International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:11, No:1, 2017

Reliable Line-of-Sight and Non-Line-of-Sight Propagation Channel Identification in Ultra-Wideband Wireless Networks

Mohamed Adnan Landolsi, Ali F. Almutairi

***Abstract*—**The paper addresses the problem of line-of-sight (LOS) vs. non-line-of-sight (NLOS) propagation link identification in ultra-wideband (UWB) wireless networks, which is necessary for improving the accuracy of radiolocation and positioning applications. A LOS/NLOS likelihood hypothesis testing approach is applied based on exploiting distinctive statistical features of the channel impulse response (CIR) using parameters related to the "skewness" of the CIR and its root mean square (RMS) delay spread. A log-normal fit is presented for the probability densities of the CIR parameters. Simulation results show that different environments (residential, office, outdoor, etc.) have measurable differences in their CIR parameters' statistics, which is then exploited in determining the nature of the propagation channels. Correct LOS/NLOS channel identification rates exceeding 90% are shown to be achievable for most types of environments. Additional improvement is also obtained by combining both CIR skewness and RMS delay statistics.

***Keywords*—**Ultra-wideband, propagation, line-of-sight, non-line-of-sight, identification.

I. Introduction

UWB communication technology is finding widespread use in wireless sensor networks (WSN) due to its ability to support important applications such as precise ranging and localization, which is mainly due to the impulse-like, high-resolution signaling waveforms that characterize UWB signals [1]. As such, many techniques based on processing time-of-arrival (TOA) and time-difference-of-arrival (TDOA) data from multiple receiving nodes have been widely adopted for UWB sensor positioning in WSNs, and found to perform well, especially when direct un-obstructed LOS links are present [1], [2]. Other methods based on angle-of-arrival (AOA) and received signal strength (RSS) have also been proposed, but have limitations related to complex array processing requirements and largely varying radio channel fading conditions [3], [4].

A major challenge that limits the accuracy of time-based positioning algorithms is related to the presence of NLOS propagation channels, which introduces a bias in the timing data. It is therefore important to identify such links and in order to apply proper NLOS bias mitigation techniques, and this has been the subject of many recent works [5]-[7]. In particular, the proper characterization of the UWB multipath channel power delay profile provides a useful mean for identifying NLOS propagation links and improving the localization accuracy. It is indeed possible to exploit certain statistical parameters derived from the channel response amplitude and delay information to determine the channel type [8]-[11]. For example, the kurtosis of the CIR magnitude samples (defined as the ratio of the 4th central moment of the data samples to its squared variance) was considered in [8]-[10], and found to have distinct ranges depending on the LOS/ NLOS conditions and the nature of environment. Likewise, the delay spread of the CIR provides information that can discern between LOS and NLOS links [9]-[11]. However, for certain cases such as indoor residential environments, these parameters do not always achieve a very high correct identification rate.

In this work, we consider a classification parameter based on the "skewness" factor (SKW) of the CIR, which is given by the ratio of the 3rd central moment of the amplitude samples sequence to the 3rd power of its standard deviation. The skewness can be easily computed and is found to provide highly reliable identification of LOS/NLOS conditions in nearly all environments. In addition, CIR delay information captured by the root mean square delay (RMSD) is also found to yield additional performance improvement when combined with the SKW factor.

We consider various UWB channel profiles in typical deployment scenarios such as residential & office indoors, outdoors and industrial sites, all based on the standard UWB channel models defined by IEEE 802.15.4a [12], [13]. Through simulations, the statistics of the SKW and RMSD parameters are extracted and shown to closely fit lognormal distributions, as was also observed with similar parameters in [10], [11]. Using these closed-form probability distribution models, a likelihood hypothesis test is then applied for the classification of a given CIR realization as LOS or NLOS. Several numerical results are presented to demonstrate the viability of the proposed LOS/NLOS identification technique under various conditions.

M. A. Landolsi is with the Electrical Engineering Dept, Kuwait University, Khalidya, Kuwait (phone: +965-2498-7701; fax: +965-2481-6467; e-mail: a.landolsi@ku.edu.kw).

A. F. Almutairi is with the Electrical Engineering Dept, Kuwait University, Khalidya, Kuwait (e-mail: ali.almut@ku.edu.kw).

