UWB Interferometry TDOA Estimation for 60 GHz OFDM Communication Systems

Ahmadreza Jafari, Theodoros Mavridis, Luca Petrillo, Julien Sarrazin, Michael Peter, Wilhem Keusgen, Philippe de Doncker, Aziz Benlarbi-Delai

UWB Interferometry TDOA Estimation for 60 GHz OFDM Communication Systems

Ahmadreza Jafari, Theodoros Mavridis, *Student Member IEEE*, Luca Petrillo, Julien Sarrazin, *Member IEEE*, Michael Peter, Wilhelm Keusgen, Phillipe De Doncker, and Aziz Benlarbi-Delai

***Abstract*—A simple technique to estimate the Time Difference of Arrival (TDOA) that necessitates only one reference device to perform 1D positioning of a mobile device is presented. Using a Multiple Input Single Output (MISO) system, this interferometric technique uses ultra wide-band signals and is particularly well suited for 60 GHz OFDM communications. The accuracy of the technique is assessed by simulation, using the IEEE 802.11ad channel, as well as by measurement.**

***Index Terms*—60 GHz, TDOA estimation, Interferometry, Localization, UWB OFDM.**

I. Introduction

In the coming years, home wireless systems are expected to provide multi-gigabyte data rates, thus replacing cables for indoor communications. Wide-band communications using complex modulations such as OFDM (Orthogonal Frequency Division Multiplexing) are used more and more in short-range applications such as video streaming, wireless USB, etc. In addition, the popularization of smart phones and tablets causes the ever growing traffic explosion in mobile communications. This fact has recently drawn increased attention to utilize higher frequency like millimeter wave bands [1], [2], [3].

Among different millimeter wave solutions, a license free bandwidth of at least 5 GHz is available at 60 GHz. Ultra-high-speed systems using 60 GHz communications such as WiGig and 802.11ad have been therefore standardized. In addition, due to the higher path loss at 60 GHz, it is possible to reuse this frequency in short range applications. In this context, beamforming techniques are considered in order to increase the link budget of such millimeter-wave communications. Therefore, in order to determine the beam's direction, base stations could use positioning techniques. For that purpose, an optimized localization method, well suited for indoor applications, benefiting from the large bandwidth available at 60 GHz is proposed.

Among different wireless indoor positioning techniques, this paper focuses on time difference of arrival (TDOA) estimation because of its high precision in wireless indoor applications. In addition, the synchronization of reference devices (RD) and mobile device (MD) is not necessary in this technique.

Contrary to classical TDOA methods, only one RD is used in the proposed technique. The RD embeds a dual-antenna system to perform 1D localization. The MD estimates the TDOA using interferences in the received power spectrum, readily available from the OFDM channel estimator. This approach allows to perform localization and data transmission simultaneously without adding much complexity compared to existing systems.

The paper is organized as follows: in section II, theory of the proposed approach is presented. In section III, implementation of TDOA estimation and estimation's errors are investigated by simulation considering the IEEE 802.11.ad channel. In section IV, experimental measurements results and some considerations due to real environment are presented. Finally, section V concludes the paper and presents the perspectives of this approach.

II. Theory: direct problem

A. Configuration

A multiple input single output (MISO) system is considered with a dual antenna system at RD and the nature of received spectrum at MD is studied. The configuration of the proposed method is shown in Fig. 1. As presented, only one single RD is used to implement the TDOA estimation.

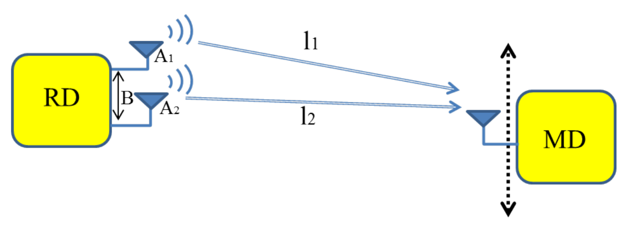


Fig. 1: Proposed TDOA estimation set-up.

This configuration involves naturally a limited baseline (the distance between two antennas at RD) that will ultimately impacts the TDOA estimation accuracy. However, by taking benefit of the huge bandwidth available at 60 GHz, it will be shown in section III and IV that acceptable accuracy can still be obtained.

