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ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 9 (1): 139-145, 2010
ISSN 1812-5638

IR-UWB Waveform Distortion Analysis in NLOS Localization System

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Abstract: The Ultra-Wide Band (UWB) signal waveform distortions in Non-Line-of-Sight (NLOS) environment and its impact on localization accuracy are investigated in this study. The localization system can offer accurate position and ranging due to the fine time resolution of Impulse Radio (IR) signal. However, in completely NLOS environment, the IR-UWB signal will undergo deeply waveform distortion due to frequency dispersion, which cause inaccuracy in peak position detection in correlation receiver, consequently result in ranging error in time based localization system. Although, IR frequency dependence has already been addressed in channel modeling, in this study, the influences of material frequency properties and IR propagation distortion on completely NLOS localization system performance are taken into account through frequency domain method. Based on transient electromagnetic theory, the IR waveform distortions are compared in time domain using Inverse Fast Fourier Transform (IFFT). The NLOS ranging errors caused by both pulse distortion and geometric configuration are derived in a simple way. Numerical results shown that larger variations of material electrical parameters in UWB bandwidth lead to more severe waveform distortion and propagation loss in obstacles, which can considerably decline the ranging accuracy.

Key words: IR-UWB, transmission, pulse distortion, localization

INTRODUCTION

Recently, IR-UWB signal has gained a lot of attentions in both communication and radar system due to its huge bandwidth, especially indoor localization system, which fully utilizing the advantages of IR signal: the signal contains different frequency components, which increase the probability that at least some of them can go through or around the obstacle; a large absolute bandwidth offers high resolution radars with improved ranging accuracy (Gezici *et al.*, 2005). According to the FCC's regulation, the band between 3.1 and 10.6 GHz can achieve a time resolution of 0.133 n sec, which corresponds to a spatial resolution of 4 cm. There are already some widely used localization systems such as the Angle of Arrival (AOA), the Signal Strength (SS) and Time of Arrival (TOA). In complicated indoor radio channel, it is difficult to accurately measure AOA or SS so that most of the independent indoor positioning systems mainly use TOA based techniques. In Line-of-Sight (LOS) scenarios, a simple triangulation scheme has been approved sufficient for precise localization.

There are three main sources of ranging errors in complicated indoor environment (Heidari *et al.*, 2007). The first source error is multipath error due to a combination of bandwidth limitation and presence of rich multipath. The absence of Direct Path (DP) due to blockage is also a dominant error source and the third source of error is associated with propagation delay and difference of the speed of the radio waves in media. Consequently, the ranging measurements between receiver and transmitter are often positively biased (Jourdan *et al.*, 2008). In practice, for a large demand in commercial, public safety and military applications, the need for accurate and reliable localization in completely NLOS situation increases, the IR propagation properties in specific environments become a serious challenge to indoor localization system. Partial and complete LOS blockage deteriorates the ranging accuracy due to refraction, which makes the real propagation distance larger than the straight line between two nodes. Furthermore, the IR signal has severe frequency dispersion undergoes per path waveform distortion when transmitted though the obstacle (Molisch, 2005), which lead to the pulse peak position biased in correlation receiver in localization system.

Up to now, several works has been done on IR-UWB waveform distortion problems. Richard *et al.* (2003) considered that the IR signals undergo waveform distortion. In terms of pulse shape and duration

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time as propagating in multipath environments. (Qiu and Tai, 1999) and (Chenming and Qiu, 2007) addressed the wide band signal waveform distortion due to frequency dependence in CDMA channel modeling and later they extend these theories to the UWB system, the IR signal diffraction distortion is taken into account using physics-based methods, which can cause template mismatch and results in a NSR loss. A physical model was developed to investigate the position-dependent distortion of UWB pulse in LOS, reflection and diffraction environments, the results indicate that both the shadowed pulse and the scattered pulse are distorted (Ma *et al.*, 2006). The UWB pulse distortion due to the blockage of human body is investigated in (Renzo *et al.*, 2007). And the propagation of IR signal through deterministic multipath channel with different antennas are analyzed in terms of bit-error-rate in correlation based receiver (Qiang and Zhang, 2008). In (Yuan and Win, 2008) the pulse-overlap coefficient is used to quantify the effect of pulse distortion on ranging accuracy. Muqaibel *et al.* (2005) measured the electromagnetic properties of construction materials in the UWB frequency range and address the potential problems of UWB though wall applications. However, all the above works had only considered the pulse distortion in reflection and diffraction, which also haven't taken into account the media frequency dependence properties. As the dielectric constant and conductivity of material vary with frequency, it's difficult to derive the time-domain expression of IR waveform distortion using Laplace transform in the whole UWB bandwidth. Furthermore, as one of the most desirable feature of IR-UWB, transmission mechanism is also different compared with the traditional narrow band system. In particular, NLOS propagation is unavoidable in indoor localization system, so the analysis of IR-UWB signal propagation and pulse waveform distortion are necessary for developing ranging algorithm with improved accuracy in NLOS environments.

