Indoor Location for Emergency Responders Using LTE D2D Communications Waveform

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Abstract. It is well known that GPS signals are very weak so they cannot be received indoors. Without GPS, indoor location is a difficult problem, especially for emergency first responders since a pre-installed WiFi or beacon transmitter infrastructure may no longer be available in an emergency situation. On the other hand, emergency first responders must carry radios for critical communication needs in emergency response missions. In this work, we use the LTE Proximity Services (ProSe) mode for Device-to-Device (D2D) direct communications and the system information resource blocks of the LTE sidelink communication signals to measure time of arrivals (TOAs) among a few such D2D communication devices that form an ad hoc wireless network, thereby providing indoor location service that uses no infrastructure, no additional hardware device, and uses very little communications payload bandwidth. This concept is tested by simulation and by implementation on a software defined radio (SDR) network which is demonstrated in a real-world indoor setting.

Keywords: Indoor location, indoor navigation, GPS-denied, LTE ProSe, First-Net, emergency first responder communication, SDR network.

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1 Introduction

Indoor location/navigation is a difficult problem due to lack of GPS signals. Many possible ways have been envisioned and tried, ranging from image-based to magnetism based location. The most successful indoor location technology nowadays is perhaps WiFi or beacon based, through a ubiquitous smart phone app. Because of the intricate and highly variable indoor floor plans and wall layouts, indoor navigation using WiFi or beacon signals would require installations of many beacons at specific locations due to potential lack of line-of-sight and the rich multipath propagation environments. For the first responder application, however, potential factors such as fire and smoke may reduce the effectiveness of image based methods, electric outage or building damage may disable WiFi or beacons, so that many if not all of the above solutions may not be applicable.

With the advent of Release 12 of the 3GPP specifications, LTE devices now have the capability to support Device-to-Device (D2D) communications enabling direct mode operations and Proximity Services (ProSe) that allows the devices to detect each other and communicate directly with one another without the aid of a cellular network infrastructure. In this paper, we present an innovative time of arrivals (TOA) based method to provide indoor location services using the readily available LTE ProSe D2D mode via the sidelink of the LTE emergency first responder communication signals, i.e., we "piggy-back" our location services onto the readily available communications signals. Therefore this approach requires no prior indoor WiFi or beacon infrastructure, no additional location service hardware, with the wireless communication signals that are guaranteed to be available. This method can be readily integrated into an LTE communications platform in software, satisfying both the mission critical communication and location based service requirements with one device. In addition, since we use the system information blocks of the LTE sidelink communication signals to measure TOAs, very little overhead in communications payload bandwidth is required.

In addition, we developed a BIM-IL (Building Information Modeling based Indoor Location) portal which serves as the front end to disparate indoor location technologies and an abundance of smart building data; this would serve as a "one-stop shop" for public safety indoor location purposes. The public safety community can utilize this portal, without a need of specific software installations and skills in BIM and data process, to import BIM files from local files or Web Services and then overlay the indoor location positioning data onto smart building data so first responders can have all needed information in one display.

Researchers have explored using the LTE waveform in a cellular infrastructure for location and navigation, see e.g. [1] and the references contained therein. In those works signals from several base stations (called eNodeB) need to be present with the locations of the base stations known. The receiver measures its pseudoranges to the base stations by the downlink signals. In this present paper, however, we use the D2D mode or the sidelink signals, and assume much fewer known user locations only for the purpose of anchoring relative locations of all involved users. No eNodeB is assumed available. All involved users are equal as user equipment (UE). We use Ettus universal software radio peripherals (USRPs) as SDRs to implement the UEs.

2 The dTDOA Method and Location Computation

There are many ways in providing user locations based on RF signals without GPS [2]. Using round-trip time of arrival (TOA) or time difference of arrival (TDOA) to estimate locations are common and reliable. However, round-trip TOA requires a radio to return its received measurement signal with a prescribed delay from its reception and requires a dedicated communications protocol among the radios. The TDOA measurements require the receiving radios' clocks to be synchronized, which in turn requires significant bandwidth resources. Unlike GPS, most radio transceivers are not accurately synchronized, making the TDOA based methods inaccurate unless labor/resource intensive synchronization of all participating nodes are performed.

