Enabling Technologies for Indoor Location-Based Services

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Abstract

Location awareness is one of the fundamental problems in tomorrow's wireless networks. With the advent of GPS, LBS have found applications in many different fields. Most of the LBS applications offered by wireless carriers as of today are mainly relied on the GPS technology. In areas where there is a clear LOS to GPS satellites, this technique provides a good estimate of the user's location on the earth. However, in indoor and dense urban environments the GPS signal is typically unavailable, and localization becomes even more challenging. In this paper, we envisioned the UWB radio as a potential technology to realize the indoor LBS applications. Firstly, an overview of some existing and commonly used TOA-based ranging and localization techniques are presented. In particular, we summarize the TOA-based ranging techniques for both time-domain and frequency-domain type of transceivers based on the UWB-IR and MB-OFDM transmission schemes, respectively. Then, we introduce an iterative type of TOA-based localization technique that exploits the channel statistics information and iterates between the ranging and localization steps in order to minimize the localization error. Finally, since NLOS condition is the dominant factor in indoor environment, various NLOS mitigation techniques will also be discussed.

1. Introduction

Location awareness has received great deal of interest in many wireless systems such as cellular networks, wireless local area networks (WLANs), and wireless sensor networks due the its capability to provide wide range of add-on applications. Nowadays, various location-based services (LBS) applications are provided by wireless carriers as optional add-on services to improve the user experience and productivity. For example, the "VZ Navigator" by Verizon Wireless offers audible turn-by-turn directions, locate points-of-interest such as landmarks, restaurants and ATMs using the global positioning system (GPS) technology. The "Family Locator" by Sprint offers the similar features as in VZ Navigator and on top of that, also provides an application that allows user to track the family members by displaying their approximate location on a map in real-time through their GPS enabled phones. On the other hand, the "TeleNav" series (e.g., TeleNav GPS Navigator and TeleNav Track) by AT&T offers various business services to their customers such as vehicle tracking, geo-fencing, and location-based time cards for field employees. In general, all of these LBS applications estimate the location information from GPS and/or trilateration from the wireless carriers nearest base stations (BSs). However, such localization techniques can only offer coarse location accuracy in the range of 150-300 m depending on whether there is a clear line-of-sight (LOS) to GPS satellites from the user's phone.

Recently, more advanced LBS applications such as location-based advertisement, location-based social networking, location-based security, indoor tracking of people and assets, and E911 emergency services have become more important in order to enhance the future lifestyle. For example, the location-based advertisement allows users to selectively receive promotional advertisement by strategically placing messaging near where buyer behavior can be most immediately influenced. For instance, a user will receive electronics sales items and coupons only when he/she entering a shopping mall. On the other hand, location-based social networking will further enhance the nowadays, Internet based social networking such as Facebook, Friendster, Hi5, MySpace, Orkut, etc. by allowing users forming groups based on their social preference and interest. The location-based security essentially allows double security protection through both user password and location information. For example, a malicious user that successfully hacked the system's password will not be granted to access the system if a legitimate user is detected to be out of the operation range from the system. The indoor tracking of people and assets are particularly useful for lost-and-found applications e.g., finding cars in a large parking lot. The above aforementioned example applications offered by location awareness will enable ubiquitous and context aware network services which necessitates the location of the wireless device to be accurately estimated under any environments.

One of the key challenges in order to realize new LBS applications in GPS denied environment with high location accuracy is the efficiency and preciseness of the estimation under non-LOS (NLOS) scenarios. NLOS scenarios occur when there is an obstruction between transmitter and receiver which are commonly encountered in modern wireless system deployment for both indoor (e.g., residential, office, shopping malls, etc.) and outdoor (e.g., metropolitan, urban area, etc.) environments. In such circumstances, the use of the GPS becomes impractical if not impossible. In general, the indoor LBS applications estimate the location information through received-signal-strength (RSS) by deploying the WLAN technology or time-of-arrival (TOA) information by deploying the ultra-wideband (UWB) technology. Such localization techniques can offer finer location accuracy typically in the range of 1-30 m depending on whether WLAN or UWB technique is being deployed. UWB technology is capable of providing highly accurate ranging in the harshest environments, owing to its inherent high delay resolution and ability to penetrate obstacles. Therefore, it is the technology of choice for range-based localization, especially in dense cluttered environments. With the combination of GPS in outdoor LOS and UWB technology in indoor NLOS scenarios, seamless indoor and outdoor positioning can be achieved. Generally, there are two phases towards realization of highly accurate LBS applications. i.e., *ranging* and *localization* as illustrated in Fig. 1.

