Non Line Of Sight effects in UWB indoor direct one-step self-localization using distributed antenna system: Measurement based study

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Summary
Non Line Of Sight effects in UWB indoor direct one-step self-localization using distributed antenna system are analyzed in this paper. The analysis is based on real measurements realized at the Ilmenau Technical University by the use of UWB MIMO channel sounder.

1 Introduction
The problem of identification and mitigation of the Non Line Of Sight (NLOS) effects in Ultra Wideband (UWB) indoor localization is a very challenging ongoing topic in the research community. There are two groups of methods applied in UWB indoor localization: indirect two-step localization methods and direct one-step localization methods [1]. Two-step localization methods are widely investigated and their theoretical performances and limitations are briefly surveyed in UWB literature [1]-[15]. These methods are based on the estimation of localization parameters (such as Receiving Signal Strengths (RSS), Direction of Arrivals (DOA) or Time Difference of Arrival (TDOA)) in the first step, and location estimation in fusion center in the second step. Direct one-step localization methods are more recent [16]-[23]. Weiss and Amar proposed in [16] a method for Direct Position Determination (DPD) of multiple radio signals. Their localization method is based on calculation of localization criteria function in frequency domain, and due to widebandness of UWB signals it is not quite appropriate for UWB localization. Erić and Vučić proposed a new MUSIC based method for direct network-centric localization in UWB systems based on the concept of steered covariance matrix [17],[18]. In the proposed method calculation of localization function is performed in time domain, whereas preprocessing is performed in frequency domain. Navarro, Closas and Nájar proposed in [20] the Direct Position Estimation (DPE) algorithm, which is based on a generalization of the pseudoperiodogram approach proposed for TOA estimation, and applied it for direct positioning in Impulse Radio Ultra Wide Band (IR UWB) in IEEE 802.15.4a channels. Erić, Dukić and Vučić proposed a new MUSIC based method for direct self-localization of synchronous IR UWB Node(s) [21]. Erić, Zetik, Dukić and Vučić presented in [22,23] results of experimental verification of the self-localization method in real indoor environment, based on real measurements performed by UWB MIMO channel sounder.

NLOS identification and mitigation is a big research challenge in both two-step indirect and one-step direct localization methods. It is known that the existence of NLOS propagation between some of referent and user UWB nodes drastically degrades localization performances when localization is performed by two-step localization methods [26,27,28]. Key approaches for NLOS identification and mitigation in UWB indoor localization considered in literature so far are commonly based on range estimates or on the channel pulse response. On the other hand, NLOS identification and mitigation in UWB indoor one-step direct localization hasn't been considered and highlighted in literature yet. That is why there are only a few papers related to direct indoor UWB localization. During experimental verification of the method for indoor UWB self-localization, the authors noticed that the proposed method was relatively robust to existence of NLOS time subintervals in observation time interval used for self-localization. Since the proposed self-localization method is based on calculation of localization function on the hypothetic locations in space of interest for localization, nature of such process offers quite new approaches to solving NLOS identification and mitigation problem. Therefore it will be the focus of this paper. It is based on theoretical foundation of direct one-step self-localization methods proposed by the authors in [21] and data obtained in measurement campaign realised by the use of MIMO UWB sounder at Ilmenau Technical University.

2 Short review of the MUSIC-based method for direct indoor self-localization in synchronous UWB system
Concept of the system for direct self-localization proposed in [21] is presented in Figure 1. The system is based on the use of one reference UWB node with distributed antenna system and one or many UWB user nodes, time and frequency synchronized with the reference node.
The same UWB localization data stream is simultaneously emitted from all the antennas. Received signals at user nodes are result of superposition of all Line Of Sight (LOS) paths from all the antennas and all multipath components which are present due to the propagation in indoor scenario. It is supposed that received signals contain LOS components from every transmitting antenna. These LOS components form in a way ‘finger print’ specific for every location and idea of direct self-localization is based on this fact.

