirements.

The rest of the paper is organized as follows. Section II explains the UWB-based localization, and a commonly used ranging method. Section III introduces new UWB-based single-tag indoor localization system, and describes its architecture. Section IV presents the proposed MAC protocol design. Section V discusses some key aspects of the proposed localization system and indicates potential directions for future research.

II. UWB-Based Localization

Indoor localization system typically consists of a set of reference nodes, so called anchors, placed at fixed locations in the area of interest, and a *tag* node carried by the person or attached to the object that needs to be localized. The UWB localization process involves two phases: (i) the ranging phase, during which the distances between the tag node and individual anchors are measured, and (ii) the localization phase, during which the current position of the tag is calculated through a multilateration algorithm by using distances from the ranging phase.

The distance between two UWB nodes is commonly estimated by carrying out the alternative double-sided two-way ranging (AltDS-TWR) method [9]. As shown in Fig.1, AltDS-TWR is a time-of-flight based method, which requires exchanging of three messages (*Poll*, *Response*, and *Final*) between an initiator (node A) and a responder (node B). During the message exchange, nodes A and B take timestamps ($t_1, \dots t_6$) of receive and send events on the physical layer using their respective local clocks. The timestamps are then used to calculate the time of flight (T_{tof}), and therefore the distance between nodes A and B.

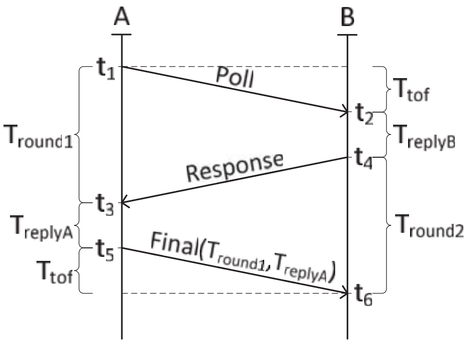


Fig. 1. Asymmetric double sided two-way ranging method

The time of flight is calculated by substituting measured round-trip times (T_{ro} , T_{ro}) and reply times (T_{replyA}, T_{replyB}) into the formula (1). Note that the distance is calculated by the responder node B after it receives T_{ro} and T_{replyA} from the initiator node A.

$$T_{tof} = \frac{T_{ro} \quad T_{ro} \quad -T_{replyA}T_{replyB}}{T_{round} \; +T_{ro} \quad +T_{replyA}+T_{replyB}} \tag{1}$$

Although UWB is not a new technology, its widespread adaptation has recently been accelerated by the commercialization of the IEEE 802.15.4-compliant UWB transceivers, such as DW1000 [10]. The DW1000 transceiver provides high precision UWB ranging and high data rate communications up to 6.8 Mbps. The DW1000 implementation of AltDS-TWR takes about $5\,ms$ with ranging precision of $10\,cm$ indoors.

III. PROPOSED UWB-BASED INDOOR LOCALIZATION SYSTEM

A. System Overview

The proposed UWB localization system aims to enable localization and tracking of a walking person in a complex multi-room indoor environment. The system is composed of multiple battery powered UWB nodes, including: *a*) a set of N static anchor nodes placed at fixed and known positions in the localization environment, and *b*) single mobile tag node carried by the person to be localized. Distances between the tag and anchor nodes are estimated through AltDS-TWR method, with anchor nodes acting as the initiators (node A in Fig. 1), and tag node as a responder (node B). The estimated distances are collected by the tag, and then sent to the location server (LS), which executes the localization algorithm to obtain the estimated location of the tag.

The choice of using TOF localization approach requires a specific MAC protocol design. First, in order to save the energy, the protocol should organize ranging operations in a way to minimize the idle listening of UWB nodes. Second, the protocol has to provide a mechanism for delivering the ranging data through the anchor nodes in cases when the location server is out of range of the tag node. Finally, the protocol needs to allow system installation with minimal setup and effort.

B. Network Architecture

The logical organization of the UWB-based localization system is shown in Fig. 2. In the proposed localization system, one of anchor nodes plays a role of network coordinator (C). In addition to participating in UWB ranging with the tag (T), like any other anchor node, the coordinator also serves as a gateway between the UWB network and the location server (LS), and provides the synchronization service for the entire UWB network. The remaining anchors are referred to as peripheral anchors (P). Each anchor is preassigned a unique identifier (ID) in range 0 to $N-1$. The anchors are organized in a time-synchronized multi-hop network of sink-tree topology rooted at the coordinator node. Each peripheral anchor has its parent node in the tree. The level number (L) of a peripheral anchor is one greater than the level number of its parent. The level number of the coordinator node is $L = 0$. The depth of a sink-tree, L_{max}, is defined as the maximum level number in the network.