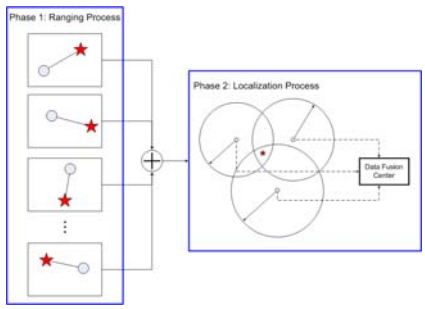


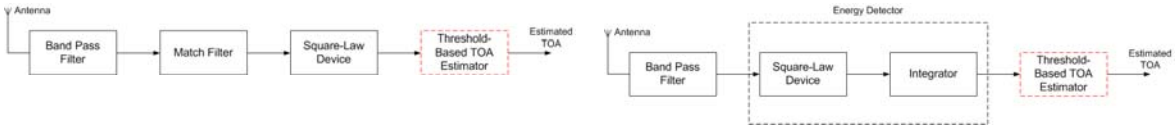
Fig. 1: Illustration of the 2-phase ranging and localization processes in order to realize LBS applications.

2. TOA-Based Ranging Techniques

The ranging process is an action of estimating the distance or angles between two nodes. The four commonly used techniques to perform ranging are the angle-of-arrival (AOA), RSS, TOA, and hybrid techniques i.e., the combination of any of the previous techniques. For UWB based system, it is natural to deploy the TOA-based techniques in order to take advantage of the good time-domain resolution which can then promise sub-centimeter resolution capability. In this section, we provide an overview of the commonly used TOA-based ranging techniques for UWB systems. For other techniques such as AOA, RSS and hybrid techniques, interested readers are referred to [1-6] and references therein.

2.1 Threshold-Based TOA Technique

Ranging estimation is mainly affected by noise, multipath components, and changes in propagation speed through obstacles. Most TOA-based ranging techniques are based on the TOA estimation of the first arriving path as in multipath channels, the first arriving path is often not the strongest path. In particular, the threshold-based TOA technique is a simple technique to detect the first arriving path by comparing the output of the match filter (MF) or energy detector (ED) with a threshold value. The threshold value can be optimized according to the channel conditions (e.g., signal-to-noise ratio (SNR)). Such a technique is gaining interest due to its low implementation complexity in which it has the potential for complete analog implementation. Furthermore, it can be deployed by both coherent (e.g., MF) and non-coherent (e.g., ED) type of receivers as illustrated by the block diagrams in Fig. 2. Such implementation is particularly attractive for applications that require low-cost and low-power consumption devices. A threshold-based TOA estimator for ED type of receivers is proposed and analyzed in [7]. It uses a practical normalized threshold that is based on the minimum and maximum values of the collected signal samples, where the value of the normalized threshold tends to decrease with the SNR. In [8], the performance analysis of both MF and ED threshold-based TOA estimators for UWB impulse-radio (IR) signals under dense multipath environments are provided. Here, the bias and the mean-square error (MSE) of the estimator are evaluated as a function of SNR. Based on this, the optimum threshold value which minimizes the MSE under any channel conditions can be determined. Results show that the peak selection detection ambiguity at the MF or ED device output is dominant in the presence of multipath and when the first arriving path is subjected to severe fading due to NLOS propagation which can lead to larger estimation errors. In general, the MF based estimators are attractive when high ranging accuracy is desired irrespective of the channel conditions, whereas ED based estimators are suitable to operate under high SNR conditions and to reduce the implementation complexity and cost.



(a) (b)

Fig. 2: Block diagrams of the threshold-based TOA estimator for UWB-IR (a) MF receiver architecture; and (b) ED receiver architecture.

2.2 Model-Based TOA Technique

The TOA estimation has been widely investigated for UWB-IR based systems such as [7-9], but has not yet been well studied for UWB OFDM-based (e.g., multiband (MB)-OFDM) systems. This is mainly due to the fact that the OFDM systems do not require precise timing for the purpose of communications as the guard interval can mitigate the multipath effects. Currently, there are growing interest in using MB-OFDM signals for both communication and ranging. For example, ECMA-368 and ISO-26907 standards which are based on the MB-OFDM require that wireless transceivers should have the add-on ranging capability on top of the high-rate communication capability. These standards have been adapted by the WiMedia as the common UWB radio platform while WiMedia UWB has been selected by the Bluetooth SIG and the USB Implementers Forum as the foundation radio of their high-speed wireless specifications for use in next generation consumer electronics, mobile and computer applications. Therefore, these clearly imply that the MB-OFDM is very likely to become the *de-facto* standard for UWB radio. For OFDM-based systems, most of the TOA estimation methods reported in the literature assume that the channel is sparse with sampled-spaced multipath delays [10,11]. However, this assumption is unrealistic, since the path delay of the real wireless

channel is always contiguously varying. Furthermore, with this assumption, the achievable TOA estimation resolution is limited by the sampling interval of the receiver. In [12], a simple model-based TOA estimation technique for MB-OFDM signals based on the ECMA-368 standard is proposed whereby; no modification at the receiver is required. The key idea of this technique is to minimize the energy leakage from the first channel path due to mis-sampling. In order to improve the resolution of the TOA estimation, multi-band signals are coherently combined. Furthermore, it was also shown in [12] that the proposed technique is robust against narrowband interference. The flow chart of the model-based TOA estimation is summarized by Fig. 3.

