Impact of NLOS Propagation upon Ranging Precision in UWB Systems

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***Abstract*— The Ultra WideBand (UWB) radiolocation functionality usually relies on the ability to perform a very precise estimation of the Time Of Flight (TOF). Unfortunately, in spite of the fine performances demonstrated by the UWB systems, indoor dense multipath channels may alter the precision of the range estimate from severe blockage situations. This paper addresses the general problem of Non Line Of Sight (NLOS) errors in the specific context of UWB range estimation. Typical ranging errors due to the NLOS propagation are exhibited by deriving experimental results from real indoor VNA measurements into realistic statistical error models.**

***Index Terms*—Ultra Wideband (UWB), Ranging, NLOS, Propagation Channel, Indoor environments**

I. Introduction

Despite the promising performances of Ultra Wideband (UWB) systems, indoor radiolocation is a tough task on its own. Since the ranging transactions usually require Time Of Flight (TOF) estimation, it is obvious that the propagation channel should degrade the ranging precision. Indeed, dense multi-paths channels may adversely affect the distance estimate by biasing pseudo-range measurements. It is specifically the case when the Line Of Sight (LOS) is present but undetectable, or when it is purely absent of the Channel Impulse Response (CIR) due to severe blockage situations. A better knowledge of the range error behavior represents a major stake since numerous positioning algorithms would use a priori models to ease the convergence [3][4][6]. This paper intends to emphasize the importance of the detection strategy in the particular context of UWB range estimation. Moreover, the errors committed on the range estimates are quantified and statistically characterized from VNA channel sounding measurements, which were performed in typical indoor environments, and then processed by a Frequency Domain Maximum Likelihood (FDML) estimation algorithm. For each detection scenario, the range errors are calculated from the known actual positions of both transmitter and receiver. Part II presents the measurement set-up and environments, Part III tackles with post-processing techniques, and finally, Part IV addresses the specific UWB ranging issue, providing experimental results and statistical error models.

II. Measurements

A. *Measurement Setup*

A Vector Network Analyzer (VNA) was used to measure the frequency response of the UWB indoor channel. See [1] for a more complete description of the measurement setup and procedure.

1) *Measurement Chain*

In the proposed measurement configuration, several active components are used in order to increase the SNR when reaching extreme measurements conditions, for instance, with several concrete walls up to 20m. So, the first port of the VNA is connected to Tx components, including a variable attenuator, a cable (25m), a power amplifier and a transmitting antenna. The Rx link is composed of a receiving antenna, a cable (3m), a high-pass filter (to reject systems operating under 2GHz), and two low noise amplifiers. This receiving chain is connected back to the second port of the VNA. Then 1601 frequency tones are saved in the band 2-6GHz, by the step 2.5MHz. Note that the antennas are omnidirectional in the horizontal plan (height: 1.5m).

2) *Dynamic Range and Sensitivity*

The VNA converts the received signal from its RF/microwave frequency into a lower intermediate frequency (IF) at 41.67 kHz. The bandwidth of the IF band pass filter is adjustable from 40 kHz down to 1 Hz. As a noise ratio of 10dB was chosen (IF bandwidth: 1kHz), the receiver sensibility is equal to S=127.8dBm. Additionally, the dynamic range is fixed to D=143.63dB, making it possible to cover a large set of configurations. A real UWB receiver would obviously not use similar components, but specific Spread Spectrum techniques (e.g. coherent integrations) would provide a sufficient Processing Gain, and hence, equivalent SNR conditions. Note that different attenuators were used to reach sufficient dynamic range and prevent from saturation.

B. Measurement Environments

Measurements were performed at spatially distributed locations throughout the test area by fixing the receiver in a central location and moving the transmitter on concentric circles. The explored distances (from 1m to 20 m) are representative of the expected available ranges of UWB systems for indoor applications. Although a quasi-static environment is required when recording, several successive measurements were averaged for each position. Two kinds of environments were analyzed: Office/Laboratory and Particular Flat environments, respectively with 3 and 9 averaged successive measurements. Moreover, for each position on a concentric circle, 4 additional positions separated by 0.2m from the initial TX position are explored (small scale study). The exact distances for all the positions are known and stored with data. Finally, among all these measurement configurations, we make the distinction between LOS, NLOS (at least one plasterboard wall between Tx and Rx), NLOS² (at least one concrete wall between Tx and Rx). Table 1 summarizes all the environment features.

