Passive Ultra-Wideband Coarse Localization and Activity Detection System for Assisted Living

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***Abstract*— Ageing of population will increase the number of people demanding the assistance and medical support. In order to increase the life quality of elderly people the medical support and assistance will be provided at people homes which require the development of new technologies to support their living and reduce needed interaction of the nursing stuff. Activity detection and deviation from daily activity patterns are recognized as the main indicators to identify modification of the people behaviour showing potential risk in the deterioration of their physical and mental health. The passive and active localization are two key technologies applied for activity detection and tracking. In this respect in this paper we specify a new communication protocol for passive and active localization applicable for assisted living applications supporting tracking one person in their apartment. Communication protocol exploits the IEEE 802.15.4-2011 UWB communication technology for ranging and channel sounding application as inputs for the passive and active localizations.**

Keywords*— *assisted living, communication protocol, indoor localization, passive tracking, UWB sensors

I. Introduction

To support elderly at their homes and observe changes in behaviour that can show the deterioration of their physical and mental health, different sensors and tools that can track their activity during the day are needed. One of the main parameters for observing their physical activity is tracking their location inside the apartment. Tracking movement of a person using active localization techniques where person is wearing an active tag is reliable and, unless a very high precision is required, not highly pretentious. Since elderly people are not particularly tech-savvy and wearing additional gadgets usually means additional burden, the passive localization solutions are preferable.

Passive localization approaches, especially those requiring no person interaction, are vastly more complex compared to active approaches regarding the localization algorithm complexity. The most suitable ones implement different forms of RF fingerprinting [1] or radio tomographic imaging (RTI) approach [2], [3]. RF fingerprinting and RTI techniques are based on RF scene analysis [4]. Usually the fixed RF devices in target environment collect RSSI measurements from all other fixed devices and localization algorithm uses this information to locate the person in the environment based on the changes in propagation characteristics on the individual link.

Solutions based on RTI techniques [5]–[7] for RSSI measurement collection often use multi-Spin protocol [8]. Multi-Spin protocol is a multi-channel TDMA protocol where time is divided into slots, cycles and rounds. In each slot only one node is transmitting and all other nodes are listening, and slots are contained in one cycle. Each cycle contains slots for all devices in a network for a particular communication channel. When the protocol cycle is finished, the network of nodes switches to another communication channel and again collect the RSSI measurements. The round consists of a full set of cycles for a list of predefined communication channels. In each slot the transmitting device sends all previously connected measurements for all the nodes it can receive the packets from and the devices that are connected to the master communication node (e.g. PC) collects all measurements for RTI application.

It turns out that ultra-wideband (UWB) technology based on IEEE 802.15.4 is a promising candidate for the measuring the variations in radio channel. IEEE 802.15.4 UWB RF technology implements pulse radio communication which is capable of precisely measuring signal time-of-flight and ranges since its superior time resolution compared to the narrowband RF technologies. In addition to basic RSSI values that can be obtained for each received packet there is also channel impulse response (CIR) information available. Using combined information of RSSI value, CIR and range in case of active localization, superior localization performance can be achieved.

The rest of the paper is organized as follows. In Section II detailed overview of localization system for assisted living is done. In Section III a communication based on IEEE 802.15.4-2011 UWB definitions is described. Section IV gives a detailed description of defined protocol for assisted living with emphasis on detailed communication frames definitions. In the last Section, final overview and conclusions are made and future work is outlined.

II. Assisted living localization system

The localization system is composed of an edge gateway running GNU/Linux OS, connecting to the internet using Wi-Fi and carrying one custom UWB radio board for UWB communication. In order to simplify the deployment complexity and cost of the localization system only master UWB device is connected directly to the relatively high-performance networked device. Other UWB devices in the environment are connected to the master UWB device using custom UWB communication protocol which handles recording propagation information, measuring ranges to all other devices and finally sending all collected information to the master UWB node. Collected information at the master UWB node is then used as an input to the localization algorithm.