In this study, without regarding the antenna effects, the localization system performance from the point of view of IR-UWB electromagnetic wave propagating through obstacles are discussed based on the TOA algorithm and the NLOS ranging errors are derived in specific configuration. Combined with modified transmission theory, the frequency dispersion of materials in UWB bandwidth is taken into account by uniformly divided the pulse frequency band into several sub-bands. The influences of IR waveform distortions on localization accuracy are compared in specific environments.

PROBLEMS IN NLOS LOCALIZATION SYSTEM

The TOA position techniques rely on measurements of travel time τ of signals between the transmitter node and the receiver node. The well known triangulation approach is depicted in Fig. 1 (The dark nodes are the reference nodes). The distance between the nodes can be calculated as: $d = \tau.c$, where c is the velocity of light and this distance determines the radius of a circle with the center at the receiver. In 2D situation, at least three reference nodes are needed to determine the location of a given node. Another important factor in TOA estimation algorithm is the synchronization between nodes, in this study, we only concerned on the electromagnetic propagation mechanism of IR signal in localization system, so we set all nodes time synchronization at first. For a single-path additive white Gaussian noise channel, the best achievable accuracy of a distance estimate d derived from TOA estimation satisfied the following inequality (Gezici *et al.*, 2005):

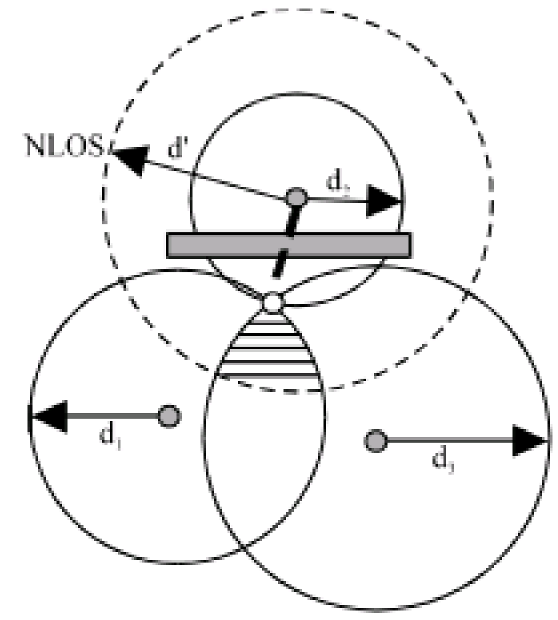

Fig. 1: Positioning via TOA approach

$$\sqrt{\mathrm{Var}(\hat{d})} \geq c/(2\sqrt{2}\pi\sqrt{\mathrm{SNR}}\beta) \quad (1)$$

where, c is the speed of light, NSR is the signal-to-noise ratio and β is the effective (or root mean square) signal bandwidth. Therefore, the accuracy of a TOA approach can be improved by increasing NSR or effective bandwidth.

The basic theories described above assume the wave propagation velocity is constant and there is no frequency dispersion when the signal interacted with materials over the whole propagation process. However, IR-UWB signal have very large bandwidth, which makes the propagation mechanisms different with the traditional narrow band signals, the frequency dependence of IR signal must take into account. Especially in NLOS environment, the characteristics of materials and IR waveform distortion influence the localization performance undoubtedly. The obstacle produce an additional delay due to the change of the geometrical way of the wave front caused by the refraction on the obstacle surfaces or inhomogeneities; and the pulse waveform distorted due to the different propagation speed in the slab. As shown in Fig. 1, the NLOS distance estimation may extend to the red dashed circle, which increases the uncertainty of the node position to the shadow region.