Office/Laboratory in CEA/Leti building	
ITEM	DESCRIPTION
Area	~ 800 m^2
Furniture	Metallic cabinet, desks, chairs, electronic instrumentation…
Distance Range	1 – 20m
Measured points	LOS (17 positions) (1-6m) NLOS (74 positions) (3-20m) NLOS² (58 positions) (2-20m) => (17+74+58)x3 = 447 CIR
Particular Flat	
ITEM	DESCRIPTION
Area	~105m²
Furniture	Domestic furniture
Distance Range	1 – 17m
Measured points	LOS (116 positions) (1-8m) NLOS (45 positions) (9-13m) NLOS² (109 positions) (7-17m) => (116+45+109)x9 = 2430 CIR

Tab. 1 : Environment features (VNA channel sounding)

III. POST-PROCESSING TECHNIQUE

This part describes a post-processing framework allowing to obtain a precise estimation of UWB channel multi-path parameters (delay, magnitude, polarity). As presented in [2], the complex VNA measurements are processed into temporal Dirac suite patterns. The main purpose is to retrieve realistic UWB impulse responses from measurements, so as to simulate the path detection which would be operated by a UWB system.

1) Temporal Signal Reconstruction

Contrary to the traditional Complex Baseband IFFT Processing (default time option implemented in the VNA), we propose to use a Passband Hermitian Reconstruction (PHR) of the signal so as to retrieve with a better precision a relevant image of the channel impulse response:

$$r(t) = \sum_{l=1}^{L} a_l d(t - t_l)$$

where L, a_l and t_l are respectively the number of paths, amplitudes and delays. The main hypothesis is that a real temporal signal has a Hermitian symmetric spectrum. So, the "Passband" signal is obtained from the measured complex signal $R_{VNA}(f)$, by zero-padding down to DC and up to an arbitrary high frequency, corresponding to a required temporal precision:

$$R_{VNA}(f) = R(f).rect\left(\frac{f - f_c}{\Delta f}\right)$$

$$r_{HR}(t) = TF^{-1}\left[R_{VNA}(f) + R_{VNA}{}^{*}(-f)\right]$$

where $R(f)$ is the channel transfer function of the actual signal $r(t)$, Δf and f_c are respectively the VNA measurement band and the central frequency. $r_{HR}(t)$ is representative of the actual channel impulse response measured by the VNA in the limited band Δf .

2) Channel Parameters Estimation

a) FDML Algorithm

At this point, the main goal would consist in retrieving initial paths modelled as Dirac suite patterns, that is to say $r(t)$. A Frequency Domain Maximum Likelihood (FDML) algorithm is used (See [2][5]). It consists in performing a Minimum Mean Square Error (MMSE) optimization on the complex measured data in the frequency domain. This MMSE is jointly performed on real and imaginary parts of VNA measurements. This algorithm imposes the use of an a priori model for the description of the measured signal. So, it is assumed that the signal measured in the VNA band is

$$R_{VNA}(f) = rect\left(\frac{f - fc}{\Delta f}\right)\left(\sum_{n=1}^{N} a_n e^{-j2pft_n}\right) + N_{VNA}(f)$$

where $N_{VNA}(f)$ is the complex noise in the measurement band. This approach is inspired in a sense by classical high-resolution estimation algorithms and provides fine temporal precision [2] as the optimization is lead upon both amplitudes and delays with continuous scales. Another advantage of the FDML algorithm is that the optimization is performed on a reduced set of data, leading to lower computational complexity. However, a PHR is still employed to feed the optimization phase with relevant initial guess at each step, i.e. each time a new path is estimated. See [2] for more details concerning the estimation algorithm and its performances.

b) Threshold Setting and Simulated Ranging

When simulating the behavior of a real UWB ranging system by applying the FDML algorithm to real VNA measurements, it is evident that the performances should be closely linked to the VNA sensitivity and dynamic range on one hand, and the stopping rules (threshold setting) in the estimation algorithm on the other hand (See [5]). However, for the purpose of simplification, the FDML is assumed to provide optimal detection performances (See [2]). Consequently, all the results exhibited in the following are considered as independent with the technological limitations, referring to ideal paths estimation. The main goal is to characterize potential errors only due to the channel, and the impact of the detection strategy. In a sense, this would represent the best achievable performances in multipaths channels by UWB devices, if perfect channel estimation were assumed.