Fig 1 shows the hybrid UWB indoor localization system composed of an edge gateway with master UWB anchor device, two slave anchors and one mobile wearable UWB device (in the middle of the figure) that tracked person carries throughout the calibration localization session later used as a ground truth localization information.

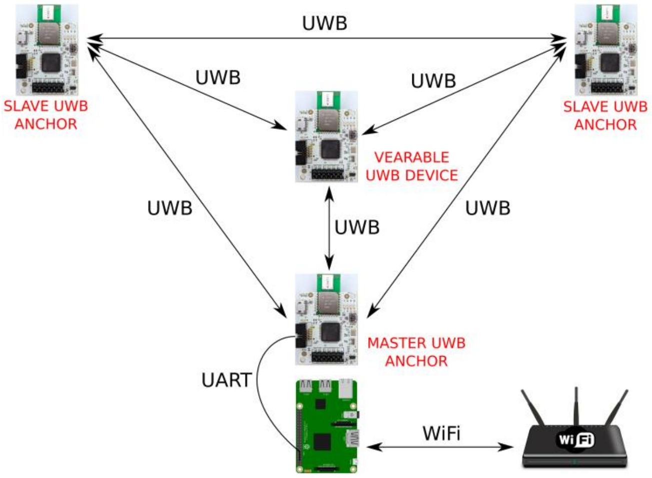

Fig. 1. Hybrid UWB indoor localization system

The assisted living application requires a localization system that is capable of passive RF localization of a single person in an apartment. The deployment of the assisted living localization system consists of two phases, namely *(i)* calibration phase and *(ii)* system in operation phase. In the calibration phase a hybrid localization approach is required where active localization is used to correctly track the ground truth location and passive localization. This means, that both ranging information applied for active localization and that the propagation information for passive localization is collected. During the in operation phase only the information required for passive localization is transmitted.

III. UWB COMMUNICATION TECHNOLOGY

UWB technology described by standard IEEE 802.15.4-2011 is pulsed radio technology where information is exchanged using very short radio pulses with length of approximately 1 ns and very high bandwidth in excess of 500 MHz. This enables the technology very high temporal resolution and thus ability to very precisely measure the time of arrival of received pulses and packets. This enables the UWB technology to be the enabling technology for precise range-based localization technology.

MAC sublayer frames are specified by IEEE 802.15.4-2011 [10]. It consists of Frame Control field, Sequence Number field, Destination PAN Identifier field, Destination Address field, Source PAN Identifier field, Source Address field, Auxiliary Security Header field, Frame Payload field and FCS parity check field a shown in Fig 2.

Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Fig. 2. IEEE 802.15.4-2011 MAC frame structure [10]

The Frame Control field contains configuration bits holding the information about the MAC frame format. More specifically, the Security Enabled field bit indicates if the MAC payload is protected by the MAC security. In the case of the enabled security the Auxiliary Security Header field is presented. Frame Pending bit indicates if the device sending the frame has additional data to send, Acknowledgment Request (AR) field indicates if the device sending the data or MAC command frame is requesting the acknowledgment while PAN ID Compression field specifies whether the MAC frame contains both destination and source PAN IDs or only destination PAN ID. Frame control field also includes Destination Addressing Mode field, Source Addressing Mode field and Frame Version field holding the compatibility information with the IEEE 802.15.4 standards.

IV. COMMUNIACATION PROTOCOL SPECIFICATION

In the system three fixed devices for passive localization and one active wearable node to be present during active localization phase are used. A master UWB device determines the communication protocol boundaries with its pilot signals. The protocol is organized in a dynamic superframe structure, where master device sends a starting beacon and after it other subframes (slots) take place in communication. Superframe structure is represented in Fig. 3.

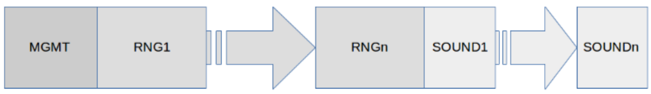

Fig. 3. Localization superframe

At the beginning of each slot master anchor device sends a beacon packet holding the information about the slot, the IDs of devices that should communicate in the slot and the duration of the frame which tells other devices for how long they can stay in the sleep state in order to conserve the energy.

