Device positioning and location-aware communications

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Abstract

Modern communication systems can substantially benefit from the availability of location information. For example tracking the user's location can help predict future position and thus increase the resource allocation performance. Location information can also help disabled people live in their apartments in the assisted living facilities. We first introduced fundamental positioning techniques and overlooked the location awareness in the communication systems. We proposed an UWB localization system for passive and active localization with sensor network definition, communication protocol overview and simple active localization technique based on least squares estimation.

1 Introduction

Knowing the position and being aware of device's location in modern communication systems can help improve user experience and help improve network optimization. It can also help residents in assisted living facilities with tracking their activity, detect exceptional events like falling and many more. The localization systems can be very diverse regarding the used technologies and location estimation principles.

Based on the location in the network where the position of a device is being computed the positioning methods can be divided into two categories [1]:

- Device-based positioning methods: The device with the unknown location calculates its own location. The device uses all the measurements to the reference points available in the network and combines them with the localization method of a choice to determine its location.
- Centralized positioning methods: The central device in the network (e.g. a localization server) uses all available measurements from the network devices to the device with the unknown location and combines them in the location of the device.

Position can be calculated using different radio signal properties and or other network-related information. They can be classified in the following groups:

- Multilateration techniques: The localization system uses range-based information obtained by time of flight (ToF), time of arrival (ToA), time difference of arrival (TDoA) or received signal strength (RSS) between the node with the unknown location and several reference nodes in the network.
- Triangulation techniques: Intersection of two (for 2D localization) or more direction of arrival (DoA) or angle of arrival (AoA) measurements of the received signals are used for position calculation.
- Proximity-based techniques: Location of device is determined by the location of the nearest reference device in the network.
- Fingerprinting techniques: Fingerprinting techniques are actually the pattern matching techniques, where a combination of measured signal features (e.g. RSS, multipath components, delay spread, etc.) is matched against the fingerprints in the fingerprint database.
- Network techniques: Network techniques are based on inter-node distances. Inter-node distances can be described by the connectivity, proximity or range information.
- Cooperative techniques: Cooperative techniques are used when the centralized localization systems are not feasible, when a scalable localization solution for large networks is needed or when the dense network of anchors is available [2]. The cooperation relies on direct communication between the nodes, where individual nodes use available information of neighbouring devices to estimate their own position.

Communication systems can benefit from location awareness at many communication protocol layers. For example as a general application of localization awareness, the channel database holding location-based channel quality metric can be used for resource allocation at different protocol layers [3].

In the physical layer, location information can be used to reduce interference, increase capacity gains and improve the resource allocation performance [3]. It can be used e.g. in combination with Gaussian processes to generate primary user power density maps that enable secondary users in the spectrum to select the most vacant channels for communication [4].

At the MAC layer, location information can help dealing with scalability, efficiency and latency challenges

[3]. In [5], authors proposed a round-robin scheduling algorithm exploiting location information for fractional frequency reuse, achieving higher total throughput by allowing temporary sharing of resources between cell-center and cell-edge users. In [6], authors propose location-based multicast MAC protocol that increases the reliability of packet delivery. In [7] authors propose a location-aware power control and scheduling protocol for IEEE 802.15.3 ultra-wideband (UWB) technology, allowing the pairs of devices communicate in parallel within a piconet, successfully lowering latencies and increasing throughput compared to a traditional round-robin scheduling. Further, location information can improve interference prediction and intercell interference coordination techniques in heterogeneous mobile networks consisting of combination of small cells and macro cells [3].

There are also applications of location-aware MAC protocols in vehicular networks. For example, authors in [8] propose a family of MAC protocols for efficiently broadcasting information only at special communication areas. Omitting the CTS and RTS signals in proposed MAC schemes lowers the message delivery time and improves the overall information flow when the flow rate of traffic increases. In [9] a decentralized location-based channel access protocol for intervehicle communication is defined, where unique channels are allocated to different geographic locations. Finally, authors in [10] propose a geocasting MAC protocol where multicast regions are defined by geographical regions and packets are sent to the nodes in the same geocasting group.

At the network layer a location-aided handover mechanism can reduce number of handovers for 30% compared to the RSS-based methods [11]. Another application of location information at network layer is geographic routing in wireless ad hoc networks [12]. It can provide a scalable and efficient information delivery but is sensitive to localization errors [13]. Geographic routing can benefit from node mobility prediction schemes as in [14].