\[
P_{\text{LOS}}(x, y, z) = \frac{1}{\|a(x, y, z)\|^2} \mathbf{E}_i^n \tag{1}
\]

Eq. (1) is calculated for \( G \) grid points \([x_i, y_i, z_i], i=1, G\) in 3D spatial sector of interest for localization. The location of user node is estimated by finding arguments of global maximum of (1). Superscript \( H \) in (1) denotes Hermit transposition and \( E_i \) denotes matrix of noise subspace of the covariance matrix \( \mathbf{\Phi} \) estimated from \( M \) available observation vectors \( r_m \) as \( R = (1/M) \sum_{m=1}^{M} r_m r_m^H \). Observation vectors \( r_m \) are formed from signal samples in received impulse frames. Signal vector \( a(x, y, z) \) for hypoethical receiving location with coordinates \((x, y, z)\) is modeled as a sum of delayed and attenuated of known transmitted UWB impulse as:

\[
a(x, y, z)^T = \sum_{l=1}^{N_{\text{LOS}}} \alpha_l(x, y, z) \mathbf{T}_{l}(x, y, z) \mathbf{W} \tag{2}
\]

Value \( \alpha_l(x, y, z) \) in (2) denotes propagation attenuation of the \( l \)-th LOS component, \( L \) is the number of transmitting antennas, vector \( \mathbf{pc}^{N_{\text{LOS}} \times 1} \) denotes the baseband DFT spectrum of the UWB impulse in impulse frame. Superscript \( H \) in (1) denotes transposition. \( \mathbf{T}(x, y, z) \in \mathbb{C}^{N_{\text{LOS}} \times N_{\text{LOS}}} \) is the diagonal matrix with elements \( \exp[2\pi j (m f_c+nf_{\text{PPN}}/N_{\text{PPN}}) \tau(x, y, z)] \) on the main diagonal with \( m=0, \ldots, N_{\text{PPN}}-1 \); \( f_c \) denotes the lowest frequency in the spectrum of the transmitted signal, \( \tau(x, y, z) = d(x, y, z)/c \) is time propagation of the LOS component between the \( l \)-th antenna and the user node location \((x, y, z)\), \( d_l(x, y, z) = [(x-x_l)^2+(y-y_l)^2+(z-z_l)^2]^{1/2} \) \( c \) denotes speed of light and \( \mathbf{W} \) denotes DFT matrix. Set of signal vectors \( a(x, y, z); i=1, G \) are a priori characteristic of the given transmitting antenna geometry, so, for grid points of hypothetic location \((x_i, y_i, z_i); i=1, G\) it can be pre-calculated. Details of proposed MUSIC based algorithm for direct self-localization can be found in [6].

## 3 Analysis of NLOS effects in UWB indoor direct self-localization based on measurement data

Method for direct indoor UWB self-localization proposed in [21] was experimentally verified based on real measurements realized at the Ilmenau Technical University by the use of UWB MIMO channel sounder in frequency range 3.5-10.5 GHz.

Results of experimental verification of proposed direct self-localization method were presented in [22], [23]. Summary results were presented in technical reports [24], [25].

Within the bilateral project software package for indoor UWB direct self-localization using UWB MIMO channel sounder was developed, [24], [25]. This software package was realized in MATLAB, with object oriented graphical user interface (GUI) shown in Figure 4. It integrates processes of real time signal acquisition by the use of IR UWB channel sounder, calibration of measurement setup (cables, antenna positions), and offline implementation of the method for direct self localization [21].

![Figure 1. UWB system used for indoor direct self-localization using distributed antenna system.](image1)

![Figure 2. Graphical user interface (GUI) of the application for UWB signal acquisition, calibration and self-localization using UWB MIMO channel sounder.](image2)
Tx and Rx antenna positions shown in Figure 3, is presented in Figure 4,

![Image](image1.png)

Figure 3: Block scheme of the measurement set-up using UWB MIMO channel sounder

Figure 4. Measurement setup in the hole of the building of Ilmenau Technical University used for measurements.