IV. UWB RANGING

Unlike traditional narrow-band ranging technologies, UWB systems benefit from a very large bandwidth, allowing to resolve dense multipaths in indoor environments. The study of the ranging error is obviously not specific to UWB transmissions, but the following results are realistic in the particular UWB context since they rely on high resolution paths representation. So, the real VNA measurements, which were processed into temporal Dirac Suite Patterns via the FDML algorithm (See III), are exploited in the following so as to characterize typical range errors in UWB systems, and hence, to propose statistical models.

1) Path Detection Strategies

a) First Path Detection

This strategy consists in detecting the first available path in the CIR as the LOS. It is likely to be the most efficient technique, but it is dependent on a precise observation window, and good local SNR conditions at the first path. However, even in the worst case when a secondary path is selected as the LOS, it would lead to reasonable performances relatively to other strategies. In the following, the corresponding Time Of Arrival (TOA) estimate will be depicted as t_f .

b) Strongest Path Detection

Contrary to the First Path Detection, this strategy is relatively simple and convenient. It only consists in considering the TOA of the strongest path in the CIR as the TOA of the LOS. In the following, the corresponding TOA estimate will be depicted as t_s . Note that t_{sf} will stand for both t_s and t_f when exhibiting the same performances (LOS environments).

2) Experimental Results

Figure 2 displays typical errors committed on range estimates, as a function of the actual range and the detection strategy, for both Particular Flat and Laboratory environments, and respectively for LOS, NLOS, NLOS[2]. As it was expected for the LOS environments, the error is maintained at a quasi-null level with both Strongest and First Path Detection strategies and for the two considered environments. Since the first path is obviously the strongest one, these two strategies lead to the selection of a same path for each measurement, and hence exhibit exactly the same performances. As it was expected too, both mean and standard deviation of the ranging error clearly increase with the actual distance for the two strategies and for both NLOS/NLOS[2] channels, what seems to demonstrate that the scattering radius increases with the actual range. This remark corroborates some experimental results obtained with real UWB ranging in indoor environments [7][8]. In the Particular Flat, the error is very sensitive to the apparition of NLOS situations around 7m, especially for the Strongest Path Detection, whereas NLOS/NLOS[2] are present in the Laboratory at shorter ranges. The First Path Detection proves to exhibit fine performances, even with penalizing NLOS[2] environments. Typically, the ranging error is maintained below 3m in the Flat, vs. 8m for the Strongest Path Detection. In addition, the Figure 3 illustrates for the Laboratory environment the relation between the ranging errors and the RMS delay spread on one hand, and the mean excess delay on the other hand. At first sight, if there is no evident link between the error and these channel statistical features, nevertheless both mean and standard deviation of the range error seem to rise with the RMS delay spread and the mean excess delay. All of these remarks agree with classical representations of the ranging error in indoor environments.

3) Statistical Models for the Range estimation Errors

a) Empirical Statistics and Interpolation

Although marginal statistics (distinct results for Flat and Lab.) had been carried out, it was decided to present the results of jointed statistics too (Flat and Lab.). One would object that these environments do not present the same propagation characteristics, and hence, ranging performances. However, the main goal is to provide a generic error model for indoor environments with sufficient data. Moreover, one could remark that the number of realizations (i.e. measurements) may be too small for several distances (See Tab. 1), even for the jointed statistics. This can be taken into account in the interpolating process. Basically, the method consists in performing a weighted optimization procedure so as to retrieve relevant polynomial coefficients.

$$\min_{c_1,c_2,c_3}\left[\sum_{d=d_{\min}}^{d_{\max}}\left(\left(N_{MEAS}(d)\right)^{C_{REL}}\times\left(\tilde{m}_{ERROR}(d)-\left[c_{4,m}+c_{3,m}d+c_{2,m}d^2+c_{1,m}d^3\right]\right)\right)^2\right]$$

$$\min_{c_1,c_2,c_3}\left[\sum_{d=d_{\min}}^{d_{\max}}\left(\left(N_{MEAS}(d)\right)^{C_{REL}}\times\left(\tilde{s}_{ERROR}(d)-\left[c_{4,s}+c_{3,s}d+c_{2,s}d^2+c_{1,s}d^3\right]\right)\right)^2\right]$$

