UWB | Ranging and Localization | Indoor LBS

Technology Reports

Ranging and Localization by UWB Radio for Indoor LBS

The UWB radio has been envisioned as one of the candidates for the future short-range wireless communications. In particular, highly accurate ranging and localization techniques for indoor environments can be achieved with the UWB radio. Hence, by exploiting such advantages that UWB radio can provide, it is anticipated that numerous new applications and indoor LBS can be realized on the future mobile terminal.

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1. Introduction

Ultra-Wideband (UWB) radio[*1] is an emerging technology that has attracted a great deal of interest from academia, industry, and global standardization bodies [1]–[3]. The UWB radio has been approved by Federal Communications Commission (FCC) for usage in consumer products in February 2002. Since then, interest in commercial applications has increased due to several advantages UWB communications systems offer, which make UWB radio a suitable candidate for future wireless systems. For instance, UWB radio has 100 times larger bandwidth than the W-CDMA system, and can achieve 100 times higher transmission data rates than the Bluetooth®[*2] system.

In this article, we will describe the technical advantages of UWB radio and the possible applications it can offer based on its fine time resolution. In addition, we also introduce new ranging and localization estimation methods, which provide improve accuracy.

2. LBS Applications

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 cellular operators as optional add-on services to improve the user experience[*3] and productivity. For instance, NTT DOCOMO is currently providing a number of LBS applications such as the "imadoco search" ("Where Are You Now?") service, which allow Japanese parents to track the location of their children. Through this application, users can obtain the location information using i-mode or Internet on PC in order to check their current location on a map. Additionally, other location-based applications such as current position identification, route retrieval, navigation, neighbor information search, etc. are also offered by using the Global Positioning System (GPS). Therefore, more new and advanced LBS applica-

*1 **UWB radio**: A wireless communications system with signal bandwidth exceeds 500 MHz or 20% of the center frequency.

*2 **Bluetooth®**: A registered trademark of Bluetooth SIG Inc. in the United States.

*3 **User experience**: Experience of user from a certain product, service, application etc.

tions will be expected in the future.

Similar services are offered by a number of cellular operators in the United States. For example, the "VZ Navigator*4" by Verizon Wireless Co. offers audible turn-by-turn directions, locate points-of-interest such as landmarks, restaurants and ATMs using the GPS technology. The "Family Locator" by Sprint Nextel Corp. 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 terminals. On the other hand, the "TeleNav®*5" series by AT&T Mobility LLC offers various business services to their customers such as vehicle tracking, geofencing, and location-based time cards for field employees.

Recently, more advanced LBS applications such as location-based advertisement, location-based social networking service*6, location-based security, indoor tracking of people and assets, and emergency services (e.g., 110 and 119 in Japan) have become more important in order to enhance the future lifestyle. **Figure 1** shows the LBS applications based on the mobile terminal. The location-based advertisement as shown in Fig.1(a) 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 is entering a shopping mall. On the other hand, the location-based security as shown in Fig.1(b) 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 two aforementioned application scenarios offered by location awareness as shown in Fig.1 will enable ubiquitous and context aware network services, which necessitates the location of the wireless device to be accurately estimated under any environments.

3. Technical Challenges and Issues

The location estimation in an outdoor environment is usually measured using the GPS satellites. A GPS receiver calculates its position by precisely timing the signals sent by the GPS