In measurement process calibration of cables was performed by standard deconvolution. Calibration of transmitting antenna positions was performed using the innovative calibration procedure developed by the authors and presented in [23].

Calibrated measurement data received on Rx1 channel (411 impulse frames, each with first 128 samples) are shown in Figure 5. As can be seen, LOS impulses received from all four transmitting antennas (Tx1-Tx4) are dominant and clearly visible. Also, Figure 5 shows that in measurement data there are three time intervals $T_1$ (impulse frames form 1 to 35), $T_3$ (impulse frames form 60 to 75) and $T_5$ (impulse frames form 325 to 411) with hard NLOS effects since there is no LOS component from Tx1 (nearest antenna) in Rx1 received signal. It was collateral effect in measurement procedure, due to movement of operator on UWB sounder during measurement. However, it is very useful for further analysis of NLOS effects in self-localization process.

Results of UWB direct self-localization (estimation of Rx1 antenna location) using 411 impulse frames x 80 samples per frames are presented in Figure 6a. As can be seen, absolute maximum of MUSIC self-localization cost function in Eq. 1 (main lobe with absolute maximum) corresponds to right location of Rx1 antenna. Realized measurements showed that with application of the proposed self-localization method using UWB MIMO sounder with signal of 7 GHz bandwidth, less than 1 mm localization accuracy can be achieved in real indoor environment [22]. Figure 6a shows that besides main lobe, there are many sidelobes, two of them being dominant. Results of self-localization using impulse frames in $T_4$ time interval (LOS components from all 4 Tx antennas are present – there is no NLOS time intervals) are shown in Figure 6b. Obviously the results are almost the same as the results presented in Figure 6a, where NLOS subintervals are included. Conclusion is that proposed direct self-localization method is relatively robust to existence of time subintervals with NLOS in observation interval used for self-localization.

![Image](image2.png)

Figure 5. Acquired UWB signal a) 411 impulse frames x first 128 samples per impulse frame, b) LOS impulses in impulse frames.

Ambiguity function [21] calculated for Rx1 location is presented in Figure 6c. Ambiguity function is defined as normalized measure of collinearity of the signal vector defined by Eq. (2) for given location and all other signal vectors for grid points in spatial sector of interests for localization [21]. As shown in Figure 6 a, b, and c, main lobe and sidelobes in localization and ambiguity function perfectly correspond, so ambiguity function can be used
for prediction of sidelobes for each hypothetic location of interest.

Nature of ambiguity function in this self-localization system (Figure 1) is closely related to constellation (geometry) of transmitting Tx antennas. Therefore positions of sidelobes in Figure 6 are related to Tx antenna geometry presented in Figures 3 and 4.

Test of coincidence of the module of signal vector for Rx1 location and LOS impulses in measurement data (module of mean values of signals in all measured impulse frames) is presented in Figure 7. Obviously there is perfect coincidence of calculated signal vector for Rx1 location and LOS impulses.

Figure 7. Test of coincidence of the signal vector for Rx1 location (red line) and LOS impulses in measurement data (blue line).

Figure 8. Constellation points of signal vectors for time samples which correspond to LOS impulses (red stars) and constellation points of LOS impulses in measurement data (blue stars).

Constellation points of signal vectors for time samples which correspond to LOS impulses (red stars) and constellation points of LOS impulses in measurement data are presented in Figure 8. As can be seen, there is almost perfect matching of constellation points of signal vector and LOS impulses.
What would happen if there was NLOS propagation between some Tx and Rx antennas, like in T1, T3 and T5 subintervals in Figure 5.? The main idea is to investigate how ambiguity function could be used for prediction, identification and mitigation of NLOS effect in self-localization process.