The rest of the paper is organized as follows: The UWB CIR characteristics are introduced in Section II. Section III presents the statistics of the skewness and delay spread parameters. In Section IV, LOS/NLOS classification with likelihood ratio tests for various channel profiles is discussed, and numerical results presented to quantify the viability of the proposed techniques. Final conclusions are given in Section V.

II. UWB CIR Characterization

We consider a discrete-time, multi-tap CIR based on the common Saleh-Valenzuela model widely adopted for UWB wireless propagation scenarios [12]. The complex baseband response is typically represented by multi-clustered path arrivals with decaying power delay profiles:

$$h(t) = \sum_{l=1}^{L} \sum_{k=1}^{K} a_{k,l} \exp\left(j\theta_{k,l}\right) \delta[t - T_l - \tau_{k,l}] \quad (1)$$

where L is the number of separate arriving clusters, K is the number of resolvable multi-paths within each cluster, $a_{k,l}$ is the path gain of the k-th component in the l-th cluster, $\theta_{k,l}$ is its uniformly distributed phase, T_l is the l-th cluster arrival time, and $\tau_{k,l}$ is the delay of the k-th component within the l-th cluster, and $\delta(.)$ the Dirac impulse function. The number of clusters is modeled by a Poisson probability density function (PDF) with mean value $\bar{L}$:

$$p_L(L) = (\bar{L})^L \exp(-\bar{L})\,/L! \quad (2)$$

It follows that the inter-cluster arrival times are exponentially distributed with mean arrival rate Λ_l

$$p(T_l|T_{l-1}) = \Lambda_l \exp[\Lambda_l(T_l - T_{l-1})] \quad (3)$$

The intra-cluster arrivals are modeled by a mixture Poisson PDF with rates λ_1 and λ_2 according to:

$$p\left(\tau_{k,l}\middle|\tau_{k-1,l}\right) = \beta\ \lambda_1 \exp\left[-\lambda_1\left(\tau_{k,l} - \tau_{k-1,l}\right)\right] + (1 - \beta)\lambda_2 \exp\left[-\lambda_2\left(\tau_{k,l} - \tau_{k-1,l}\right)\right] \quad (4)$$

where β is the mixture probability. On the other hand, the cluster multipath power profile is given by Nakagami-m distributed path gains, with PDF:

$$p_{a_{k,l}}(a) = \frac{2m^m a^{2m-1}}{\Gamma(m)\Omega_{k,l}^m} \exp\left(-\frac{ma^2}{\Omega_{k,l}}\right) \quad (5)$$

where $\Gamma(.)$ is the Gamma function and $\Omega_{k,l}^m$ is the average k-th path gain within the l-th cluster, assumed to follow an exponentially decaying profile:

$$E\left[\Omega_{k,l}^2\right] \propto \Omega_l \exp(-\tau_{k,l}/\gamma_l) \quad (6)$$

with Ω_l denoting the l-th cluster total power and γ_l the intra-cluster power decay constant.

The different parameters defining the above model (with proper adjustments) are discussed in [12], [13] for typical deployment environments, and numerical values validated by extensive experimental results are tabulated therein. For our purpose, details are omitted here for brevity, and we mainly use the general S-V model parameters with MATLAB simulation [13] to generate a large number of realizations for typical scenarios in order to extract the relevant CIR parameters of interest as discussed previously (skewness and RMS delay). In total, eight types of channel profiles defined by the IEEE 802.15.4a channel models [12], [13] and designated by CM1 through CM8, where the odd-numbered (CM1, CM3, CM5, and CM7) represent LOS links, and the even-numbered (CM2, CM4, CM6 and CM8) are NLOS ones. More specifically, CM1 & CM2 are for residential indoors, CM3 & CM4 correspond to office premises, CM5 & CM6 apply to open outdoors; and CM7 & CM8 are for industrial sites. As an illustration, a typical realization for the CM1 LOS CIR profile is shown in Fig. 1.