Conventionally, TOA estimation is performed via correlator or matched filter receiver. The position of the first peak is used as the input time of arrival in the localization algorithm. In completely NLOS environment, two major factors degrade the accuracy of the first peak arrival time are:

- The geometrical difference caused by refraction
- The peak position biased due to IR waveform distortion

Assumed the dielectric interface was plane and homogeneous, see from Fig. 2, considered only one IR path transmitted through obstacle with thickness d, incidence angle θ, (x, y) and (x_i, y_i) are the coordinate of transmitter and receiver and their distance between the wall are d_1 and d_2, respectively. The transmitter was fixed and the receiver can move along the dashed line which is parallel to the interface of obstacle and free space. In the absence of bandwidth and pulse distortion, the geometrical error can be calculated as follow:

The straight path between the transceivers is:

$$L = \sqrt{(x_i - x)^2 + (y_i - y)^2} \quad (2)$$

The actual transmitted distance between the transceivers is:

$$L' = d_1 / \cos\theta + d / \sqrt{1 - \sin^2\theta / \varepsilon_r} + d_2 / \cos\theta \quad (3)$$

where, e_r is the relative dielectric constant of material. So, the geometrical error is defined as Geo error and can be calculated as:

$$\text{Geo\_error} = L' - L \quad (4)$$

When considering the frequency dispersion, the IR signal undergo pulse distortion in transmission lead to the position of first peak biased, the peak position error defined as Peak-error can be expressed as:

$$\text{Peak\_error} = (\tau' - \tau) \cdot c \quad (5)$$

where, τ' is the first peak arrival time in the period of actual received pulse, τ is the ideal peak arrival time in the absence of pulse distortion and c is the speed of light.

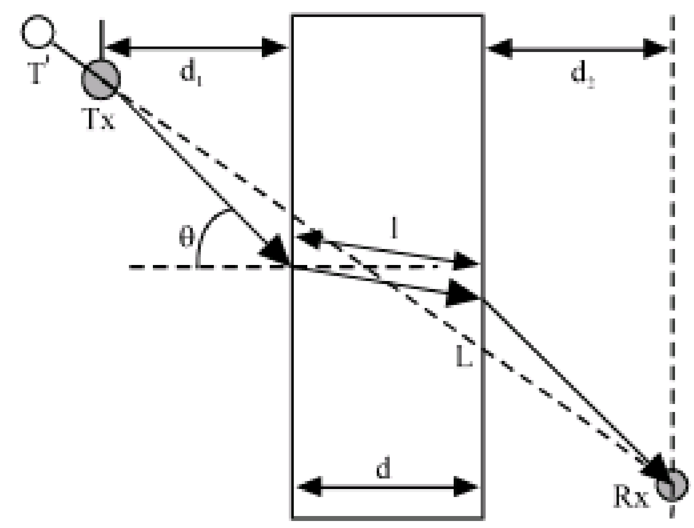

Fig. 2: Geometric error transmitted in slab

The total distance error in completely NLOS environment is

$$\text{Total\_error} = \text{Geo\_error} + \text{Peak\_error} \quad (6)$$

Apparently, this will result a TOA estimation error and the transmitter may bias to T' as shown in Fig. 2. Theoretically, using the incidence angle, the location of transceiver and thickness of obstacle, the geometrical error can be easily calculated, however, the ranging error due to pulse distortion in transmission is determined by its actual waveforms and this is the main point of present study.

PROPAGATION THEORIES AND METHODS

Properties of materials: Generally, the effective permittivity of a material can be described as: $\varepsilon = \varepsilon' - j(\sigma + \omega\varepsilon'')/\omega$, where ε' and ε'' are the real and imaginary part of dielectric constant, σ is conductivity and $(\sigma + \omega\varepsilon'')/\omega\varepsilon'$ is often defined as the loss tangent. When the electromagnetic wave propagated in loss media, the propagation constant k is a complex and a function of frequency, furthermore, ε is also vary with frequency, which determined by the media's inherent characteristics. As the propagation of IR-UWB signals is governed by the properties of materials in the propagation medium, several studies had been done to investigate the characteristics of materials on UWB bandwidth (Muqaibel *et al*., 2005; Cuinas and Sanchez, 2002; Lao *et al*., 2003). The dielectric constant and loss tangent of common materials in indoor environment over UWB frequency range are compared in Fig. 3. These materials can be approximately divided into three categories: (1) glass: dielectric constant doesn't change with frequency and loss tangent near zero, can be considered as perfect dielectric, (2) dry wall, structure wood, wooden door and plywood: their dielectric constant near 2.3 and