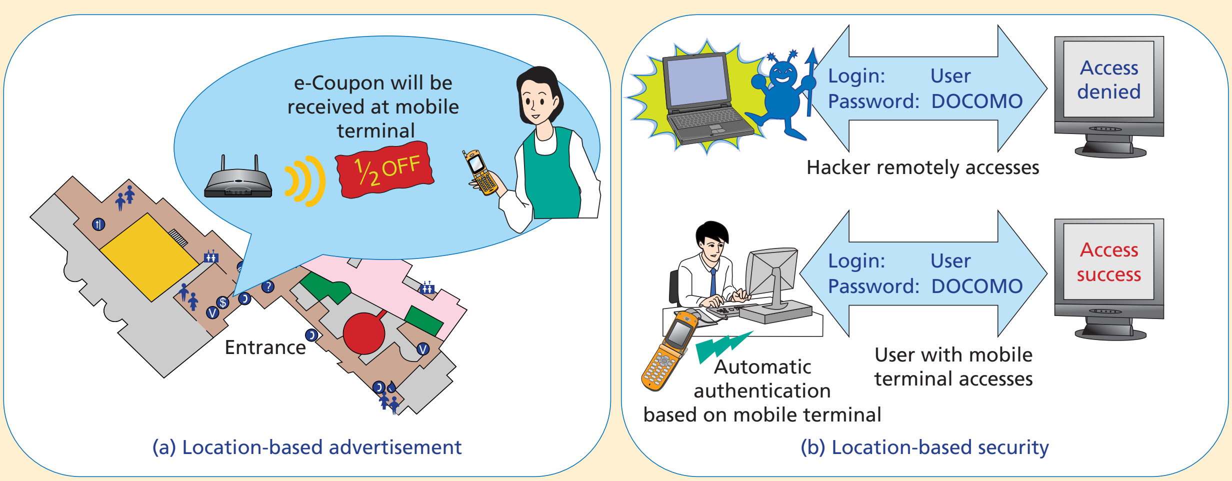

Figure 1 LBS applications based on the mobile terminal

*4 **VZ Navigator**: A trademark of Verizon Wireless Co. in the United States.

*5 **TeleNav®**: A registered trademark of TeleNav, Inc. in the United States.

*6 **Social networking service**: A service that promotes communications and sharing information between users and their acquaintance such as their friends and families.

satellites. The GPS receiver measures the transit time of each message and computes the distance to each GPS satellite. Theoretically, the GPS receiver's location can be determined by combining at least three of these distances with the location of the GPS satellites. However, in reality the accuracy of the location estimation is highly depending on the channel condition between the transmitter and the receiver such as whether it is under Line-Of-Sight (LOS) or Non-Line-Of-Sight (NLOS) scenarios.

One of the key challenges in order to realize new LBS applications with high location accuracy is the efficiency and preciseness of the estimation under 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. When the use of the GPS becomes impractical especially in indoor environment, embedded WLAN and UWB in the mobile terminal can be used as an alternative in order to provide precise location information.

In general, the indoor LBS applications estimate the location information through Received Signal Strength (RSS) by deploying the WLAN or Time-Of-Arrival (TOA)[*7] information by deploying the UWB technology. Such localization techniques can offer finer location accuracy typically in the range of 1-10 m depending on whether WLAN or UWB technique is being deployed. UWB technology is capable of providing highly accurate ranging in the harshest multipath[*8] environments, owing to its inherent high delay resolution and ability to penetrate obstacles. Therefore, UWB technology can achieve higher location accuracy as compared to WLAN.

4. Indoor Location Based Techniques

Generally, there are two phases towards realization of highly accurate LBS applications: ranging and localization. In this chapter, UWB technology for indoor localization is being considered. Firstly, the TOA-based ranging estimation technique is discussed. Then, the improved Linear Least Squares (LLS) method for localization estimation is presented.

4.1 TOA-based Ranging Estimation Technique

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)[*9], RSS, TOA, and hybrid techniques i.e., the combination of any of the previous techniques [4]–[6]. 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. Here we provide an overview of the commonly used TOA-based ranging techniques for UWB systems.

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, which is not typically the strongest path in NLOS environments. In particular, the TOA estimation has been widely investigated for UWB Impulse-Radio (UWB-IR)[*10] based systems such as [7][8], but has not yet been well-studied for UWB Multiband-Orthogonal Frequency Division Multiplexing (MB-OFDM)[*11] 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[*12] can mitigate the multipath effects.

Currently, there are growing interest in using UWB MB-OFDM signals for both communication and ranging. For example, standardization body such as the International Organization for Standardization (ISO) under the ISO-26907 standard requires that wireless transceivers should have the add-on ranging capability on top of the high-

*7 **TOA**: Time required by the electromagnetic wave to propagate from the transmitter to reach the receiver.

*8 **Multipath**: A phenomenon that results in a radio signal transmitted by a transmitter reaching the receiver by multiple paths due to propagation phenomenon such as reflection, diffraction, etc.

*9 **AOA**: The angle of the received electromagnetic wave seen from the receiver generally estimated utilizing two antennas or more.

*10 **UWB-IR**: A communication technique in which short pulses with time width on the order of 1 ns or less are transmitted, using a bandwidth of 500 MHz or more.

