Real-Time Identification of NLOS Range Measurements for Enhanced UWB Localization

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***Abstract*—Despite of the ultra-wideband (UWB) system's robustness against multipath in cluttered environments, a number of challenges remain before UWB localization can be implemented. In particular, non-line-of-sight (NLOS) propagation is especially critical for high-resolution localization systems because non-negligibly positive biases will be introduced in distance measurements, thus degrading the localization performance. Here, based on received and first path powers obtainable from channel impulse response (CIR), we propose a simple but very efficient method to distinguish between NLOS and LOS conditions. Our method needs neither the training data nor the prior knowledge about the environments, thus enabling real-time NLOS identification. Despite the simplicity of our method, the experimental results verify its speediness and highly correct detection rate.**

I. Introduction

Localization in manned and unmanned vehicle networks is critical for many applications, including formation control and self-configuring of unmanned vehicle networks. In many practical environments such as enclosed areas, urban canyons, high-accuracy localization becomes a very challenging problem [1] in the presence of multipaths and NLOS propagations. Among various wireless technologies such as the Bluetooth, the Wi-Fi, the UWB and the ZigBee, UWB is the most promising technology to combat multipaths in cluttered environment. The ultra-wide bandwidth in UWB results in well separated direct path from the multi-paths, thus enabling more accurate ranging using TOA of the direct path. However, before UWB localization [2], [3], [4] can be deployed, the NLOS propagations must be identified and mitigated; otherwise non-negligible positive biases will be introduced in distance measurements [2], thereby ruining the localization performance.

Normally, the NLOS can be reliably identified from the channel impulse response (CIR) because the CIR under NLOS conditions behaves very differently from that under the LOS conditions. Many identification methods have been proposed based on CIR. In [5], [6], the authors proposed a technique based on the multipath channel statistics (MPCs) such as the kurtosis, the mean excess delay spread, and the root-mean-square delay spread. This technique needs to model the distribution of multiple statistics, thus requiring huge amount of training measurements. Obviously, this technique is environmentally dependent. In [1], the authors model the probability distribution of mean excess delay spread and received total power, thus necessitating training measurements. In [7], a support vector machine (SVM) classifier has been established based on the training data. Without exception, the training phases of these techniques are inevitable. The dynamic environments would thus prevent these techniques from the real-time implementation.

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Moreover, it has not escaped our notice that there are channels in which the visual LOS is blocked, but the radio LOS is not. We term such channels as visual NLOS (or V-NLOS). From the CIR perspective, the V-NLOS CIR behaves very similar to LOS CIR, but the range measurements under V-NLOS are still positively biased. In such situations, the above-mentioned CIR based identification approaches can no longer be reliable to differentiate V-NLOS from the LOS. Hence, it urges us to find an alternative solution to identify the LOS from both NLOS and V-NLOS.

In this paper, we present a real-time NLOS identification technique by comparing the difference between the the received power and first path power with a predefined threshold e.g. 6 dB. If the difference is smaller than 6 dB, we consider the channel as LOS. Our technique needs no training phase and no prior knowledge about the environments. The experimental results verify its fast computation rate and its high accuracy in terms of correct detection rate in the presence of NLOS and V-NLOS. Our technique is motivated by two facts:

1) LOS CIR has much stronger direct path (or first path) than NLOS CIR [9], [10], [11], [12].
2) The received signal power would be much lower in case of obstructed LOS path [9], [13], [14].

This rest of the paper is organized as follows: Section II formulates the problem; Section III describes our experimental setup and reviews how CIR behaves in case of NLOS, and the existing NLOS identification technique based on the MPCs; Section IV introduces the other sources of errors in identifying a NLOS scenario and presents an insight into the V-NLOS cases; Section V proposes our identification technique; Section VI provides a comparison of the results based on the proposed scheme and some existing techniques [5], [6], in terms of probability of correct and fault detections in different LOS, NLOS and V-NLOS situations; Section VII draws a conclusion.