A. Communication frames

All communications in protocol consist of exchange of communication frames. These frames can be divided in the following categories: beacon frames, ranging frames and data frames which are described below.

1) Beacon frames

In the protocol three beacon frames are specified for handling the communication between the nodes in the network. SoSB beacon requests that all the participants in the network response with their device IDs, REQRNG beacon initiates the ranging procedure between two devices in the localization network while the REQMEAS beacon starts the channel measurement procedure between defined pair of the UWB nodes.

2) Ranging frames

All ranging frames are part of the ranging process, where RNGINIT frame requests the ranging procedure from an addressed device to the destination device. Both addresses are previously defined by the master anchor device in REQRNG message. The destination device responds to the RNGINIT message by the POLL message with the recorded transmission time of POLL message for the final ToF measurement. Source device receives the POLL message, records the time stamp of the receipt and sends a RESP message to a destination device. Destination device records a time stamp of a received message and prepares and later sends the FINAL message that includes precisely defined transmission time stamp and all other locally recorded time stamps to the source device. Source device calculates ToF form, all available time stamps and sends the ranging report to the master anchor device.

3) Data frames

In addition to the IRF data frame for identifying the devices and their roles, RNGREPORT data frame holds the information about the measurement range between two devices, where MEAS data frame only holds the IDs of source and destination address for channel measurements. The last message is MEASREPORT message which holds the information of the measured RSS and channel impulse response information used for passive localization algorithm.

B. Communication slots

Each dynamically constructed superframe consists of network management slot (MGMT), ranging (RNG) and channel sounding (SOUND) slots. During the MGMT slot master anchor device listens which devices are present in the network. After the MGMT slot master anchor device delegates communication and measurements according to the table of devices built during the MGMT slot. If the master anchor device does not have all ranges between all anchor devices in a device table, it delegates the range measurements between anchors before the range measurement between anchors and wearable device.

1) Network management slot

After the system startup, a master anchor device has an empty device table. Master anchor at the beginning of management slot (MGMT) of the duration 100 ms sends a start-of-superframe beacon (SoSB) where it waits for the response of any slave device present in the network.

Slave devices response to the SoSB events by identity response frame (IRF) containing device's ID and role. Allowed roles for slave devices are ANCHOR and AGENT. After the reception of the IRF response anchor updates the device table. If device is already included in the table anchor resets its activity counter, which counts the number of subframes till last successful response to the SoSB frame, to zero. If the activity counter reaches 10, device is recognized as inactive and thus removed from the device table. Automatically adaptable protocol excludes the inactive devices from the device table in order to unleash their time slot and improves the measurement refresh rate. The communication during the MGMT slot is shown in Fig.4.

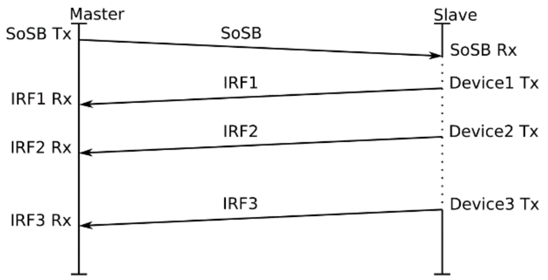

Fig. 4. MGMT slot communication events with one master anchor device, two anchor slave devices and one wearable agent

2) Ranging slot

The role of the ranging slot (RNG) is to measure range between two devices in the network. Master anchor sends a REQRNG message with source and destination IDs of the devices between whom the range needs to be measured. To initialize the ranging process between selected devices, source device sends RNGINIT message to the destination device which responses with the POLL message containing a local Tx time stamp (Tpoll Tx) already contained in the message payload. Source device records the Rx time stamp of received poll message (Tpoll Rx) and responses at predefined fixed reply delay time with the RESP message at local time Tresp Tx. Destination device records the Rx time stamp of received RESP message (Tresp Rx) and attaches it together with pre-set response Tx time stamp (Tfinal Tx) to the FINAL message. Source device receives the FINAL message, records Rx time stamp (Tfinal Rx) of the message and calculates the time of flight from all 6 previously recorded time stamps (Tpoll Tx, Tpoll Rx, Tresp Tx, Tresp Rx, Tfinal Tx, Tfinal Rx). The range is calculated using