*11 **UWB MB-OFDM**: A type of UWB signaling that uses OFDM, where subcarriers are grouped in 14 subbands each of which has 528 MHz of bandwidth.

*12 **Guard interval**: Idle part included in a signal when data is transmitted to ensure the signal is not being interfered by multipath delays.

rate communication capability. This standard has been adopted by the WiMedia Alliance[*13] as the common UWB radio platform. Note that WiMedia's UWB MB-OFDM has also been selected by the Bluetooth Special Interest Group (SIG)[*14] 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. Since these imply that the UWB MB-OFDM is very likely to become the de-facto standard for high data-rate UWB radio, we proposed a high accuracy TOA-based ranging method based on the UWB MB-OFDM.

For OFDM-based systems, most of the TOA estimation methods reported in the literature assume that the channel is sparse with sampled-spaced multi-path delays [9], [10]. 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. Here, a simple model-based TOA estimation technique for UWB MB-OFDM signals based on the ISO-26907 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. Based on this technique, the TOA estimation can be carried out in a two-step procedure in order to detect the first arrival path as shown in **Figure 2**.

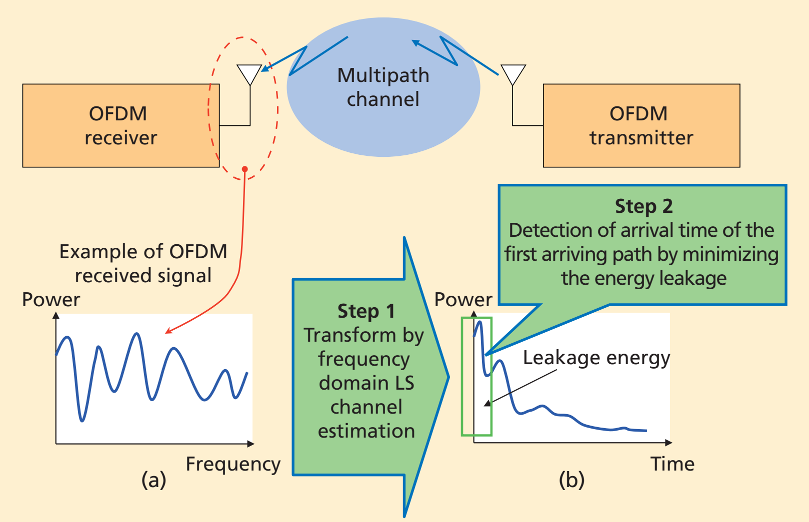

Figure 2 Two-step model-based TOA estimation technique for UWB MB-OFDM

- Step 1

  As shown in Fig.2(a), it is not possible to detect the first arriving path of OFDM signal in the frequency domain. Therefore, the first step is to recover the time domain Channel Impulse Response (CIR) using the frequency domain Least Squares (LS) channel estimation[*15], whereby the first arriving path embedded in the frequency-domain OFDM signal can be transformed into the time domain signal. However, the frequency domain LS solution will tend to induce energy leakage [11].

- Step 2

  The energy leakage induced in Step 1 will be minimized in Step 2 as shown in Fig.2(b). The tap which corresponds to the first channel arriving path is selected and its delay is used as the TOA estimate. The energy leakage will vanish when this path is exactly sampled by one tap of the model.

Figure 3 shows the TOA estimation results based on the two-step approach TOA estimation technique under different energy leakage conditions. The red lines and blue lines represent the amplitudes of one realization of the Institute of Electrical and Electronics Engineers 802.15.3a (IEEE 802.15.3a) LOS channel and the absolute amplitude of the channel esti-

*13 **WiMedia Alliance**: A non-profit open industry association that promotes wireless multimedia and interconnectivity based on UWB radio.

*14 **Bluetooth SIG**: A non-profit industry group that is representative of Bluetooth standard, overseeing the development and licensing of Bluetooth technology.

*15 **LS channel estimation**: In this article, a technique for estimating channel through linear processing of the received signal, and converting it from the frequency domain to the time domain.