II. Problem Formulation

As seen in Figure 3, the probability model based on the MPCs do not provide sufficient information to differentiate the LOS from the V-NLOS case. However, as shown in Figure 6, the range measurements under V-NLOS are still positively biased. Without any priori information about the operating

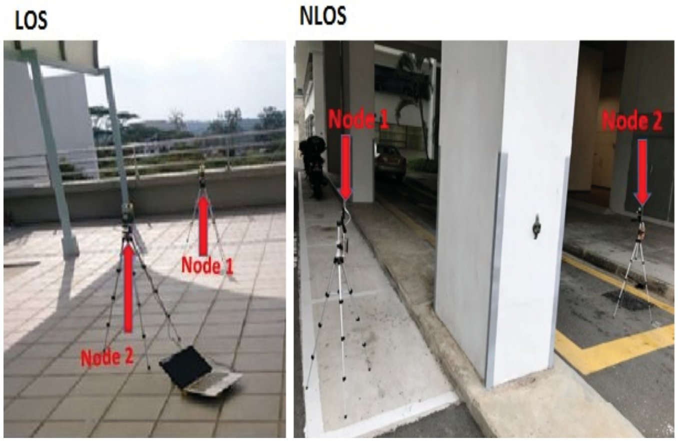

Fig. 1: Test setup in LOS and NLOS environment.

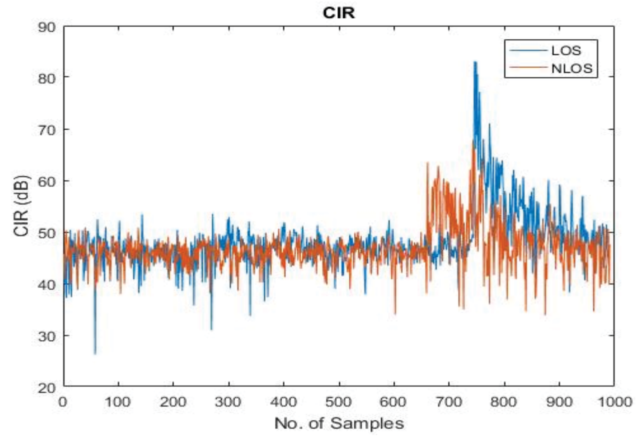

Fig. 2: Channel impulse response from LOS and NLOS tests.

environment, we intend to develop a real-time identification technique that is able to reliably identify the LOS from both NLOS and V-NLOS.

III. NLOS IDENTIFICATION

In this section, the use of CIR to identify a NLOS case will be described. The CIR will be used to extract the MPC statistic information in order to assess the characteristics in detail.

An example of the test beds for both LOS and NLOS are shown in Figure 1. As part of this study, the LOS tests are conducted in the corridor and roof, while the NLOS tests are performed in the corridor, indoor offices and in parking areas (partially outdoor). The initial setup consist of two nodes: 1 and 2 that are mounted on the tripod and separated by a certain true distance d. The tests are conducted in different environments and the measurement results are recorded.

A. Channel Impulse Response

The channel impulse response (CIR) is usually referred to as:

$$h(t) = \sum_{k=1}^{K} \alpha_k \delta(t - \tau_k), \tag{1}$$

where $h(t)$ is the channel impulse response, K is the total number of multipath components, and α_k and τ_k represent the amplitude and delay characteristic of the kth MPC, respectively. The CIR is very useful in terms of analysing different characteristics of the received signal that can be used to distinguish between LOS and NLOS.

From the CIR, the first arriving path can be used to identify whether a node is NLOS from the other by looking at the ToA of the received signal, which is given by $\tau_{\text{TOA}} = \tau_k$. Thus, the true distance can be estimated if τ_k can be estimated accurately. This is true for LOS scenarios, as the first arriving path is the strongest/shortest, whereas in case of NLOS, the first path will be obstructed and the distance estimate will include a positive bias. In some NLOS (VNLOS) scenarios, the CIR is quite similar to the LOS case, but the first path might arrive with a certain delay due to different propagation speed through various obstacles. Hence, it is essential to look at the delay characteristics of the signal, which is given by the MPCs, such as the kurtosis, the mean excess delay and the rms delay spread.

Based on the tests conducted in an indoor LOS and NLOS scenario, the CIR sample of the received signal is depicted as in Figure 2. In the case of LOS, the first arriving path is the strongest, thus estimating the accurate distance between the two nodes 1 and 2. In case of NLOS, there are multipath's and the first arriving path is very close to the noise floor. This is because the signal is either diffracted or attenuated by the wall in Figure 1. Hence, the estimated distance includes a certain bias.