where $N_{MEAS}(d)$ is the number of measurements used to compute the empirical mean and standard deviation at distance d; C_{REL} a coefficient allowing to discard the influence of irrelevant distances (with few measurements); $\tilde{m}_{ERROR}(d)$ the empirical mean error on the range estimate at the distance d; $\tilde{s}_{ERROR}(d)$ the empirical standard deviation of the error on the range estimate at the distance d; c_1, c_2, c_3 and c_4 the interpolating polynomial coefficients. Moreover, this basic optimization process can be adapted with particular constraints on the variable bounds. $c_4 \geq 0$ allows to have systematically positive means at d=0, but other conditions could be added such as a convex behavior of the interpolating function by forcing the sign of c_3.

b) Error Models on the Range Estimate

In the following C_{REL}=1.5, all the interpolating coefficients are maintained to positive values. Table 2 provides a complete set of positive interpolating coefficients so as to reach a precision of 1mm in the representation of statistical parameters.

C_{REL}=1.5			c_{4s} 10^{-3}	c_{3s} 10^{-4}	c_{2s} 10^{-5}	c_{1s} 10^{-6}	c_{4m} 10^{-3}	c_{3m} 10^{-4}	c_{2m} 10^{-5}	c_{1m} 10^{-6}
F	First Path	NLOS	22.0	37.7	0.0	0.0	0.0	0.0	0.0	16.9
		NLOS2	0.0	0.0	0.0	155.9	0.0	0.0	0.0	256.0
	Strong. Path	NLOS	260.2	20.0	0.0	400.0	0.0	0.0	0.0	534.8
		NLOS2	1597.9	0.0	0.0	0.0	31.3	0.0	0.0	955.5
L	First Path	NLOS	11.0	89.4	53.8	0.0	56.8	0.2	0.0	98.9
		NLOS2	20.4	271.5	728.9	0.0	338.6	133.5	0.0	441.6
	Strong. Path	NLOS	172.7	849.4	452.8	0.0	1166.7	0.0	0.0	465.0
		NLOS2	330.3	1530.7	1202.7	0.0	1279.4	1620.7	0.0	618.1
F & L	First Path	NLOS	11.0	89.4	53.8	0.0	56.8	0.2	0.0	98.8
		NLOS2	20.4	271.4	728.9	0.0	338.6	133.5	0.0	441.6
	Strong. Path	NLOS	172.7	849.4	452.8	0.0	1167	0.0	0.0	465.0
		NLOS2	330.3	1530.7	950.8	0.0	1279.4	1620.7	0.0	618.1

Tab. 2: Polynomial Coefficients for the Ranging Error Model (F:Flat, L: Lab., F&L: Flat and Lab.)

Figure 4 displays a particular illustration of the proposed ranging error model for NLOS^2 and typical indoor environments. The First Path Detection criterion clearly outperforms the Strongest Path Strategy.

c) LOS/NLOS/NLOS^2 Probability

At this point, we make the distinction between the number of realizations for each distance and the probability of measurement, which is basically a normalized number (realizations for a channel kind divided by the total realizations). Moreover, since the measurement positions are uniformly distributed over a typical indoor area (See II), in first approximation, the probability of measurement for each kind of channel may be sufficiently significant and interpreted as the probability of occurring LOS/NLOS/NLOS^2 channels for any distance. Gauss-like distributions (See Figure 1) can be attached to each kind of channel. In other words, for further high level models (used to test positioning algorithms for instance), each time a real distance is randomly chosen between two terminals, we are to determine what is the channel kind (LOS/NLOS/NLOS^2) taking into account these specific probabilities, and hence, associate the corresponding error model.

V. Conclusion

Coarse but realistic models for the range error estimate due to the propagation channel are proposed in this paper. They correspond to UWB LOS/NLOS/NLOS^2 indoor channels and could be used so as to test positioning algorithms. At first sight, the first path detection strategy seems to be much more viable in the specific UWB ranging context than the Strongest Path Detection strategy. It leads, in the worst case of NLOS^2, to a mean error on the range estimate lower than 4m and a standard deviation of 3m (at the actual range of 20m). However, since the expected maximum reachable range is below 12m for the UWB systems, the corresponding mean error on range estimate could be maintained below 1m. So we highly recommend the use of this detection strategy in the future ranging UWB systems.