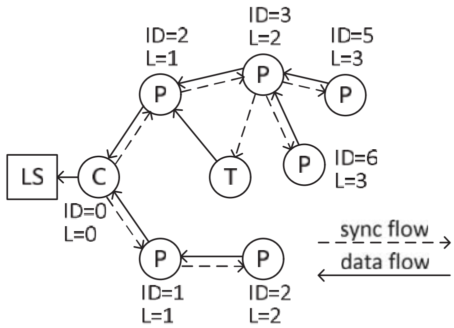


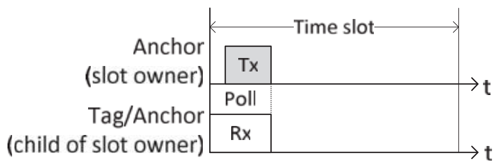
Fig.2. Sink-tree network of depth $L_{max} = 3$. **Notice**: C – coordinator node, P – peripheral anchor, T – tag, and LS – location server.

The parent-child relationship between nodes is used for both time synchronization and routing of ranging data from the tag to the coordinator node. A network-wide synchronisation is achieved through distribution of sync beacons. The coordinator node periodically broadcast a sync beacon to all its children. After receiving the sync beacon from its parent node, a peripheral anchor adjusts its local clock and rebroadcasts the beacon to its children. Due to its mobility, the tag node does not have a permanent parent node. Instead, it chooses one of anchors in the radio range as its temporal synchronization parent. After it stops receiving the sync beacons, the tag chooses a new synchronization parent.

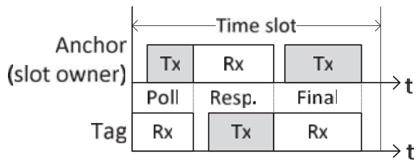
Periodically, the tag initiates a ranging process, which includes performing ranging operations with all anchors in succession. For each successfully completed ranging operation, the tag calculates the distance to the corresponding anchor. At the end of the anging process, the tag formulates a report message containing the ranging data and sends it to one of neighboring anchors. Note that the tag is the only data source, while the coordinator node is the only data sink in the network. The peripheral anchors never generate their own data, but they only serve as relay nodes for forwarding ranging data. A peripheral anchor can only receive data from the tag or from its children. After data is received, the peripheral anchor is obligated to send the data to its parent. In this way, by forwarding data from upper level to lower level nodes, the report message finally reaches the coordinator node.

IV. MAC Protocol Design

In order to organize UWB nodes in the sink-tree network, the time is divided into fixed-length periodic frames, and each frame is composed of N time slots of equal duration. The time slots are numbered, and each anchor owns one slot in the frame according to its ID. A peripheral anchor or tag is considered to be a part of the network only if it is in SYNC state, i.e., it is time synchronized with its parent node. In the SYNC state, anchor is active in its own time slots, and in the slots owned by its parent, only. At the beginning of its own time slot, anchor sends the *Poll* message containing its ID and level number. The *Poll* messages play role of sync beacons. In the parent's slot, peripheral anchor or tag receives a *Poll* message from its parent (Fig 3(a)). Peripheral anchor or tag uses parent's *Poll* message to adjust is local clock, and to set its level number to one greater than the level number contained in the message. After sending the *Poll* message in its own slot, the anchor waits for a possible response. If the *Response* message is received from the tag, the anchor completes the ranging procedure by responding with the *Final* message (Fig. 3(b)). If a data message (*Data*) is received from a child node, the anchor temporary buffers the received message (Fig. 3(c)). The buffered message will be resent by the anchor in the first next slot owned by its parent.



(a)



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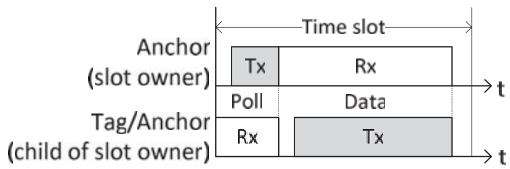
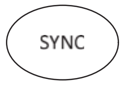


(c)

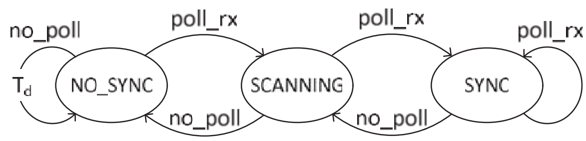
Fig. 3. Activities in a time slot: (a) synchronization only, (b) ranging, and (c) synchronization and data forwarding.