$$T_{resp} = (T_{resp\_Rx} – T_{poll\ Tx}) - (T_{resp\ Tx} - T_{poll\ Rx}) \quad (1)$$

$$T_{final} = (T_{final\_Rx} – T_{resp\ Tx}) - (T_{final\ Tx} – T_{resp\ Rx}) \quad (2)$$

$$d = c * ((T_{resp} + T_{final}) /4), \quad (3)$$

where c is speed of light [9]. Finally, source device reports the measured range to the master device in RNGREPORT message. Complete ranging slot is represented in Fig. 5 where MASTER device is a master anchor device in the network, SRC device is a device that initiates the ranging process between two devices (typically one of anchors in the network) and DEST device is the device to which the range is measured from the SRC device (it can be any type of device in the network).

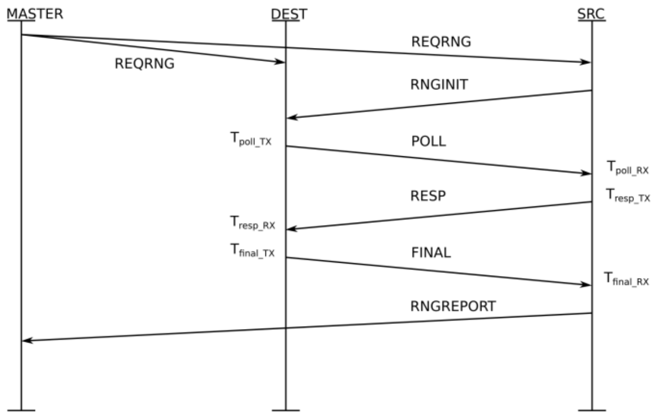

Fig. 5. Ranging slot

3) Channel sounding slot

In a channel sounding slot (SOUND), channel sounding measurements are made between a selected pair of the UWB nodes. Channel impulse response (CIR), power delay profile (PDP), RSS and first path received signal strength (RSSFP) are measured. MASTER device broadcasts a request for channel sounding procedure (REQMEAS) with the SRC and DEST device IDs as a payload. SRC device sends a MEAS packet without any payload to the DEST device. For the received MEAS packet, DEST device records CIR, RSS and RSSFP and sends them in a report message (MEASREPORT) to the MASTER device. PDP is calculated on a MASTER device or in an application that runs on a GNU/Linux-based edge gateway computer. The packet exchange procedure during the SOUND slot is presented in Fig. 6.

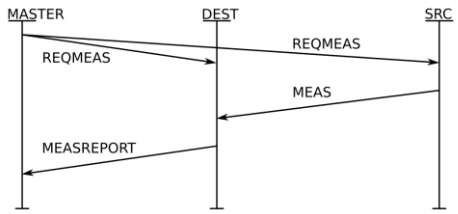

Fig. 6. Channel sounding slot representation.

C. Communication slot duration calculation

To properly control the behaviour of wireless UWB devices in the network without introducing excessive complexity, master anchor device sends pilot packet at the beginning of each communication slot containing slot duration in microseconds. The slot duration informs devices that are not intended to communicate during the communication slot at hand, for how long they can power off the receiver before listening for the next pilot signal and thus conserving power. The duration of communication slots can be calculated according to the predefined packet payload lengths, transceiver settings and known communication symbol timings. In addition, fixed device response delays induced by the UWB device firmware processing should be introduced.

In the following subsections packet length calculation is introduced and structures of all packets used in the protocol definitions is presented.