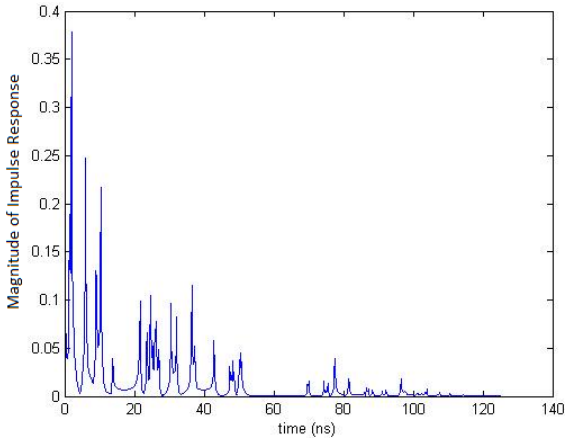

Fig. 1 A typical UWB CIR profile: Example shown for CM1-Residential Indoor, LOS link

III. Skewness and RMS Delay Statistics

To proceed with the LOS/NLOS UWB parametric channel identification, the PDFs for both LOS/NLOS links (in a given environment) were obtained from normalized histograms with up to 1000 CIR realizations. In addition, in order to obtain mathematically tractable results, a PDF fitting using lognormal models was adopted for the statistics of the CIR skewness m_{SKW} and RMS delay spread τ_{RMSD}, which will greatly simplify the likelihood classification tests, as will be discussed subsequently. As noted previously, for a given CIR realization $h(t)$, the skewness parameter is defined by:

$$m_{SKW} = \frac{E[(|h(t)| - \mu_{|h|})^3]}{(E[(|h(t)| - \mu_{|h|})^2])^{3/2}} \quad (7)$$

while the RMS delay is given by:

$$\tau_{RMS} = \frac{\int_0^\infty (t - \tau_m)^2 |h(t)|^2 dt}{\int_0^\infty |h(t)|^2 dt} \quad (8)$$

with τ_m denoting the mean excess delay:

$$\tau_m = \frac{\int_0^\infty t\,h(t)|^2 dt}{\int_0^\infty |h(t)|^2 dt}$$

To model the statistics of these parameters, we adopt the well-known lognormal PDF model [10], given by:

$$p(x) = \frac{1}{x\sqrt{2\pi}\sigma_x}\exp\left[-\frac{(ln(x)-\mu_x)^2}{2\sigma_x^2}\right] \quad (9)$$

where μ_x and σ_x are the mean and standard deviation of ln(x), respectively. The relevant parameters of the lognormal PDFs for each channel type are given in Table I. As an example, to illustrate the suitability of this model, the experimental PDFs (normalized histograms) and lognormal ones for channel models CM1 and CM2 (residential indoor LOS and NLOS) are shown in Fig. 2, and it is clearly seen that a very good match is verified. Similar conclusions were also observed with the other channel models as well.

TABLE I
LOG-NORMAL PDF MODEL PARAMETERS

Parameters / Channels	μ_{SKW}	σ_{SKW}	μ_{RMSD}	σ_{RMSD}
CM1	2.426	0.299	2.771	0.294
CM2	1.795	0.229	3.016	0.208
CM3	2.196	0.247	2.276	0.372
CM4	1.241	0.221	2.544	0.141
CM5	3.784	0.225	2.348	0.788
CM6	2.198	0.225	4.259	0.417
CM7	3.029	0.559	2.972	0.767
CM8	0.920	0.118	4.457	0.021

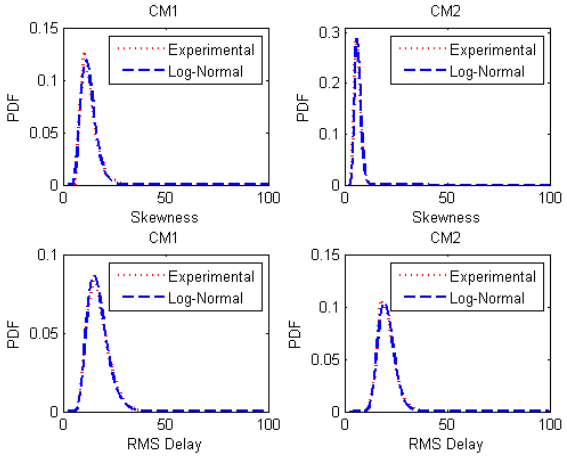

Fig. 2 Close match between experimental and lognormal PDFs

With the highlighted approach, we can then reliably model the PDFs of the CIR parameters by closed-form lognormal PDFs, and this was done under LOS/NLOS conditions for all channel models CM1 to CM8. The results are shown for skewness and RMS delay in Figs. 3 and 4, respectively. It can be seen that there are clear differences between the PDFs under LOS and NLOS conditions, and this can be exploited to identify the CIR type reliably, as discussed next. For example, it is noted that LOS links consistently demonstrate lager skewness ranges compared to NLOS ones. On the other hand, the RMS delay tends to be larger for NLOS links, although the distinction is a bit blurred for CM1&CM2, and CM3&CM4 environments (which will affect the identification accuracy, as reported in the numerical results).