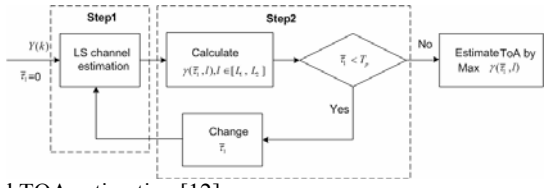


Fig. 3: Flow chart of the model-based TOA estimation [12].

3. Localization Techniques

When the range estimates are available, it is possible to use different techniques for localization of the mobile node. In [13], localization techniques are classified into two categories: 1) geometric techniques, and 2) statistical techniques. Geometric techniques evaluate the intersections of the position lines (e.g., circles for the case of TOA based localization, and hyperbolas for the case of time-difference-of-arrival (TDOA) based localization) obtained from different range estimates in order to estimate the position of the mobile node. On the other hand, statistical techniques such as the minimum mean square error (MMSE) estimation, maximum a-posteriori probability (MAP) estimation, and maximum likelihood (ML) estimation provide more flexibility in terms of the number of reference nodes that may be used. A commonly used statistical technique for estimating the location of a mobile node is the non-linear least squares (NLS) estimator, where the location of the mobile is given by [14]

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \left\{ \sum_{i=1}^{N} \beta_i \left(\hat{d}_i - \left\| \mathbf{x} - \mathbf{x}_i \right\| \right)^2 \right\} \tag{1}$$

where there are N measurements, β_i denotes the weight for the i-th measurement, and $\boldsymbol{x}_i$ denotes the location of the i-th fixed terminal (FT). Since the NLS requires numerical search techniques, it may be computationally complex. In [15], a linearization technique to obtain a simple closed-form solution from the distance measurements is proposed. The linearization is achieved by selecting one of the FTs as a reference. In [16], a linear least squares (LLS) technique that uses the FT with the smallest measured distance as a reference FT is proposed. The simulations in [16] shown that the average localization accuracy can be improved compared to a fix selection of the reference FT. Also, covariance matrix of the observations may be utilized to further approach to the Cramer-Rao Lower Bound (CRLB) of the location estimation error. The improved LLS estimator is illustrated in Fig. 4.

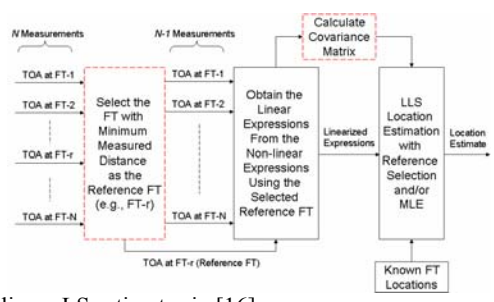


Fig. 4: Block diagram of the improved linear LS estimator in [16].

4. NLOS Mitigation Techniques

Even if the TOA of a certain received signal can be perfectly identified, in certain scenarios, the first arriving path may be subject to NLOS error due to propagation through obstructions. This implies a positive bias in the distance measurement, which may seriously degrade the localization accuracy. Different techniques have been proposed in the literature to mitigate the effects of the NLOS bias on localization. A class of techniques assume that for a moving terminal, the variance of distance measurements will be larger for an NLOS mobile terminal compared to a LOS mobile terminal. Therefore, simply comparing the variance of the distance measurements with a threshold would yield if a certain terminal is in LOS or in NLOS (see e.g., [17]). However, for a static mobile terminal, the statistics of the measured distances may not be significantly different for LOS and NLOS terminals. Fortunately, large number of multipath components in a UWB signal carries important information related to LOS/NLOS characteristics of a signal, and may be used for NLOS identification. For instance, channel statistical parameters such as kurtosis, mean excess delay, and RMS delay spread have different probability distributions depending on if the LOS path is obstructed or not. In [18], such parameters are utilized to develop a NLOS identification technique as illustrated in Fig. 5. When the NLOS nodes are identified, they may simply be discarded during localization, or, may be used to determine appropriate weights to implement a weighted least square (WLS) algorithm.

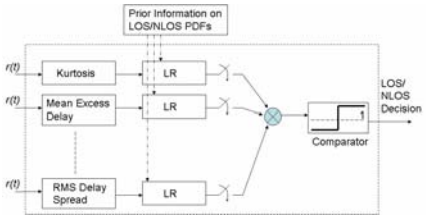


Fig. 5: Block diagram of the NLOS identification technique in [18].

5. Conclusion

It is widely anticipated that LBS applications will become more important for the future wireless world. In this paper, the potential of location awareness capabilities to provide new applications and usage models for future mobile users are outlined. In particular, the UWB radio is visualized as an enabling technology to realize the indoor LBS. This technology offers significant benefits such as robustness against fading, high precision ranging, high data rate transmission, scalability, and low loss penetration (i.e., can operate under both LOS and NLOS conditions), making it a suitable candidate to complement other wireless technologies to achieve ubiquitous communications. Two types of TOA-based ranging techniques for UWB-IR and MB-OFDM transmission schemes based on the IEEE 802.15.4a and ECMA 368 standards, respectively, are summarized. Improvements to a linear LS algorithm as in [15] are briefly explained. Furthermore, an NLOS identification/mitigation technique utilizing the statistics of the multipath components is described.

6. References

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