We utilize the dTDOA method [3, 4] that does not require tight time synchronization or round-trip TOA measurements. The central idea of the dTDOA is to construct differential TDOA rather than TDOA. During the ranging process, each sensor in the network takes turns to transmit a ranging signal, and all other sensors listen and measure TOAs based on their own clocks. When all sensors have finished transmitting the ranging signals, each sensor then takes turn to pass the TOAs of the received ranging signals to a central processing unit. No tight time constraints need to be imposed on any of these transmissions. Due to space limitation, the dTDOA method is not described here. The interested reader can refer to [3, 4] for details.

As discussed in [3], for high SNR we obtain $N(N-3)/2$ independent dTDOA equations with N users forming an *ad hoc* network. Since all locations are relative, subject to rotation, shifting and reflection,we need to know ground truths of some user location parameters in order to anchor all other locations relative to, say, a building. For example, we need to designate some user(s) outside a building having access to GPS, or designate some user(s) at known locations relative to a building layout. It is easy to see that in a 2D case where each user location is determined by two parameters x_i and y_i, we need to know 3 parameters to anchor all other user locations. Therefore, in 2D we need to have at least 6 users in an *ad hoc* network to obtain 9 independent dTDOA equations to compute all user location parameters. In a 3D case, we need to know 5 parameters to anchor all other user locations, so that we will need to have at least 8 users in an *ad hoc* network to obtain 20 independent dTDOA equations to compute all user location parameters.

Once all dTDOA measurements/estimates are collected, we obtain a set of non-linear dTDOA equations in terms of user locations. An iterative method can be used to solve for a maximum likelihood solution, see [3] for more details.

3 The LTE Sidelink Waveform and TOA Estimation

Initial acquisition of transmitter information is obtained by synchronization at the receiver. The details of different types of synchronization signals are described in [6]. Two types of synchronization signals are used in the present implementation, they are 1) Sidelink Synchronization Signals (SLSS) for synchronization in time and frequency, and 2) Master Information Block SL (MIB-SL) for additional information. In SLSS there are Primary Sidelink Synchronization Signals (PSS) and Secondary Sidelink Synchronization Signals (SSS). Since there are multiple USRPs, we assign an SLSS ID to each USRP to distinguish among all estimated TOAs of different USRPs. Consequently, the receiver would know based on the detected SLSS ID which USRP it is estimating TOA from. On the other hand, MIB-SL is transmitted over the PSBCH and carries information regarding a few parameters such as bandwidth and frame number. The PSBCH is transmitted in the same subframe as the SLSS, indicated in the following resource block (RB) diagram of Figure 1.

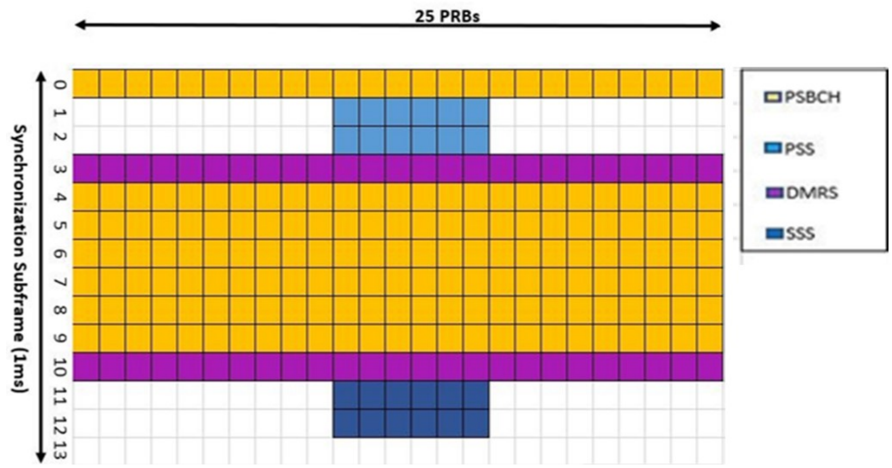

Fig. 1. Synchronization Subframe resource block structure of LTE SL air interface, 5 MHz mode. Vertical coordinate: time, horizontal coordinate: frequency.