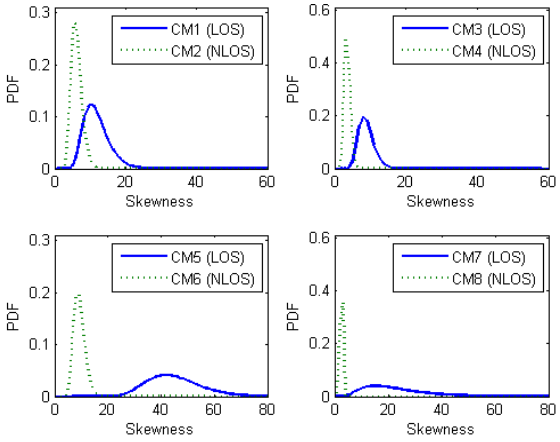

Fig. 3 PDFs of the skewness parameter for LOS & NLOS links

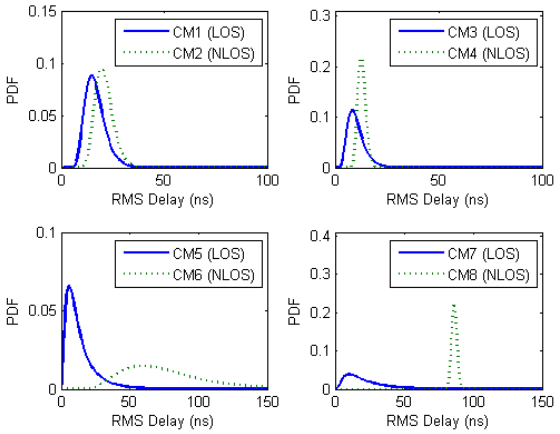

Fig. 4 PDFs of the RMS delay parameter for LOS & NLOS links

IV. LOS/NLOS Numerical Classification Results

LOS/NLOS classification can be performed based on the classical binary hypothesis likelihood ratio test (LRT) from detection theory [14], implemented as follows. With the known LOS/NLOS PDFs, and for a measured CIR realization of unknown type in a given environment (e.g., office, outdoors, etc.), the CIR SKW and RMSD parameters are computed and used for the evaluation of the PDFs to get the LRT. From known detection theory principles [14], if the LRT is larger than 1, the LOS hypothesis (H_0) is chosen. Otherwise, the NLOS hypothesis (H_1) is selected instead, i.e.:

$$\frac{P_{SKW}^{(LOS)}(m_{SKW})}{P_{SKW}^{(NLOS)}(m_{SKW})} \underset{H_1}{\overset{H_0}{\gtrless}} 1 \quad (10)$$

$$\frac{P_{RMSD}^{(LOS)}(\tau_{RMS})}{P_{RMSD}^{(NLOS)}(\tau_{RMS})} \underset{H_1}{\overset{H_0}{\gtrless}} 1 \quad (11)$$

With the aid the LRTs, simulation runs for each channel type were carried out to estimate the accuracy (percentage) of the LOS/NLOS identification procedure, presented in Table II.

It is also possible to use a "joint" LRT decision [10] by multiplying the ratios in (10) & (11), which implicitly assumes independence of the skewness and RMSD parameters, an assumption that was supported by the low correlation of the two parameters that was verified numerically.

TABLE II
CORRECT LOS/NLOS IDENTIFICATION RATES

Channels \ Parameters	SKW	RMSD	JOINT
CM1	82.3%	60.5%	83.4%
CM2	88.9%	81.6%	90.2%
CM3	98.6%	65.1%	98.3%
CM4	95.9%	90.7%	96.7%
CM5	99.8%	93.3%	99.9%
CM6	99.6%	96.4%	99.8%
CM7	99.9%	99.7%	99.9%
CM8	99.1%	99.9%	99.6%

From the above results, it is clearly observed that highly reliable LOS/NLOS link classification is feasible. Indeed, for all cases, except CM1 (with SKW) and CM1-3 (with RMSD), correct identification rates above the 90% range are always achieved, and for many cases, rates exceed 95% correct identification, especially for outdoor/industrial sites.