In order to study the effects of multipath in detail, the features of the multipath components, such as the kurtosis, mean excess delay and the rms delay spread, has been modelled based on the test results.

B. Kurtosis

Kurtosis is a measure, which gives information about how peaky a probability distribution curve is. The kurtosis as mentioned in [5] of a certain set of data sample is defined as the ratio of the fourth-order moment of the data to the second-order moment (variance) of the data, which is given by,

$$\kappa = \frac{\mu^4}{\sigma^4} = \frac{E[(|h(t)| - \mu_{|h|})^4]}{E[(|h(t)| - \mu_{|h|})^2]^2}, \tag{2}$$

where μ denotes the mean, and σ denotes the standard deviation of $h(t)$. The kurtosis provides only the information about the amplitude statistics of the estimated MPCs.

The kurtosis value is estimated for each CIR sample when estimating the range information. The tests are performed in different LOS and NLOS environments and based on the collected results, the kurtosis values are modelled as a histogram.

C. Mean Excess Delay Spread

The mean excess delay signifies the first moment of the power delay profile of a channel, which is given by,

$$\tau_m = \frac{\int_{-\infty}^{\infty} t|h(t)|^2 dt}{\int_{\infty}^{\infty} |h(t)|^2 dt}, \tag{3}$$

where $\epsilon = \int_{-\infty}^{\infty} |h(t)|^2 dt$ is the energy of the received signal. The mean excess delay gives information about the time delay during which the multipath energy falls below a certain level. This is a potential parameter used to study about the delay characteristics of the received signal.

D. RMS Delay Spread

The rms delay spread is defined as the square root of the second central moment of the power delay profile, which is given by,

$$\tau_{rms} = \frac{\int_{-\infty}^{\infty} (t-\tau_m)|h(t)|^2 dt}{\int_{-\infty}^{\infty} |h(t)|^2 dt}. \tag{4}$$

The delays are measured based on the first path of the received signals CIR. The delay spread is a measure which characterizes the richness of the multipath in a channel.

Figure 3 shows the histogram distribution of the MPCs for both the LOS and NLOS cases. The histogram distribution has been modelled based on the real-time measurement results collected during the tests. The red histogram represents the NLOS case, while the blue one denotes the LOS case. If the direct path is clearly detectable and if the energy of the received signal is very high, then the Kurtosis value tends to be higher. The higher the kurtosis value means that it is more likely for the nodes to have a LOS path between one another. The mean excess delay and the rms delay spread give a rational information about the presence of multipath and their effects in an indoor environment. The threshold can be chosen in such a way that the two cases could be distinguished quite accurately.

IV. Sources of Error in Identification

The MPCs values are very environment dependent. Thus, by using the amplitude and delay statistics of the MPC, it is possible to detect and differentiate between a strong LOS and NLOS case, but some sources of error has been encountered in identifying a NLOS case. This is because, as mentioned before in Section I, a NLOS case can be differentiated into two typical cases; a true NLOS and visual NLOS (VNLOS).

The first case is when the direct path is completely blocked and the received signal is either diffracted or reflected from the objects present in a dense environment, which has a very large bias in the range estimate. Whereas in the latter case, the direct path arrives at the receiver with a delay due to the varying propagation speed introduced by the blockage, and has a comparatively lesser bias. Identifying VNLOS scenario is much critical as it is a subset of (lies in-between) the other two cases.

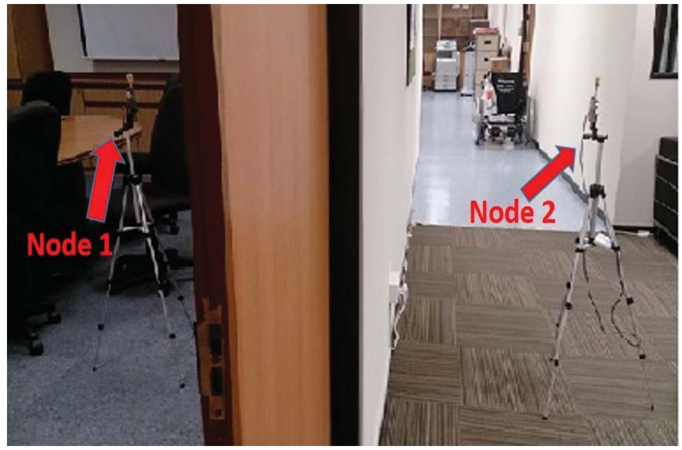

Fig. 4: An example of a typical indoor VNLOS situation.