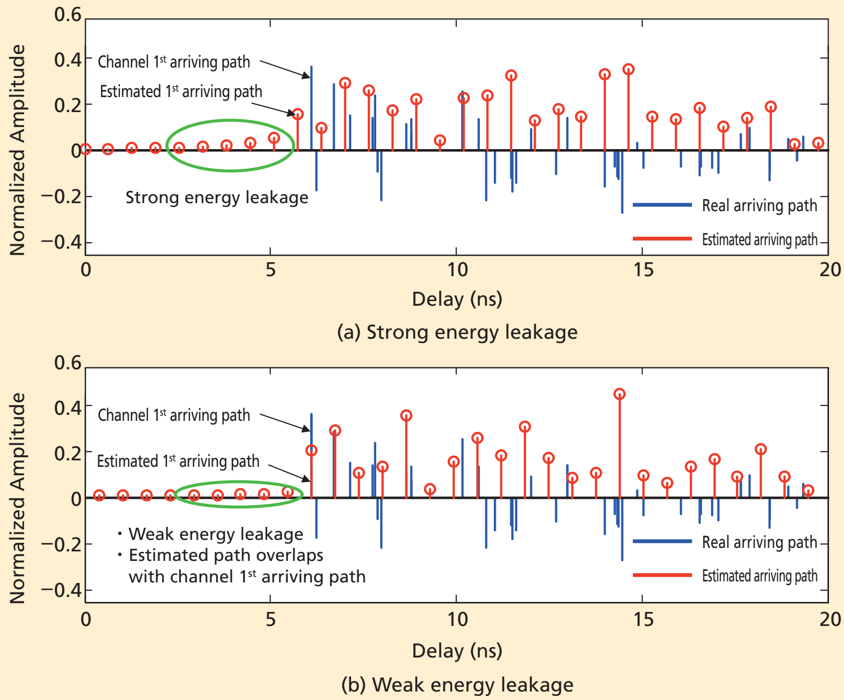

Figure 3 TOA estimation results based on the two-step model-based TOA estimation technique under different energy leakage conditions

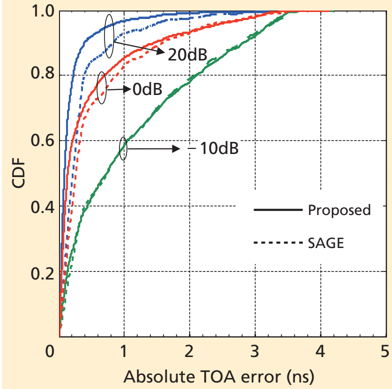

Figure 4 CDF of the absolute TOA error with different SNR values

mates of this channel realization, respectively. In Fig.3(a), the recovered CIR has a strong energy leakage from the first path because no estimated channel path is close to the first arriving of the channel. In Fig.3(b), it is shown that the energy leakage is sufficiently mitigated i.e., weak energy leakage, when one estimated path in the model becomes very close to the first channel path. As a result, there is a sharp change of amplitude in the channel estimates in the area around the first arriving path. The location of this sharp change can be detected and used to estimate the TOA.

The proposed technique is compared with the well-known Space-Alternating Generalized Expectation-maximization (SAGE) algorithm*16. The Cumulative Distribution Function (CDF) of the absolute TOA error with different Signal to Noise Ratio (SNR)*17 values given by **Figure 4** shows that 90% of the TOA error of the model-based approach is less than 0.4 ns, which corresponds to 12 cm at high SNR values. In order to improve the resolution of the TOA estimation, multiband signals are coherently*18 combined. It was also shown in [11] that the proposed technique is robust against narrowband interference.

4.2 TOA-based Localization Estimation Method

Once the range estimates are available between the fixed terminal (whose position is already known) and the mobile terminal (whose position is unknown) by using the technique in Section 4.1, it is possible to utilize several methods for estimation of the mobile terminal location [12]. Here, the fixed terminal is assumed to be an indoor UWB Access Point (UWB-AP). As shown in **Figure 5**, range estimates from different UWB-APs to the mobile terminal will be transferred to a central unit in order to obtain a location estimate of a mobile terminal using different types of localization techniques [12].

A commonly used statistical technique for estimating the location of a mobile terminal is the Non-linear Least Squares (NLS)*19 estimator. Since the NLS requires numerical search tech-

*16 **SAGE algorithm**: A method for high resolution estimation of parameters of wideband signals.

*17 **SNR**: Ratio of electromagnetic power of desired wave in wireless communication to electromagnetic power of noise.

*18 **Coherent**: Both amplitude and phase of a signal must be aligned.