1) UWB frame structure

The localization solution is based on the DWM1000 UWB radio module from DecaWave which is compliant with the IEEE 802.1.5.4-2011 UWB pulse radio standard. The UWB frame consists of four parts shown in Fig. 7:

- Preamble sequence (SYNC): setting automatic gain control algorithm, channel estimation and packet synchronization at the receiver. Using pulse repetition frequency (PRF) of 16 MHz and 64 MHz, the symbol duration is T_{sym} = 993.59 ns and T_{sym} = 1017.63 ns, respectively [9].
- Start-of-frame delimiter (SFD) determines the exact frame timing and marks the precise switch to the BPM/BPSK modulated PHY header at the receiver. The SFD sequence consists of 64 symbols for 110 kbps mode and 8 symbols for all other modes.
- PHY header (PHR) consists of 19 BPM/BPSK modulated bits for data rate, frame length, ranging, header extension, preamble duration and 6-bit SECDEC (single error correct, double error detect) parity check sequence settings.
- Data field holds the frame data for transferring to the receiver. According to the IEEE 802.15.4-2011 UWB standard data field has a place for 127 octets but DW1000 UWB radio supports an extension to the standard supporting 1023 octets in a payload [9].

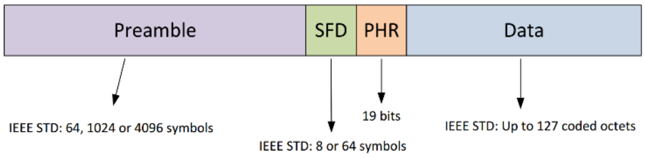

Fig. 7. IEEE 802.15.4-2011 UWB frame structure [9].

2) Frame duration calculation

A transmission time of a frame can be calculated according to the settings of a radio and length of a data field. Complete frame transmission time T_{Tx} consists of a sum of preamble sequence duration T_{SYNC}, start-of-frame delimiter duration T_{SFD}, PHY header duration T_{PHR} and data field duration T_{DATA}

$$T_{Tx} = T_{SYNC} + T_{SFD} + T_{PHR} + T_{DATA}. \quad (4)$$

Preamble sequence length T_{SYNC} is defined by the preamble symbol repetitions (PSR) of preamble sequence as

$$T_{SYNC} = PSR \times T_{sym}. \quad (5)$$

Start-of-frame delimiter (SFD) duration T_{SFD} can be calculated as

$$T_{SFD} = SFD_{len} \times T_{sym}, \quad (6)$$

where SFD_{len} defines the SFD sequence length.

The PHY header duration (PHR) T_{PHR} is defined by

$$T_{PHR} = 19 \times T_{sym} = \begin{cases} 155897.47 \text{ ns; for DR } = 110 \text{ kbps} \\ 19487.16 \text{ ns; for DR } \in \{850 \text{ kbps; } 6.81 \text{ Mbpsg}\} \end{cases} \quad (7)$$

where DR is data rate.

The duration of the data field T_{DATA}, which contains the actual payload, is defined as

$$T_{DATA} = N_{coded} \times T_{sym} \begin{cases} T_{sym} = 8205.13\, ns;\ for\ DR\ =\ 110\ kbps \\ T_{sym} = 1025.64\, ns;\ for\ DR\ =\ 850\ kbps \\ T_{sym} = 128.21 \text{ ns; for DR } = 6.8 \text{ Mbps} \end{cases} \quad (8)$$

and depends on the data rate supported by DW 1000 UWB radio. In the previous equation the number of data symbols at the transmitter output N_{coded} is defined by multiplying the number of octets in the data field N by 8 and adding 48 for each Reed-Solomon coding block x.

$$N_{coded} = N \times 8 + x \times 48 \quad (9)$$

where

$$x=[(N\times 8)/330]. \tag{10}$$

V. Conclusion

In this paper we specify the communication protocol for active and passive localization in assisted living applications using UWB devices compatible with IEEE 802.15.4-2011 standard. First, a high-level hybrid localization system overview is presented. Next UWB communication technology is overviewed. After that, a detailed protocol definition is made. It contains a superframe definition, communication frames definitions, definitions of all communication protocol slots and concludes with detailed frame duration calculation specifications.

As a future work an evaluation of protocol performance in real-life applications should be made. Further a passive localization algorithm based on radio tomography imaging principles will be developed.

Acknowledgment

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