A. VNLOS Identification

The Figure 4 shows a typical visual NLOS case. Here, we can assume that the two nodes are truly NLOS from each other, whereas in the sense of radio technology, it is not, because the UWB radio signal transmitted by node 1 could still be detected by the node 2 as in LOS case, but only with a certain delay.

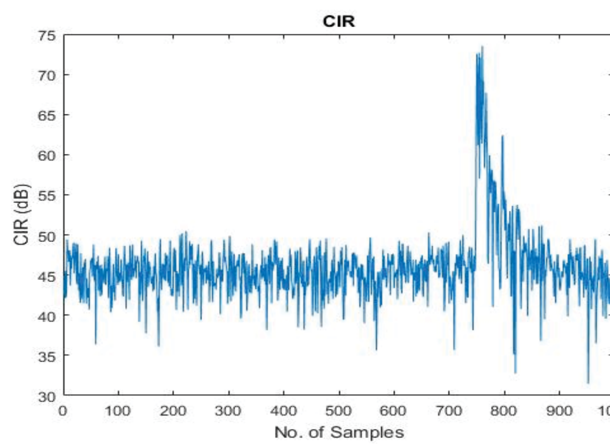

Fig. 5: Channel impulse response from an VNLOS situation.

From Figure 5, the direct path is still detectable as in LOS case. Although, it is possible to detect the direct path, it cannot be completely regarded as a LOS case, because the range estimate is still positively biased. From the test results in Figure 6, the range has a bias of about 40 cm for a distance of about 4 m, which contradicts with our expected accuracy of less than 10 cm. The range is biased as there could be some combination of multipath during the propagation. The actual fastest path through the wall is more likely to be a multipath, which could be due to the presence of beams/pillars (material) inside the wall. Since we are looking at a very precise range accuracy, we would still regard such scenarios as NLOS and discard the range estimates.

From Figure 3, it can be further observed that for the optical NLOS case (yellow histogram), the MPCs values seem to

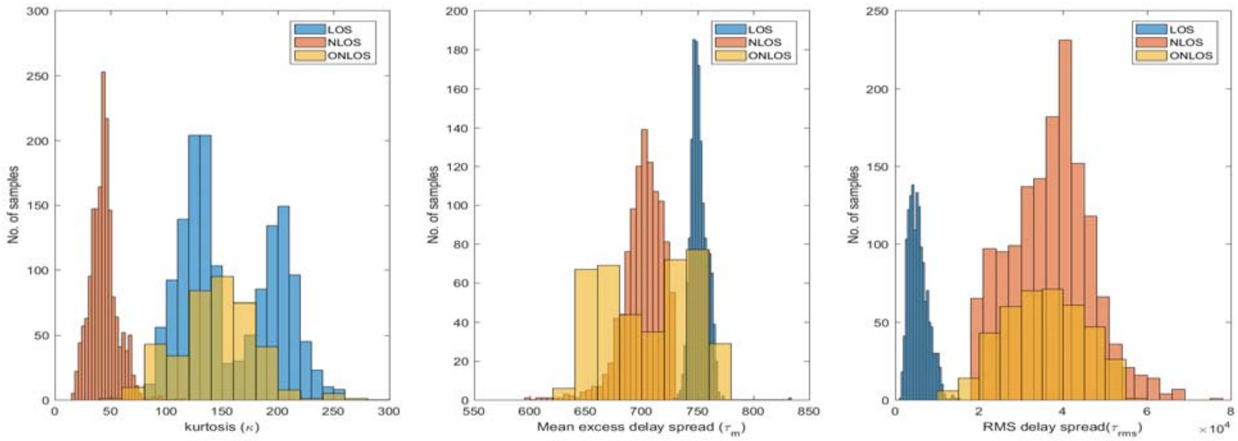

Fig. 3: MPC statistics for all the three cases.