*19 **NLS**: A technique for estimating a parameter by repetitive improvement whereby the model function is a non-linear equation with respect to the parameter to be estimated.

niques, it may be computationally complex. In [13], a linearization technique to obtain a simple closed-form solution from the distance measurements has been proposed. The linearization is achieved by selecting one of the fixed terminals as a reference. Here, we proposed a Linear Least Squares (LLS) technique that uses the fixed terminal with the smallest measured distance as a reference terminal [14]. We refer the resulting estimator as LLS with Reference Selection (LLS-RS). An example scenario is shown in **Figure 6**, where range estimates at four different fixed terminals are used to obtain four different non-linear expressions (corresponding to the four circles). Since UWB-AP$_4$ has the smallest measured distance, the expression corresponding to this fixed terminal is used to linearize the non-linear equations, yielding three linear equations as shown in Fig.6. Then, the mobile terminal location may be easily calculated through an LLS solution utilizing these three linear equations. The simulation results in **Figure 7** shows that the average localization accuracy can be improved compared to a random selection of the reference terminal (conventional LLS approach) and the accuracy becomes closer to the Cramer-Rao Lower Bound (CRLB)[*20] with our proposed LLS-RS technique.

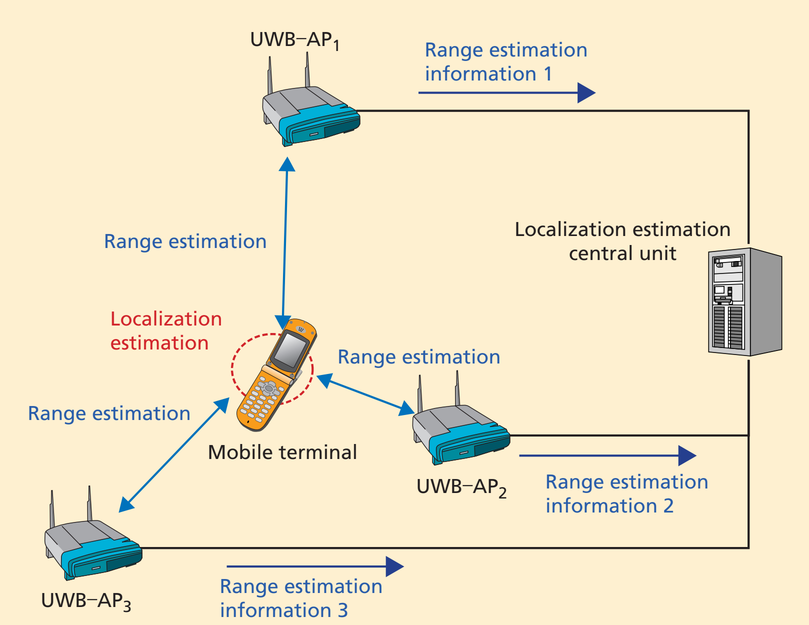

Figure 5 Range-based estimation of a mobile terminal's location

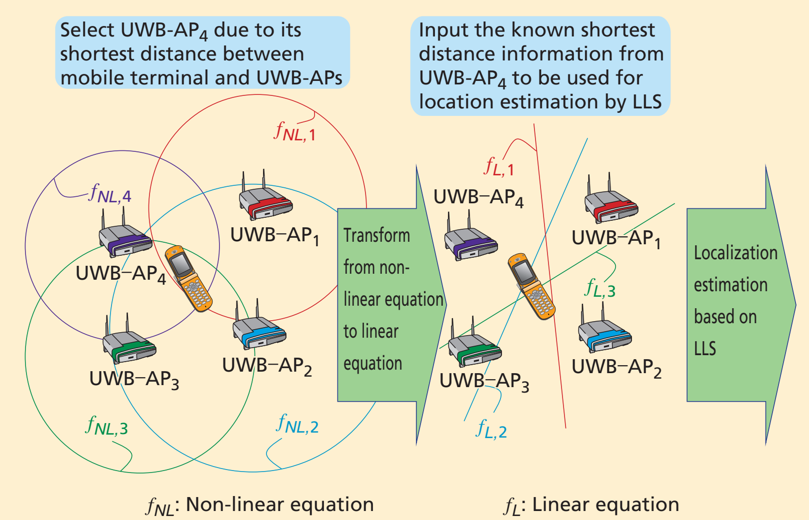

Figure 6 Obtaining linearized equations from non-linear equations for the LLS localization technique

4.3 NLOS Error Mitigation

Even if the TOA of a received signal can be perfectly identified, in certain scenarios, the first arriving path may be subject to NLOS bias 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

20 **CRLB**: The best root mean square error performance any possible unbiased estimators can achieve.