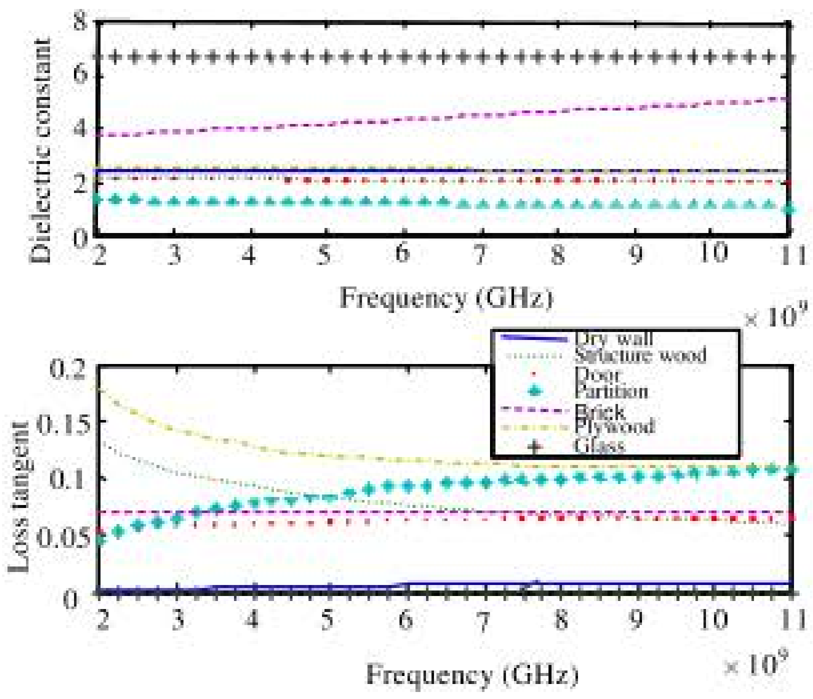

Fig. 3: Electrical parameters of materials

only loss tangent is frequency dependence, (3) partition and brick: both dielectric constant and loss tangent change with frequency. Clearly, the electrical parameters vary with frequency in a random way. So, the analysis of IR propagation is no longer the same as the traditional narrow band system.

Propagation of IR-UWB signal: Due to the complexity of material's properties with frequency, the frequency domain method was used to analysis the propagation of IR signal. Suppose the plane wave incidence in the direction of $\hat{\beta}_t = \hat{x}\sin\theta_t + \hat{z}\cos\theta_t$, the electric field in the media is

$$E_t = \frac{1}{\pi}\int_0^\infty E_i(\omega)\,|T|\exp(-\alpha z)\ldots \cos[\omega t - \beta(x\sin\theta_t + z\cos\theta_t) + \varphi]\,d\omega \qquad (7)$$

where, E_i (ω) is the Fourier transform of incidence IR signal $T = |T|\exp(j\varphi)$, is the refraction coefficient at the interface, for a linear polarization wave T = 1+R, R is the Fresnel reflection coefficient. At the interface of loss media, the refractive angle θ satisfied the generalized refraction theory $\beta_o \sin\theta = \beta \sin\theta_t$ that is

$$\frac{\sin\theta}{\sin\theta_t} = \frac{\beta}{\beta_0} = \sqrt{\frac{\varepsilon_r}{2}}\left(\sqrt{1+\frac{\tan^2\delta}{\cos^2\theta_t}}+1\right)^{1/2} \qquad (8)$$

As the waveform and transmission loss are very important to localization system, when the thickness of the obstacle is not too large compared to IR pulse wavelength, traditional Fresnel reflection coefficient need to be corrected in both amplitude and phase. The actual propagation characteristics in obstacle can be approximated by a multi-ray model (Qiu, 2004). The reflection coefficient and propagation loss in (7) should be replaced by the modified transmission coefficient as follow:

$$T' = \frac{(1-R^2)e^{-jkl}e^{-\alpha l}}{1-R^2 e^{-j2kl}e^{-2\alpha l}e^{jk_0 s\sin\theta}} \qquad (9)$$

where, k_0 and k are propagation constant in free space and obstacle respectively, l is the path length inside the slab show in Fig. 2, s is path length difference of two departing consecutive reflections and α is attenuation constant.