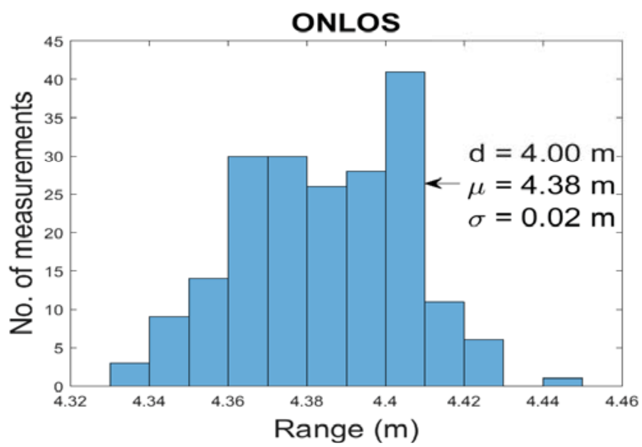

Fig. 6: Ranging accuracy in VNLOS situation.

overlap with the other two cases (LOS and NLOS). This makes it more critical to identify such a scenario in real-time. The rms delay spread provides sufficient information about this special case, however, there is a drawback with the computation time and effort. The disadvantage with the MPC statistics is that, they usually require a longer computation time and are based on the probability models, which are not based on real-time identification. Hence, we propose a real-time identification technique that is based on the power metric.

V. Power-Based Formulation

In this section, we present a received-power-based approach. This is a classical approach that uses the total received power, which is compared against the power of the first arriving path in order to identify if the two nodes are LOS or NLOS (VNLOS) with respect to one another. This approach is used in real-time and does not need any prior information about the environment or the biases.

A. Receive Power (RX Power)

An important metric that can be obtained from the channel profile is the power metric. It is possible to estimate the total power (here referred to as receive power: P_{RX}) from the CIR. This is available from the registers of the IEEE 802.15.4 standard UWB system as proposed by Decawave. This power refers to the total received signal power. The receive power can be estimated using the following equation [15]:

$$P_{RX} = 10\log_{10}(\frac{C \times 2^{17}}{N^2}) - A, \tag{5}$$

where C is the CIR, A is a constant that is equal to 113.77 pulse repetition frequency (PRF) for 16 MHz or 121.74 PRF for 64 MHz and N is the preamble accumulation count value that can be obtained from the register.

B. First Path Power (FP Power)

An estimate of the first path power can also be obtained based on the power profile of a given channel and the amplitude of the first arriving path. This power refers to the power level or energy of the first arriving path. This information is hidden in the CIR and can be retrieved using the registers in Decawave [15], which is given by,

$$P_{FP} = 10\log_{10}(\frac{F_1^2 + F_2^2 + F_3^2}{N^2}) - A, \tag{6}$$

where F_1, F_2 and F_3 refers to the magnitude value of the first path amplitude at points 1, 2 and 3. As before, A is a constant that is equal to 113.77 PRF for 16 MHz or 121.74 PRF for 64 MHz and N is the preamble accumulation count value that can be obtained from the register.

For this case, the estimated first path power can be compared against the estimated receive power as mentioned by Decawave in their user manual, in order to identify the LOS and NLOS case. Based on the estimated receive power and the first path power, a so-called power-performance index (P_{PI}) has been devised in our firmware, which is given by,

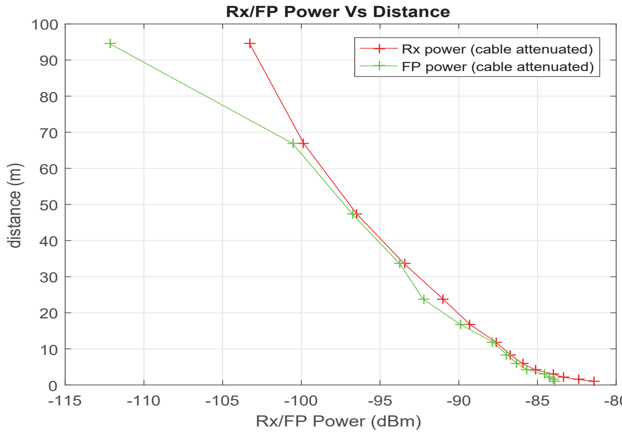

Fig. 7: A reference model based on the estimated receive power and first path power for different distances.