For any available LTE bandwidth (BW) setting such as 3MHz, 5MHz, 10MHz and 20MHz, the occupied bandwidth in the resource grid by PSS/SSS signals is constant regardless of the LTE signal BW, always 1.4 MHz with an effective bandwidth of 1.08 MHz. This synchronization signal BW, although adequate for communication purpose, is too narrow for TOA and location purposes resulting in poor TOA measurement and estimation. The TOA signal should be selected to encompass as large a BW as possible while keeping the pseudorandom properties which will make an effective signal for correlation and precise time estimation. Such a signal is readily available in the MIB block of the LTE waveform, such as the PSBCH resource block. In order to maximally use the available BW for better TOA and location accuracy, we use the PSBCH signal other than the PSS/SSS signals for TOA estimation, see Figure 1. The PSBCH signal in the OFDM "frequency domain" (to be transmitted) turns out to be pseudorandom in nature, therefore suitable for TOA timing estimation. In addition, since the MIB is a control signal, using it for TOA estimation does not incur any additional BW overhead.

Table 1 lists the available LTE sidelink signal BWs and their corresponding PSS/SSS and PSBCH resource block signal BWs, respectively. It is seen that the PSBCH signal uses the available LTE sidelink waveform BW much more fully than the PSS/SSS signals. The asynchronous TOAs are estimated by calculating the relative time delay between two USRPs. Coarse time delays are estimated by calculating the Sync point in a subframe obtained from correlation of synchronization (PSS/SSS) signals that lock at a time sample. Fine time delay estimation uses PSBCH signals for its larger BW, and is performed by early-prompt-late correlators that achieve better time resolution than the sampling interval.

While the TOAs are measured using the PSBCH signal which is part of the LTE communication signal overhead to be transmitted with or without location service, the estimated TOAs are transmitted to a processing center (one of the UEs) in the form of payload data along with their corresponding IDs to distinguish between different TOAs.

Physical Sidelink Discovery Channel (PSDCH) in a payload subframe carries the user data. Hence, we use PSDCH to transmit the needed TOA values, whose decoding at the receiver is done normally as in [5]. OFDM demodulation and turbo decoding are performed on PSDCH resource blocks in order to acquire the TOA values.

Table 1. LTE sidelink signal BW modes and signal BWs

LTE BW Mode (MHz)	**Effective Signal BW (MHz)**	
	PSS/SSS	**PSBCH**
1.4	1.08	1.08
3	1.08	2.7
5	1.08	4.5
10	1.08	9
15	1.08	13.5
20	1.08	18

4 A Multiuser Communications Protocol

There is no eNodeB in D2D communication, all devices are considered as UEs. Also, there is only one carrier frequency in sidelink. Since multiple users need to be involved in using the dTDOA method to compute user locations, a multiuser communications protocol must be developed to ensure that only one UE transmits at any given time so no over-the-air (OTA) collision will occur. A cooperative communications protocol was proposed to avoid collision and achieve efficient communication among multiple devices in LTE cellular mode of operation [7]. To our knowledge no multiuser cooperative communications protocol exists today for ProSe D2D operation. In this section we describe such a simple protocol that we developed for our purpose.

Such cooperative multiuser communication is achieved by giving unique IDs to all UEs and providing different time slots for them to transmit and receive, see Figure 2. User ID is attached to the Sidelink waveform by inserting the user ID into the payload of transmitting waveform which is collected and decoded at the receiver at the time of TOA measurement.