State diagrams of coordinator node, peripheral anchor, and tag are shown in Fig. 4. Being the only source of sync beacons, the coordinator node is considered to be permanently in SYNC state (Fig. 4(a)). Any other node (i.e., peripheral anchor, or tag) has to follow a specific procedure to synchronize with the coordinator, i.e. to enter the SYNC state.

The peripheral anchor begins its lifetime in NO_SYNC state (Fig. 4(b)). In this state it keeps its UWB transceiver in the receive mode. If no *Poll* message has been received for the duration of an entire frame, the peripheral anchor turns off UWB transceiver, makes a pre-specified pause of T_d, and then it tries again. After receiving a *Poll* message, the peripheral anchor adjusts its local clock and moves to SCANNING state. In the SCANNING state, the peripheral anchor wakes up in every time slot during an entire frame. Among all the anchors from which the *Poll* message was received, the peripheral anchor chooses the one with the smallest level number as its parent, and then sets its own level number accordingly. By selecting the lowest-level neighbouring anchors for the parent nodes, the protocol tries to construct a sink-tree of as small depth as possible. In SYNC state, the peripheral anchors continues to receive *Poll* messages from its parent, and resynchronises its local clock with each message received. In the case of missing *Poll* message, the anchor returns to SCANNING state in order to select a new parent.



(a)



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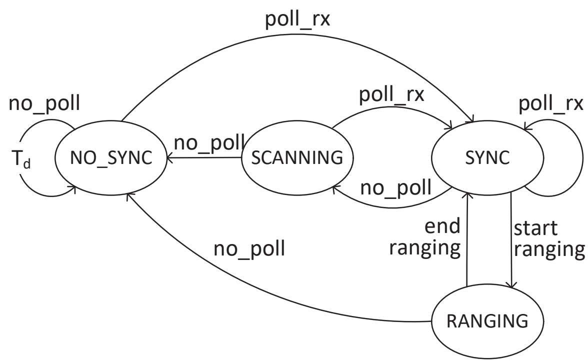

(c)

Fig. 4. State diagram: (a) coordinator, (b) peripheral anchor, and (c) tag

The synchronization procedure for tag node is somewhat simpler. Because there is no need to choose the lowest level neighboring anchor as the synchronization parent, the tag enters SYNC state as soon as a *Poll* message is received in NO_SYNC state. Also, after the synchronization is lost in SYNC state, the search for a new synchronization parent ends once the first *Poll* message is received in SCANNING state. The ranging process is implemented by RANGING state, and can only be started if the tag is in SYNC state. At the end of the ranging process, the tag sends the report message to the anchor at the lowest level of all the anchors with which it performed the successful ranging. Also, before returning to SYNC state, the tag selects the anchor at the smallest measured distance as its new synchronization parent. To prevent interference between ranging operations and forwarding of the report message, the tag should not initiate the new ranging process for at least L_{max} frame periods.

V. Discussion and Conclusion

Location update period, T_L is the most critical parameter of the proposed UWB localization system because it determines the frame period and hence the maximum system size (i.e., the number of anchors). As already pointed out, the tag is allowed to initiate a new ranging process only after the report message from the previous ranging process is delivered to the location server. The report message is forwarded in $L+1$ hops, where L is the level number of anchor to which the tag sent the report message. The time needed for one hop depends on the relative positions of time slots of transmitting and receiving anchors within the frame, and it ranges from one time slot to the entire frame period, T_F. Therefore, in the worst case, the report message forwarding time equals $(L_{max}+1)T_F$. Also, one entire frame period is needed for the ranging process. Hence, $T_L \geq (L_{max}+2)T_F$. For example, in system with the depth of the sink-tree of $L_{max}=3$, which is set to operate with the location update period of $T_L = 1s$, the frame period must be shorter then $T_F = 200ms$. Assuming the time slot duration of $5\,ms$, the system can comprise at most 40 anchors, which is sufficient for most practical use cases.

In conclusion, the single-tag restriction, which enables the adaptation of pre-determined time slot allocation within the frame, and sink-tree topology for data forwarding and time synchronization, considerably simplifies the MAC protocol design and allows obtaining significant power savings without performance loss in terms of network scalability and location update rate. One possible direction of further research would be to explore opportunities to increase the location update rate through scheduling transmissions of individual UWB nodes. Of particular importance is also the generalization of the protocol to the case of multi-tag localization.

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