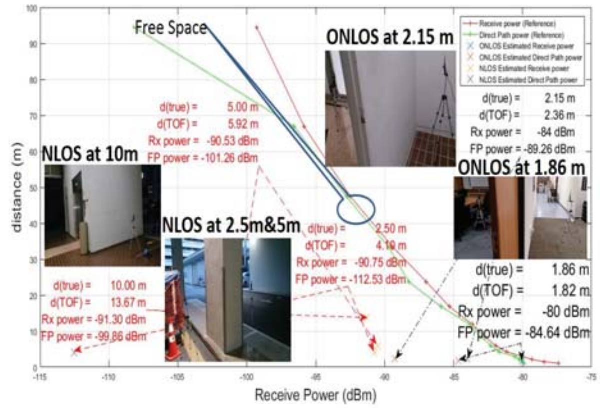

Fig. 8: Real-time test results for NLOS and VNLOS environments.

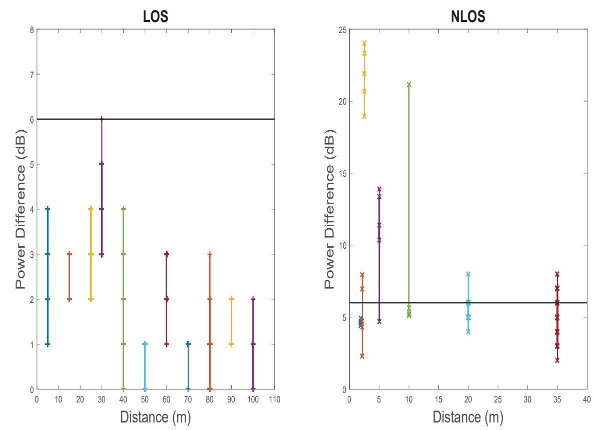

Fig. 9: Real-time test results obtained from different LOS and NLOS (VNLOS) environments.

$$P_{PI} = P_{RX} - P_{FP}. \tag{7}$$

The power-performance index is the difference between the receive power and the first path power, which tells us about how much energy is accumulated at the first path in comparison to the total energy of the received signal. Thus, as a rule, we assume that in any given situation, if the difference in power is below 6 dB, then the two nodes are LOS from one another, while it is greater than 6 dB, it is expected to have NLOS (VNLOS) links.

In Figure 7, the estimated receive power is plotted along with the first path power for different distance. The distance is estimated using the free space path loss (FSPL) equation based on the received power. The estimated power model is used as reference to perform further tests in different LOS and NLOS (including VNLOS) scenarios.

The Figure 8 presents some further results that are obtained from different NLOS and VNLOS scenarios. It is very clear that this power-performance index can be one of the useful metric in potentially identifying both the NLOS and VNLOS scenarios. The results in Figure 8 are obtained from real-world, i.e., typical NLOS and VNLOS scenario tests. It includes any bias (due to surface reflections, obstacles and environment) that may affect the estimation of power in free space. It portrays how the environment and other biases would influence the estimation of the power level.

The Figure 9 shows how the power-performance index performs (with a threshold of 6 dB) for different distance in LOS and NLOS environments. Figure 10 shows how the range is affected with respect to different environments and how large the bias is in case of a NLOS. The range in LOS has an accuracy of less than 10 cm, whereas in case of a NLOS case, the range has a positive bias of over 1 m. Using this NLOS range will eventually deteriorate the localization performance.

VI. Experimental Results

An experimental test is conducted based on the results collected using the rms delay spread of the MPC statistics and the power metric in different LOS, NLOS and VNLOS scenarios. This is done in order to check the probability of correct detection (P_{CD}), misdetection (P_{MD}) and false alarm (P_{FA}). Here, a false alarm is raised when an VNLOS measurement is detected as LOS and a misdetection refers to any missed LOS detections. A missed detection is acceptable, but a false alarm can induce a large bias on the range and positioning estimates. Hence, according to this test, we are expecting to have a low false alarm rate.