Considering the frequency dispersion, the transmission coefficient in the whole UWB bandwidth is the combination of each subband, this process can be expressed as:

$$T_{Total} = \sum_{i=1}^{M} T_i(\omega)w_i(\omega) \qquad (10)$$

where, $T_i(\omega)$ and w_i (ω) is the frequency transmission coefficient and the window function at the th subband, respectively and M is the total number of subbands.

PULSE DISTORTIONS IN TRANSMISSION

The second derivative of Gaussian pulse is used as IR-UWB waveform in the simulation, the original pulse can be expressed as:

$$s(t) = A(1-4\pi(t-T_c)^2/\tau^2)e^{-2\pi(t-T_c)^2/\tau^2} \qquad (11)$$

where, A is the pulse amplitude, T_c is the time shift and τ is the characteristic time of the pulse. Here these parameters are set as A = 1V, τ = 0.134 n sec and T_c = 0.

In completely NLOS indoor environment, the IR waveform distortions caused by signal propagation in different obstacles are investigated here. The obstacles are assumed to be isotropic and homogeneous. Classical electromagnetic theory indicated that there is no waveform distortion and loss in perfect dielectric medium, such as glass. The IR pulse waveform distortions transmitted through several materials are shown in Fig. 4 with different incidence angle and slab thickness. The IR waveforms through dry wall, structure wood and wooden are distorted slightly and retain general shape characteristics of the original Gaussian pulse. This can be explained by the fact that the electrical parameters of those materials are almost constant in the whole UWB bandwidth. Another phenomenon is the right trough of the pulse attenuated faster than the peak and left trough of the pulse, according to transient electromagnetic theory, the pulse's higher frequencies arrive at later times, as we see the right trough of the pulse in time