In this experiment six UEs are involved to find their 2D locations. Since all six user IDs are assigned beforehand, a pre-assigned user Tx and Rx timing diagram is followed as shown in Figure 2. For simplicity, all UEs start manually at approximately the same time, then the timing of Figure 2 is followed by all UEs. A more sophisticated protocol should take into consideration of UE discovery and participation into such a multiuser network at random times. However, that is beyond the scope and budget of this project.

In real time implementation, manually starting at the “same time” does not result in synchronization.It has been concluded from our USRP tests that, to ensure successful reception, the transmitted signal (40ms of LTE SL subframes for all needed information) should be repeated for a certain time period which is the time for each stage in Figure 2. During this time period, the receiver UEs keep receiving the transmitted waveform and 1) perform correlation to find TOAs and 2) decode the received waveform to find the ID of the transmitting device and other TOAs in other stages. In this experiment, six stages of transmission and reception are required to obtain all the measured TOAs at the processing center. Details are omitted due to space limitation.

	Stage 1	Stage 2	Stage 3	Stage 4
UE1	Transmit Discovery Waveform (TDW)	Idle State	Idle State	Idle State
UE2	Receive and Measure TOA with UE1	TDW with TOA UE1-UE2	Receive and Measure TOA with UE3	Idle State
UE3	Receive and Measure TOA with UE1	Receive and Measure TOA with UE2	TDW with TOA UE1-UE3, UE2-UE3	Idle State
UE4	Receive and Measure TOA with UE1	Receive and Measure TOA with UE2	Receive and Measure TOA with UE3	TDW with TOA at UE4- UE1, UE2, UE3
UE5	Receive and Measure TOA with UE1	Receive and Measure TOA with UE2	Receive and Measure TOA with UE3	Receive and Measure TOA with UE4
UE6	Receive and Measure TOA with UE1	Receive and Measure TOA with UE2	Receive and Measure TOA with UE3	Receive and Measure TOA with UE4

Fig. 2. Multiuser D2D Protocol Timing Diagram (Only 4 stages are shown)

UE6 will be the processing center where all TOAs are collected and will be used to calculate the locations by using the dTDOA algorithm. Once the locations are found, if desired UE6 can send out the locations to all other UEs through payload, and a communication cycle ends after this stage. If the TOAs are not available or not received for UE6 to calculate locations, then this final stage transmission will not happen since locations cannot be calculated at the processing center. Since there are 6 UEs, there are 15 different combinations of TOAs by the end of one communication cycle. These 15 TOAs form 9 independent dTDOA equations.

5 Multipath Mitigation

Multipath propagation is a significant problem in indoor environments. Communication signals are easily reflected and attenuated by interior walls and equipment. This causes signal distortion and erroneous TOA estimates at the receiver. While the LTE standard includes OFDM techniques to tackle some issues of multipath, such as the introduction of cyclic prefix, it was developed for efficient bandwidth use for communication, but not as a location-finding waveform for precise timing. In particular, the basic pulse of the LTE waveform is "shaped", unlike the GPS signals having unshaped pulses. These shaped pulses make the correlation function look like sinc rather than triangular, so multipath mitigation is especially challenging since the conventional correlation-based methodswill have poor resolution with closely spaced paths.

Several line-of-sight (LOS) TOA estimation and multipath mitigation techniques have been investigated, including some well-known methods in or outside the GPS literature. Due to the reasons mentioned in the previous paragraph, many of those methods do not work well for the LTE waveform, such as the slope differentiation method and the MUSIC method. The projection onto convex sets (POCS) method works well but is computationally intensive. Instead, we proposed a simple modified correlation method (MCC) and tested it in both simulation and actual OTA field tests.

The MCC method sets a dynamic threshold which is empirically set at the average plus three times the standard deviation of the received power of each frame. It then selects the earliest peak above this threshold as the LOS TOA peak. Fine time delay estimation is performed by early-prompt-late (EPL) correlators with a quadratic curve fit that achieves better time resolution than the sampling interval. As discussed before, we use PSBCH signal for better TOA estimation accuracy. A larger signal BW not only results in better correlation resolution or tighter correlation peaks, it also allows multipath signals that are closely spaced in time to be more easily resolved.