A. Probability of Detection

Since this test is based on the recorded data, we assume that the following information are known priori: 1. the operating environment, 2. the type of blockage and 3. the true position (range) of the nodes. With these information, we know which measurements are LOS, NLOS and VNLOS. Thus, based on the assumptions we estimated the probability of detections.

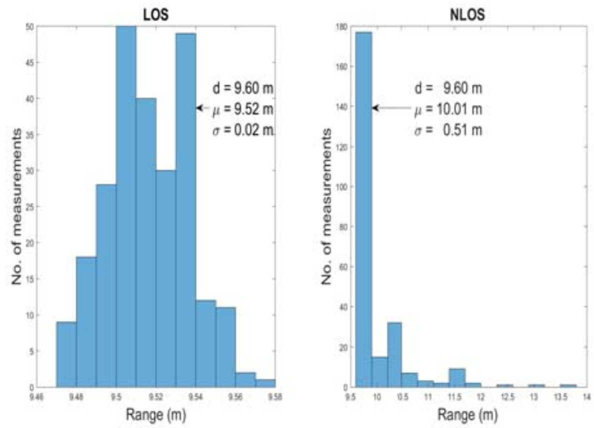

Fig. 10: Ranging accuracy in LOS and NLOS cases.

From the Table I, the false alarm and the misdetection rate based on the rms delay spread (τ_{rms}) is about 3.09 % and 0.61 % respectively, while for the power difference parameter (P_{PI}), it is about 2.54% and 0.77% respectively. The accuracy of correct detection (P_{CD}) can be estimated by,

$$P_{CD} = 1 - (P_{FA} + P_{MD}). \tag{8}$$

TABLE I: Probability of Detection.

Parameter	P_{FA}	P_{MD}	P_{CD}
τ_{rms}	3.09 %	0.61 %	96.30 %
P_{PI}	2.54 %	0.77 %	96.69 %

Based on the tests, the detection accuracy based on the power model is almost similar to that of the rms delay spread, but there is a trade-off between the two parameters in terms of the computation time.

B. Timing Information

As this paper is mainly focussed on real-time identification of the NLOS (VNLOS) cases, it is highly important to take the timing information into account.

For the MPC statistics, the CIR data must be retrieved from the Decawave register (written in C) using the USB serial. This CIR data is then used to extract the MPCs kurtosis, mean excess delay and rms delay spread values. The extracted values are then modelled as a histogram distribution in MATLAB. The time taken to extract the CIR information for each new range measurement is about 2 s to 3 s, which eventually makes the whole process slower. This process requires an off-line computation of the MPCs data.

For the Power model, the power metrics are modelled in the firmware in C. This does not require any modelling of the distribution and performs real-time identification of the NLOS (VNLOS) cases. It is completely an online estimation. The computation process takes as low as 0.25 ms. The power-performance index is sent along with the range information to the higher level to do the positioning estimation. Thus, providing a confidence about the range estimate in real-time.

VII. Conclusion

In this paper, we have presented a novel technique to identify a node that has NLOS/VNLOS link with the other one in real-time. Unlike other existing approaches that are limited to probabilistic models and simulation results, in this paper, we do not assume to have any prior information and the tests are performed in real-time. Based on the results, it is clear that the rms delay spread could be an useful parameter to identify VNLOS case, but it has a major drawback, as it requires a lot of training data and a longer computation time. Hence, we have proposed to use a performance index (P_{PI}) based on the received signal power and the first path power in order to perform real-time identification of the NLOS/VNLOS cases. From the experimental results, the proposed method proves to achieve a very high accuracy in terms of the probability of detections and also requires very low computation time.

Although the proposed model works well in NLOS/VNLOS identification, it becomes crucial in mitigating and handling such circumstances. When a mobile node does not have any LOS link for a certain period of time, in these situations it may then be useful to use the VNLOS link, which will have a comparatively lesser bias than the NLOS case. Hence, it is necessary to use a number of parameters, which have a direct effect on the environment in order to improve the confidence. The future work will be focused on mitigating and handling such situations, so as to improve the localization performance.

Acknowledgments

The research was partially supported by the ST Engineering NTU Corporate Lab through the NRF corporate lab@university scheme Project Reference C-RP10B

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