Results of self-localization using impulse frames in T5 interval (there is hard Tx1->Rx1 NLOS) are presented in Figure 9a. Ambiguity function calculated for Rx1 location with omitted signal component which corresponds to Tx1->Rx1 NLOS is presented in Figure 9b. As can be seen, the lobe with absolute maximum is now in the position $\hat{Rx}_1$ on the dominant sidelobe (see Figure 6). Besides that, the lobe with absolute maximum in ambiguity function is also in the $\hat{Rx}_1$ position of the dominant sidlobe. Hence there is an error in estimation of Rx1 location. We can assume that the location of the maximum lobe doesn't correspond to the position of Rx1 due to the NLOS components, or we can assume that the maximum lobe position corresponds to the position of Rx1. If it is possible to resolve this problem, then it is possible to identify and mitigate NLOS effects. The first idea is to see what ambiguity function looks like on the location of the sidelobe, estimated as the main lobe with absolute maximum.

Ambiguity functions for the sidelobe location with all LOS components and omitted Tx1->Rx1 LOS component are presented in Figures 10 a and b, respectively. It is obvious that in both situations the lobe with absolute maximum is on the same location, and sidelobes are also in the same positions as in ambiguity function for real Rx1 location (Figure 9b). So, conclusion is that ambiguity function could not be used to resolve previously mentioned problem.

Result of the test of coincidence of the signal vector for the $\hat{Rx}_1$ and LOS impulses in measurement data is presented in Figure 11. It would be expected that four impulses in signal vector would be visible, but there are just three of them. The first one is highest because signal components which correspond to Tx1->Rx1 and Tx3->Rx1 are perfectly overlapped and perfectly collinear. That is the reason why estimated location when NLOS exists is the position of dominant sidelobe. So, there is a kind of ambiguity of the proposed system used for UWB indoor self-localization which is related to some points in the space on equal distances to pairs of Tx antennas. Possible solution to that ambiguity problem is improvement of the UWB system used for indoor direct self-localization shown in Figure 1. Instead of transmitting the same UWB signal from all antennas, UWB signal with different starting phases should be transmitted simultaneously from different antennas. This modification offers an opportunity to find a solution to the problem of identification and mitigation of NLOS effects in such a system.
Figure 10. a) Ambiguity function for Rx1 location with included all signal components which correspond to all LOS components and b) Ambiguity function for Rx1 location with omitted signal component which corresponds to Tx1->Rx1 NLOS.

Figure 11. Result of the test of coincidence of the signal vector for the Rx1 location (red line) and LOS impulses in measurement data (blue line).

4 Conclusion

- Proposed method for self-localization is robust to existence of NLOS intervals (like T1, T3, T5 in Fig. 8) in observation interval (like interval T = T1 + T2 + T3 + T4 + T5) used for noise subspace matrix $\mathbf{E}_n$ estimation.
- It was expected that if there are some hard NLOS propagation conditions between Tx and Rx antennas in observation time interval used for self-localization, proposed direct self-localization should be is still robust to its existence, especially if number of Tx antennas is large. But self-localization by the use T5 interval with Tx1-Rx1 NLOS, give estimated location of the Rx1 antenna on the position of sidelobe. That is result of a kind of system ambiguity, related to the assumption that the same UWB signal is simultaneously transmitted from all Tx antennas. That kind of ambiguity is also contained in ambiguity function. What is possible solution to that problem? Instead of transmitting the same UWB signal from all antennas, UWB signal with different starting phases (or different UWB signals) should be transmitted simultaneously from different antennas. This modification offers an opportunity to find a solution to the problem of identification and mitigation of NLOS effects in such a UWB system.
- If hard NLOS between some Tx and Rx antenna can be identified, then corresponding components of signal vectors should be omitted in formulation of signal vector $\mathbf{a}$, and direct self-localization will provide right position estimation. Of course, if we want to estimate location in 3D space, then at least 4 LOS components have to be present.
- If soft NLOS propagation can be modeled, than signal vector for such a NLOS component can be formulated, and MUSIC method should be extended for NLOS environment. But there is a problem related to the modeling of such a NLOS propagation and to its statistical nature.

5 References


[26] Ismail Guvenc, Chia-Chin Chong, and Fujiyo Watanabe “ NLOS Identification and Mitigation for UWB Localization Systems”