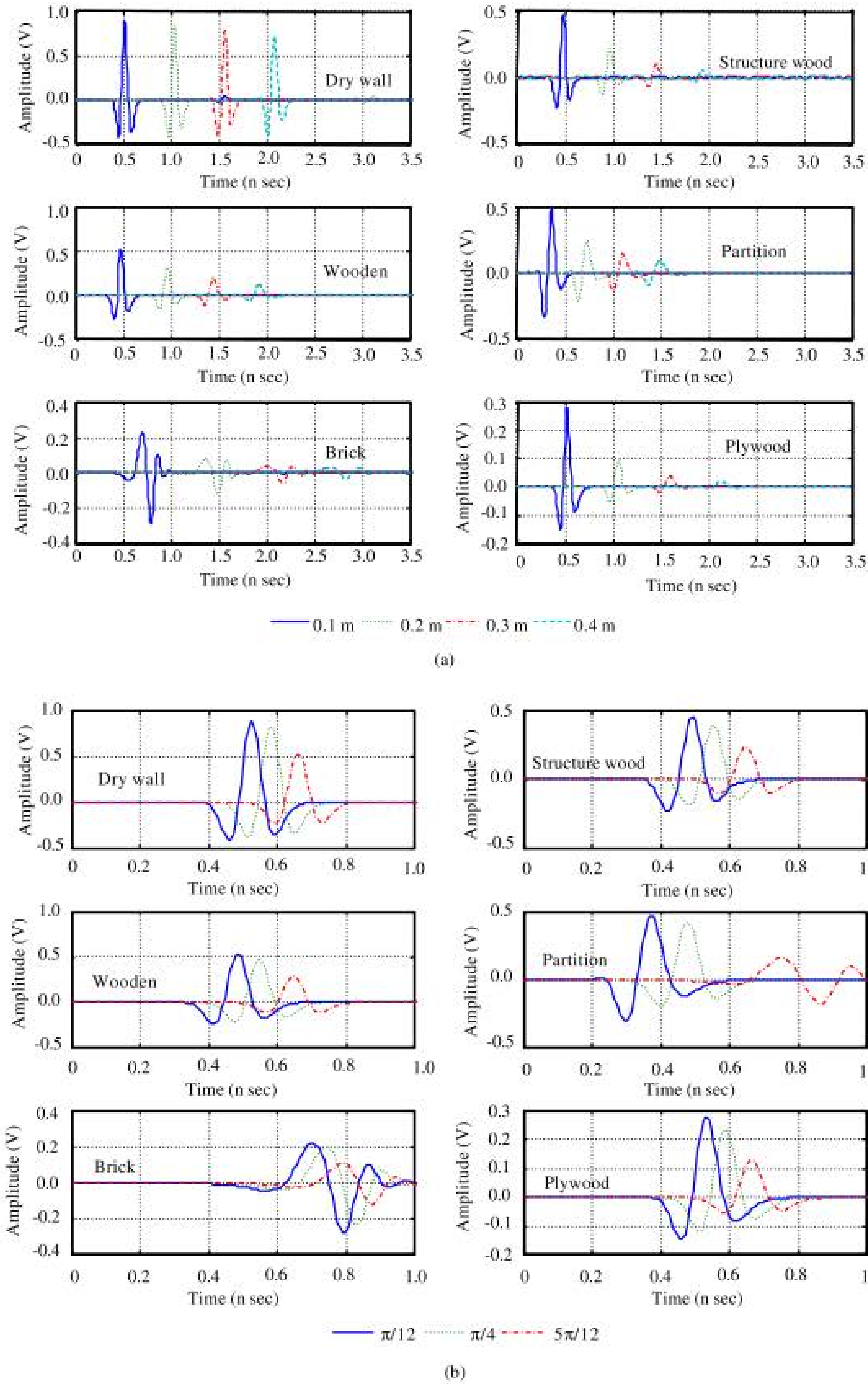

Fig. 4: IR transmitted waveforms through obstacles. (a) $\theta = 0$, $d = 0.1\text{~}0.4$ m and (b) $d = 0.1$ m $\theta = \pi/12\text{~}5\pi/12$

domain is correspond to the higher frequencies. In contrast, the pulse waveforms were noticeable changed in amplitude and phase when transmitted through partition, brick and plywood. The received waveform can't keep its original shape: the pulse waveform is no longer symmetric and has much wider tail than the transmitted pulse. And the position of the first peak is no longer in the central of the pulse duration time apparently compared with the second derivative of Gaussian pulse.

Further compared these results, there are several +similar trends when IR penetrated through obstacles: the waveform distortion is inherently determined by the bandwidth of IR signal, the electrical properties of media which interact with the transmitted pulse and the geometric configuration of obstacle. In indoor environment, the change of incidence angle doesn't distort the pulse waveform apparently; however, the waveform distortions become obviously as the thickness of obstacle increases, also with deeper propagation loss.

IMPACT OF PULSE DISTORTION ON NLOS ERROR

The pulse distortion through obstacles lead to the time of arrival of IR signal biased to some degrees in the correlation receiver and finally result in a NLOS error in TOA based ranging system. As shown in Fig. 2, suppose the coordinate of transmitter is (0, 0) and d_1, d and d_2 are known, the geometric coordinate of receiver node $d_1 + d + d_2$ $d_1 \cdot \tan\theta + d \cdot \sin\theta / \sqrt{\varepsilon_r - \sin^2\theta} + d_2 \cdot \tan\theta$ is and the linear distance between the transceiver can be calculated using Eq. 2. The transmitted distance estimated by the pulse peak position in correlation receiver is calculated through frequency domain method mentioned in previous parts.

The NLOS ranging errors due to the blockage of brick with different conditions are compared in Fig.5. Set the distance of d_1 and d_2 equal to 1m, when θ increases from 0 to 5π/12, the thickness of slab d is set as 10 cm and when the thickness of slab increases from 5 to 40 cm, the IR signal is normal incidence. Notice that when the slab thickness is fixed and the incidence angle is relative small, for $\theta<\pi/6$, the Geo_error and Peak_error are keep in the same degree, but it is clear that the Geo_error is extremely larger than Peak_error, which is the main NLOS error in this situation. As the IR signal is perpendicular incident on the interface of obstacles, the Geo_error is identically equal to zero. The NLOS error is totally decided by the Peak_error. From Eq. 5 in part II, the propagation time in loss media with thickness d and no waveform distortion is $\tau = d \cdot \sqrt{\varepsilon'} / c$, τ' is the actual IR peak arrival time. The value of Peak_error is negative means IR peak is arrived in advance and in contrast positive value means the peak is delayed in some degrees. In Fig. 5, it's clearly that the absolute value of Peak_error increases with slab thickness approximately in a linear manner which is different compared with the incidence angle. Moreover, the pulse width of IR signal used in this paper is about 6cm, but the peak biased caused by waveform distortion almost reaches the pulse width in specific situation.