6 Building Information Modeling – Indoor Location

Successful indoor location-based service (LBS) applications rely not only on indoor maps, spatial data, and additional semantic building information, but also additional dimensions regarding the operational performance of indoor devices, objects, and physical environments. The Building Information Modeling (BIM) software platform is now widely used throughout the life cycle of a building from design and construction to operation. These ready-to-use models are gradually replacing paper-based drawings and pure geometry-based electronic models [8]. BIM has the potential to provide valuable data (e.g., real-time occupancy numbers, physical environment information, etc.) to support first responders' decision-making.

We developed a BIM-IL (Building Information Modeling – Indoor Localization) portal which serves as the front end to indoor LBS and an abundance of smart building data as a "one-stop shop" for public safety indoor location purposes. The public safety community can utilize this portal, without a need of specific software installations and skills in BIM and data process, to import BIM files from local files or web services and then overlay the indoor location positioning data and smart building data, so first responders can have all needed information in one display. An existing BIM file can be obtained from ownersor construction teams. The portal then automates the generation of a BIM-based userinterface, including three main modules: simplified geometric data, emergency-related semantic information, and a spatial data network for navigation. Each module could be used separately or collectively for various public safety-based indoor location purposes in terms of indoor positioning data integration, navigation and mapping, and emergency-related semantics display. If BIM is not available, e.g., an old building, then any available building layout or any additional information can still be imported into the portal for integration with location data.

The methodology used to generate this interface is through the Unity software platform which offers various visualization methods and potential immersive user experiences via virtual reality. The BIM file is automatically converted to a .FBX file (containing simplified geometry data) and a .CSV file (containing emergency-related semantic data). The simplified geometric data include the main structures – walls, roofs, ceilings, floors, windows, and stairs; and the emergency-related semantic data are related to fire rating hours, fire cabinet, room numbers, exit locations, hazard material locations and types, etc. For example, semantic data visualization can use pseudo color – walls with 3-hr fire rating are colored pink, and 2-hr fire rating red.

7 Real-Time OTA Test & Integration with BIM-IL

We performed field tests of the proposed system in an indoor setting and integrated with BIM-IL portal. Six UEs are deployed using six USRPs, among them two are anchored, the other four UE locations are computed using the proposed system and methods. Shown below in Fig. 3 are a screenshot of BIM-IL portal with all six UE locations indicated by colored icons (four are computed). The test room size is approximately 15m x 30m. The LTE signal BW is 5 MHz. Visual inspection against actual locations indicate that 2D location errors are about a few meters.

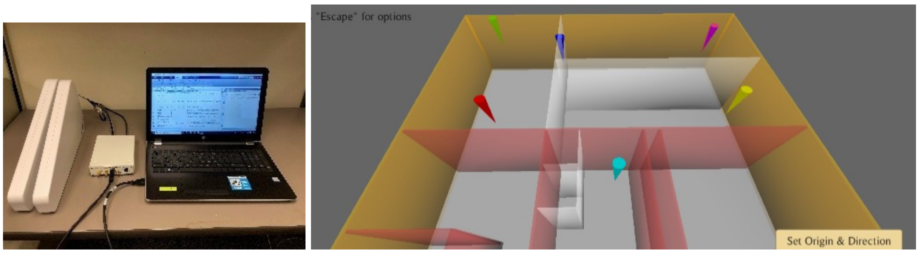

Fig. 3. Left: Each USRP set (one UE) includes a laptop and antennas for additional gain; Right: Screenshot of OTA indoor field test result integrated with BIM-IL portal, the white colored dividing walls are absent in the test, the dark blue and purple icons are anchor UEs, the light blue UE is purposefully set in an adjacent room separated by a wall so line-of-sight path is completely blocked from all other UEs.

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