As noted previously, the performance of the SKW parameter is superior, especially for CM 1-4, as the RMSD PDFs under LOS/NLOS have a more pronounced overlap, which hinders their correct identification. It is finally noted that the use of the joint LRT criterion adds small incremental improvements to the correct identification rates as well.

V. Conclusion

The paper dealt with LOS/NLOS link identification in UWB networks for the purpose of improving localization capability in WSN. A parametric approach was developed using the statistics of the CIR skewness and RMSD spread parameters, found to exhibit noticeable differences under LOS and NLOS conditions. A close fit with lognormal PDFs was proposed for the statistics of the two parameters, and later used with a likelihood ratio hypothesis test to identify the LOS/NLOS nature of the CIR observations. Numerical results showed that very good identification rates in excess of 90% accuracy were achievable for different channel models. The joint use of the skewness and RMS delay also yielded slightly better identification capability as well. Further extensions to this work may consider the application of the demonstrated reliable classification capability to mitigate the errors introduced by NLOS-biased timing data in TOA localization and ranging applications.

Acknowledgment

This work is supported by a grant from Kuwait University Research Sector, under Project No. EE01/15.

References

[1] M. Benedetto *et. al*., "UWB communication systems: a comprehensive overview," *EURASIP Book Series on Signal Processing and Communications*, vol.5, 2006, pp. 5-25.
[2] Z. Sahinoglu, S. Gezici and I. Guvenc, *Ultra-Wideband Positioning Systems: Theoretical Limits, Ranging Algorithms and Protocols*, CA: Cambridge University Press, 2008.
[3] H. Soganci, S. Gezici, H. Poor, "Accurate positioning in ultra-wideband systems," *IEEE Wireless Comm.*, vol.18, no.2, Feb. 2011, pp.19-27.
[4] I. Guvenc and C. Chong, "A Survey on TOA-based wireless localization and NLOS mitigation techniques," *IEEE Comm. Surveys & Tutorials*, vol.11, no.3, March 2009, pp. 107-124.
[5] A. Abbasi and H. Liu, "Improved line-of-sight/non-line-of-sight classification methods for pulsed ultra-wideband localization," *IET Communications*, vol. 8, no. 5, May 2014, pp. 680–688.
[6] S. Venkatesh and R. Buehrer, "Non-line-of-sight identification in ultra-wideband systems based on received signal statistics," *IET Microwaves, Antennas and Propagation*, vol. 1, no. 6, June 2012, pp. 1120-1130.
[7] J. Khodjaev, Y. Park and A. Malik, "Survey of NLOS identification and error mitigation problems in UWB-based positioning algorithms for dense environments," *Annals of Telecom*, vol.65, 2010, pp. 301-311.
[8] J. Zhang, J. Salmi, and E. S. Lohan, "Analysis of Kurtosis-based LOS/NLOS identification using indoor MIMO channel measurements," *IEEE Trans. on Vehic. Tech*., vol. 62, no.7, July 2013, pp.2871-2874.
[9] L. Mucchi, and P. Marcocci, "A new parameter for UWB indoor channel profile identification," *IEEE Trans. Wireless Comm.*, vol. 8, Aug 2009, pp. 1597-1602.
[10] I. Guvenc, C.-C. Chong, F. Watanabe and H. Inomura, "NLOS identification and weighted least-square localization for UWB systems using multipath channel statistics", *EURASIP Jour. Adv. Signal Proc.*, vol.2008, Article ID 271984.
[11] A. Muqaibel, M.A. Landolsi, and N. Mahmoud, "Practical evaluation of NLOS/LOS parametric classification in UWB channels," *Proc. of Int. Conf. Com., Sig. Proc. App*., DOI 10.1109/ICCSPA.2013.6487304.
[12] A. Molisch, "Ultra-wide-band propagation channels", *Proceedings of the IEEE*, vol.97, no.2, Feb. 2009, pp. 353-371.
[13] A. Molish, K. Balakrishnan, C.-C. Chong, S. Emami, A. Fort, J. Karedal, H. Schantz, U. Schuster, and K. Siwiak, "IEEE 802.15.4a channel model-final report," *Tech. Rep*., *Environments*, vol. 15, Sep. 2005, pp. 1-40.
[14] S. M. Kay, *Fundamentals of Statistical Signal Processing, Vol. II: Detection Theory*, Upper Saddle River, NJ: Prentice-Hall, 1998.