The Total_error is the sum of Peak_error and Geo_error in both conditions, the Total_error becomes considerably larger with incidence angle and slab thickness increase. So under completely NLOS environment, due to the variation of electrical characteristics of materials, the IR waveforms were distorted undoubtedly. In order to achieve higher localization accuracy, the incidence angle needs to be as small as possible and the straight line between transmitter and receiver should perpendicular to the interface of free space and obstacle to obtain better penetration gain.

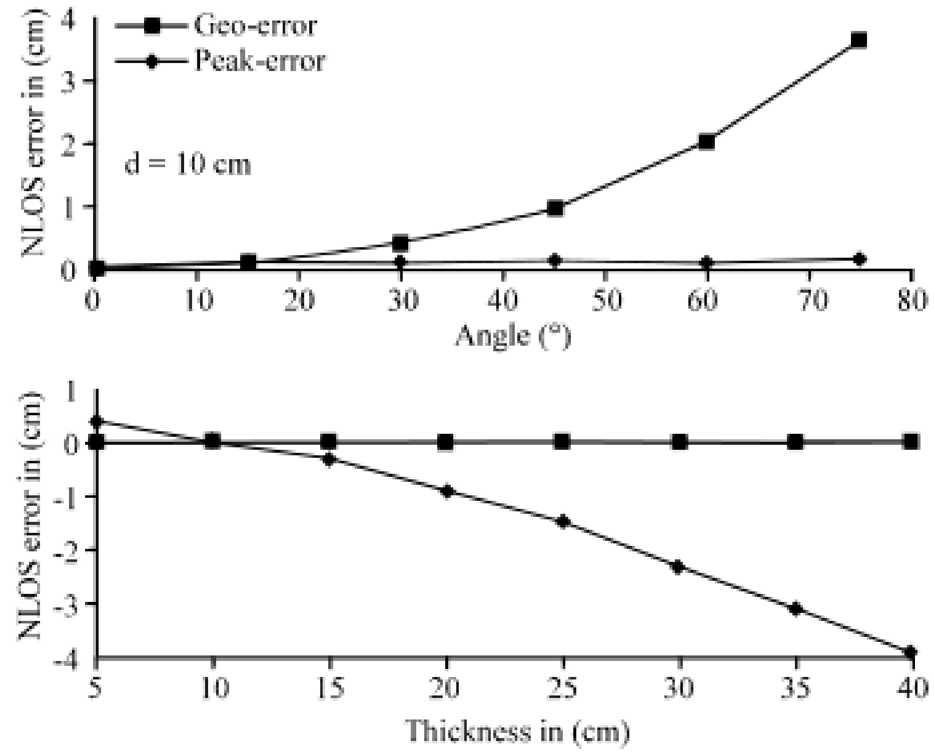

Fig. 5: NLOS ranging errors

Above all, it is obviously that the media characteristics, NLOS geometrical configuration and IR signal propagation property are important factors which affect the accuracy of indoor localization system. Although, 802.11.4a channel model has already addressed the pulse distortion problem in a statistical manner, its impact on system performance in complicated indoor environment is not very clearly. Since different materials cause complicated waveform distortions, IR pulse distortion described in statistical way need further corrected, especially in specific environment.

CONCLUSION

In this study, we have investigated the IR-UWB pulse distortions in several specific indoor environments and its influences on the TOA based localization accuracy through the aspect of electromagnetic theory. In completely NLOS environment, due to the extremely large bandwidth, the IR signals undergo waveform distortion with amplitude decreased and phase shifted when transmitted through obstacles. In time based localization system, this distortion result in pulse peak position biased and ranging estimation error in correlation receiver. For larger incidence angle and obstacle thickness, the localization error is bigger, under the conditions set in this paper, this ranging error most approximates to the pulse width. In order to achieve high accuracy localization in completely NLOS situation, the position of transceiver need to be adjusted to make the straight line of the two nodes perpendicular to the surface of obstacle and further more a relative small incidence angle is even better. However, the indoor environment is always complicated and unpredictable, it's necessary to investigate IR signal propagation properties in specific environment with different structures and search for NLOS error mitigate algorithm to improve the localization accuracy is still an important task need to be done.

ACKNOWLEDGMENTS

This study was supported by the National Nature Science Foundation of China under Grant No. 60702034. The author would like to thank Mr. T.T. Zhang and Ms. T. Lu for their assistance in this study.

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