At higher network layers, location information supports navigation and location-based services [3]. First, there come location-aware information delivery [15] enabling location-based advertising, sending location-based notification, delivering to-do lists connected to the current location and many more. Location information can help also with multimedia streaming applications by capturing user mobility patterns and predicting future network planning events [16].

Regarding the intelligent transportation systems intervehicle communication protocols are being developed. The work of [17] provides a location-aware application-layer communication protocol supporting distributed ad hoc, best effort service infrastructure over vehicular ad hoc networks providing drivers time-sensitive information about traffic conditions and traffic related services on their route. Location information can also be beneficial for autonomous vehicles, tactile internet [18] and other cyber-physical systems as unmanned aerial vehicles and robots.

2 Localization for assisted living

Assisted living (AL) systems can substantially benefit from the accurate and reliable location information. Localization can help applications such as activity recognition, mobility pattern analysis and anomaly detection improve their reliability while supporting decisions of caregivers and automated systems helping the elderly in their home.

AL can benefit the most by exploiting the ultra-wideband (UWB) radio signals because of the high temporal resolution of the UWB communication equipment. High temporal resolution enables UWB communication systems to accurately timestamp the beginning of received and sent frames enabling the localization schemes based on time-of-flight (ToF) information. ToF localization systems with sub-nanosecond resolution can provide the localization accuracy in centimetre accuracy range. Other benefit of using UWB systems is also great multipath component (MPC) resolvability, which is a key enabler for a multipath assisted localization systems and propagation conditions analysis for reducing the impact of NLoS ranges on the localization accuracy [19].

IEEE 802.15.4-2011 standard defining low-rate personal area networks (LR-WPANs) for very low-cost, low-power communications, introduces the UWB technology as an alternative physical layer (PHY) specification. UWB PHY implements communication interface based on short pulses with duration in range of 1 ns with bandwidths between 499.2 MHz and 1354.97 MHz all in frequency range between 3.1 to 10.6 GHz. FCC limits the power spectral density emission by -41.3 dBm/MHz for UWB transmitters in this frequency range. IEEE 802.15.4-2011 UWB standard supports the ranging functionality which enables the unsynchronized localization in low-power sensor networks.

2.1 Localization system

For AL applications several localization system types can be used. For the range-based localization active systems are required but for passive systems several approaches based on fingerprinting [20] and radio tomographic imaging [21] are suitable. To deploy a localization system that is capable of both active and passive localization we defined the minimalistic UWB communication system that is presented in Figure 1. Master anchor device is connected to computer with GNU/Linux operating system, two slave anchor devices are connected to the master anchor device using UWB radio link and slave peripheral device is connected to anchor devices with UWB radio links. For a passive localization process, anchor devices are sending messages to all their neighbour anchor devices and measure channel impulse response (CIR) and RSS information for received packets. This information is used for scene analysis and thus passive localization process.

First thing when the localization system is turned on is that the master anchor device periodically sends a bea-

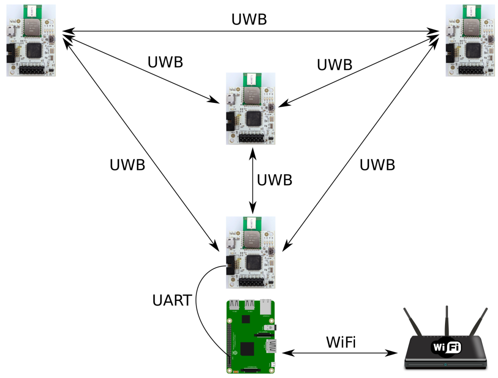

Figure 1: UWB localization system scheme capable of active and passive localization in assisted living scenarios.

con with device discovery request and builds the table of active devices. According to the table of active devices master anchor device then requests the ranging procedure for all pairs in the localization network. Based on the measured internode distances local coordinate system is defined where each anchor device gets its reference location. The reference location in the local coordinate system is crucial for locating the nodes or objects with unknown location. When the local coordinate system is defined master anchor device starts coordinating ranging process from the anchor devices to the device with the unknown location in a case of active localization and coordinates measurements of CIRs between anchor devices in case of passive localization.