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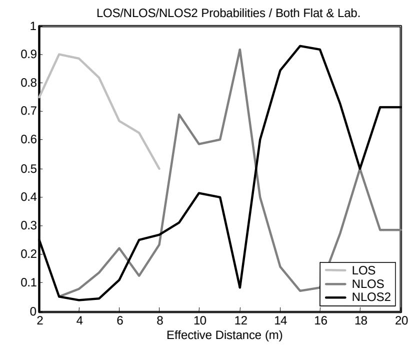

Fig. 1: LOS/NLOS/NLOS^2 probability (Flat & Lab.)

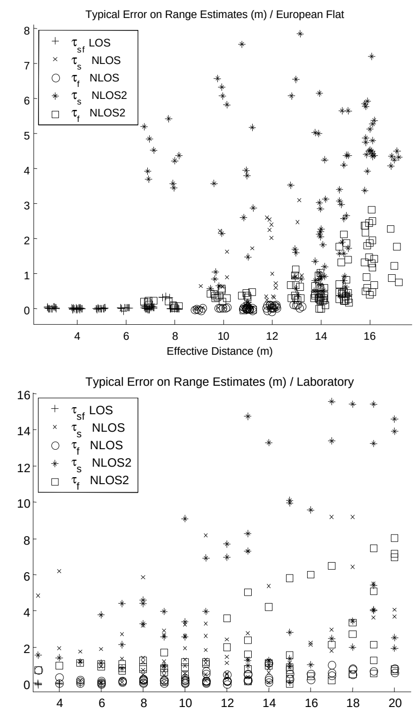

Fig. 2: Typical Errors committed on the Range Estimates for LOS/NLOS/NLOS^2 as a function of the actual Distance and the Detection Strategy (Flat & Lab.)

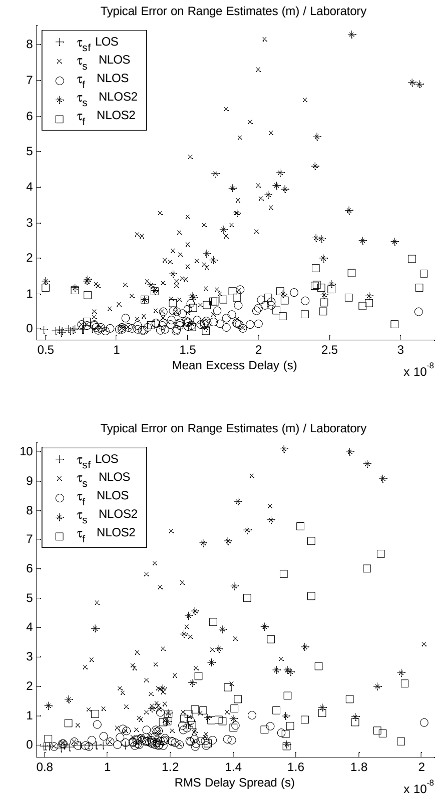

Fig. 3: Expended views of typical Ranging Errors as a function of RMS Delay Spread and Mean Excess Delay (Lab.)

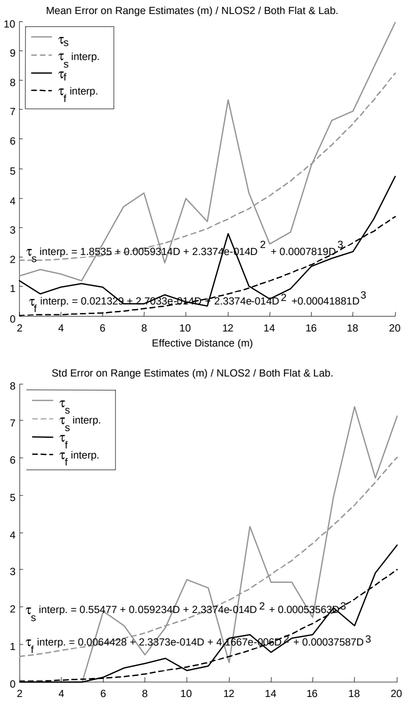

Fig. 4: Empirical mean and standard deviation of the error on NLOS^2 range estimates and third order weighted ($C_{RELIABILITY}$ = 0.4) interpolating polynomial (Flat & Lab.)