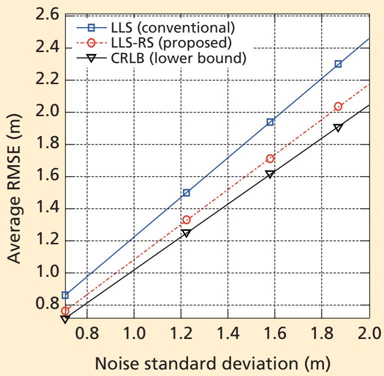

Figure 7 Average RMSE of the conventional LLS and proposed LLS localization techniques and their comparison with the CRLB

the literature to mitigate the effects of the NLOS bias on localization. A class of techniques assumes that for a moving mobile 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 determine whether a certain mobile terminal is under LOS or NLOS condition [15].

However, in indoor environment where most mobile terminals are relatively static, the statistics of the measured distances may not be significantly different for LOS and NLOS mobile 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 example, statistical parameters such as kurtosis[*21], mean excess delay[*22], and Root Mean Square (RMS) delay spread[*23] have different probability distributions depending on if the LOS path is obstructed or not. In here, we utilize such parameters to develop an NLOS identification technique [16]. For example, as shown in **Figure 8**, the Probability Density Functions (PDFs) of the mean excess delay spread and the RMS delay spread are considerably different for LOS and NLOS channels. Hence, once such parameters of a received signal is estimated, it may be used to accurately detect whether the channel is under LOS or NLOS condition (e.g., through a simple log-likelihood test). 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 [16].

5. Conclusion

In this article, 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

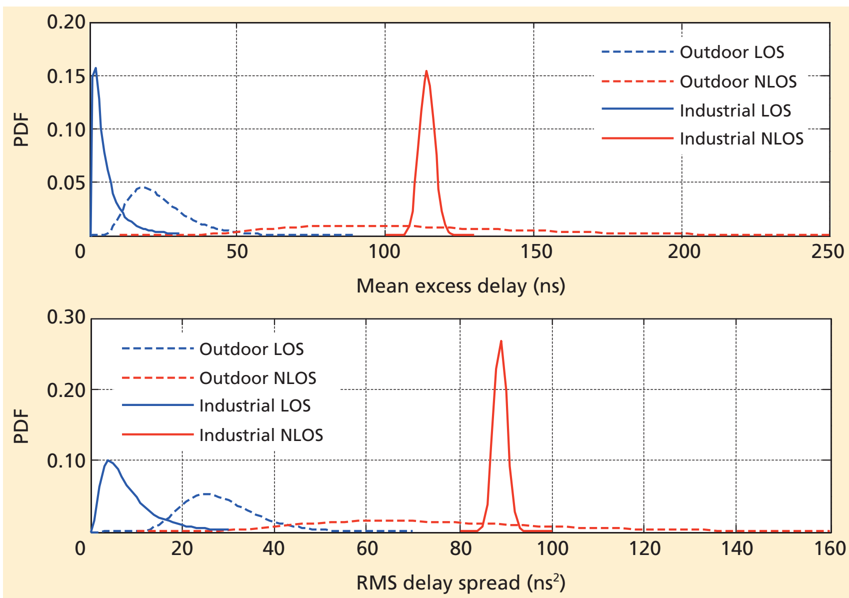

Figure 8 Log-normal PDFs of the mean excess delay and RMS delay spread of the outdoor and indoor industrial environments under LOS and NLOS conditions of the IEEE 802.15.4a channels

*21 **Kurtosis**: Statistics that measures the peakedness of a PDF.

*22 **Mean excess delay**: Average delay time of a multipath delay profile.

*23 **RMS delay spread**: A numerical value that measures the amount of scattering of a multipath delay profile.

complement other wireless technologies to achieve ubiquitous communications. In particular, the TOA-based ranging technique for UWB MB-OFDM schemes based on the ISO-26907 standards is reported. Improvements to the LLS algorithm that uses a random selection of the reference are briefly explained and verified through simulation results. Furthermore, an NLOS identification/mitigation technique utilizing the statistics of the received multipath components is described.

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