2.2 Communication protocol

Communication protocol takes care of communication between al the devices present in a localization network. Communication is organized in a superframe structure with three basic building blocks. First type of communication slot is network management slot (MGMT) where master anchor device requests response from all devices in the network. According to the response the master anchor device builds a device table that is later used to direct the communication between devices.

Next slot type is ranging slot (RNG) where master anchor device master anchor device sends a ranging beacons containing the packet ID that represents the ranging request packet, destination and source addresses of the devices that should measure the range between them and duration of RNG slot in microseconds.

The last slot type is channel sounding slot (SOUND), where CIR is measured for selected device pairs. Master anchor device at the beginning of SOUND slot sends beacon packet with sounding request. The sounding request contains the packet ID, source and destination of device pair involved in the sounding procedure and slot duration in microseconds.

The structure of a superframe is dynamic and depends on the number of devices present in the localization network and desired mode of operation. The network can support three localization modes: active, passive and hybrid localization mode. The MAC superframe structure

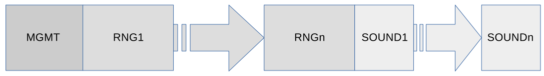

Figure 2: Localization MAC superframe structure.

is depicted in Figure 2.

2.3 Active localization system

We estimate the location of a node with the unknown location using multilateration approach with least squares (LS) method. As in (1) distance between a node with an unknown location $\mathbf{p}$ and i-th anchor $\mathbf{p_i}$ is defined by Euclidean distance.

$$d_i = \|\mathbf{p} - \mathbf{p_i}\| = \sqrt{(x_i - x)^2 + (y_i - y)^2}, \qquad (1)$$

By writing the equations for all anchors and corresponding ranges d_i we get a predefined system of equations that can be written in a matrix form $\mathbf{b} = \mathbf{A}\boldsymbol{\theta}$ (2, 3) by introducing a new variable $R = x^2 + y^2$ where $\boldsymbol{\theta} \doteq [x, y, R]^T$.

$$\mathbf{A} = \begin{bmatrix} -2x_1 & -2y_1 & 1 \\ -2x_2 & -2y_2 & 1 \\ \vdots & \vdots & \vdots \\ -2x_N & -2y_N & 1 \end{bmatrix} \qquad (2)$$

$$\mathbf{b} = \begin{bmatrix} \hat{d}_1^2 - x_1^2 - y_1^2 \\ \hat{d}_2^2 - x_2^2 - y_2^2 \\ \vdots \\ \hat{d}_N^2 - x_N^2 - y_N^2 \end{bmatrix}, \qquad (3)$$

By introducing the variable R the system becomes a system of linear equations where location can be estimated by a linear matrix equation (4) in a normal form.

$$\hat{\boldsymbol{\theta}} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b}. \qquad (4)$$

The system of linear equations (4) can be solved if the matrix $\mathbf{A}$ is not singular, which is the case when the anchors are not collinear. In the case of anchor collinearity, the rank of $\mathbf{A}$ is less than the number of anchors and therefore the matrix $\mathbf{A}$ cannot be inverted which is a crucial step in location estimation using LS method.

LS-based localization method is computationally one of the simplest methods for location estimation. The drawback of this method is that it is stateless and thus it does not use any information of a previous state of the system. It also does not include any kind of kinematic system model as it is used with Kalman filters. Because of such method simplicity the method use less computational resources than more complex algorithms and can be thus easier to use on small embedded devices which are limited regarding computational resources.

3 Challenges and conclusions

In this paper we presented a high-level overview of localization techniques based on location in the network where the location is being estimated. We also presented an overview of localization techniques based on the radio signal properties that are used for localization.

We looked also into aspects of location awareness in the general communication systems. Communication technologies can benefit by using the location information at many communication protocol layers. Location information can be used to reduce interference, to improve the resource allocation, to increase throughput, reduce number of handovers, enable location-based services and to support navigation.

We presented the UWB-based localization system for assisted living applications which supports both active and passive localization. UWB anchor nodes are wirelessly connected to the master anchor node using UWB technology while measuring range between the nodes and measure channel impulse responses between the nodes for passive localization algorithms. We presented an active localization scheme based on multilateration and least squares location estimation.

Passive localization algorithms still represents a challenge for the future work where a combination of principles from fingerprinting techniques and radio tomographic imaging techniques will be used as a hybrid and easy to install passive localization system.

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