The dual antenna system transmits the same signal provided by a unique source in the RD. The TDOA can be extracted by observing the spectrum of the received interfered signal based on frequency domain interferometry [4]. This received

A. Jafari, J. Sarrazin and A. Benlarbi-Delai are with L2E Dept., Sorbonne Universites, UPMC Univ Paris 06, UR2, L2E, F-75005, Paris, France e-mail: (ahmadreza.jafari@etu.upmc.fr; julien.sarrazin@upmc.fr; aziz.benlarbi_delai@umpc.fr)

T. Mavridis, L. Petrillo and P. De Doncker are with OPERA Dpt. - Wireless Communications Group, Universite Libre de Bruxelles (ULB), B-1050 Brussels, Belgium e-mail: (tmavridi@ulb.ac.be ; lpetrillo@ulb.ac.be ; pdedonck@ulb.ac.be)

M. Peter and W. Keusgen are with Wireless communications Group, Fraunhofer HHI, Berlin, Germany.

spectrum exhibits a periodic shape and the periodicity is related to the TDOA as explained in the following section. Consequently, not only a single RD is required with this technique, but also only a single front-end is necessary at the RD, the signal being splited into two antennas.

It should be mentioned that a single input multiple output (SIMO) system can also be used to perform this technique (with a dual antenna system at MD), which is completely reciprocal. In this paper, a MISO system is chosen in order to have the added complexity only at the RD.

B. OFDM signal-based interferometry

In the frame of IEEE 802.11ad standard, A_1 and A_2 transmit the same OFDM 60 GHz signal with a sampling frequency F_s, N sub-carriers and M data sub-carriers. A delay τ_p is applied between A_1 and A_2 as suggested in [5], to be able to extract the TDOA even in cases for which the defined bandwidth is not enough for visualizing periodicity in the received interfered spectrum or in the case that the TDOA tends to zero. If $x(t)$ is the baseband complex envelope (CE) signal and, $x_{RF}(t)$, the RF representation of the transmitted signal, following equations are obtained [6], [7]:

$$x(t) = \sum_{k=-N/2}^{N/2-1} c_k e^{i2\pi k F_s t/N} = \sum_{k=-M/2}^{M/2-1} c_k e^{i2\pi k F_s t/N} \quad (1)$$

and

$$x_{RF}(t) = \Re\left(x(t)e^{i2\pi F_{RF} t}\right) \quad (2)$$

where $\Re$ is the real part operator, c_k are complex coefficients, with k the carrier index and F_{RF} the RF frequency. Calling channel gains between A_1 and MD, and A_2 and MD, h_1 and h_2, respectively, the time invariant channel impulse responses in the CE domain for the two different delays of propagation, τ_1 and τ_2, are [8]:

$$h_1(t) = h_1 e^{-i2\pi F_{RF}\tau_1}\delta(t-\tau_1) \quad (3)$$

and

$$h_2(t) = h_2 e^{-i2\pi F_{RF}(\tau_2+\tau_p)}\delta(t-\tau_2-\tau_p) \quad (4)$$

where δ is the Dirac function. Then, the received signal at MD, $y(t) = x(t) \otimes h(t)$ in CE domain is equal to:

$$y(t) = h_1 x(t-\tau_1)e^{-i2\pi F_{RF}\tau_1} + h_2 x(t-\tau_2-\tau_p)e^{-i2\pi F_{RF}(\tau_2+\tau_p)} \quad (5)$$

The two antennas at RD being relatively close to each other, a perfect LOS scenario is assumed. Consequently, $h_2 = h_1$ is considered as a first approximation. Assuming that $\tau = \tau_p + \tau_2 - \tau_1$, the received signal in the frequency domain can be presented as follows:

$$Y(f) = h_1 \sum_{k=-M/2}^{M/2} c_k \delta(f - kF_s/N) e^{-i2\pi(kF_s/N+F_{RF})(\tau_2+\tau_p-\tau)} \times 2e^{-i\pi(kF_s/N+F_{RF})\tau} cos(\pi(kF_s/N + F_{RF})\tau) \quad (6)$$

From equation (6), it can be inferred that the envelope of received signal spectrum is periodic with a cosine variation and the periodicity is directly related to τ. Knowing the value of τ_p, TDOA can be easily derived by this approach. In order to be able to estimate the periodicity with a reasonable accuracy at least one and a half period in the bandwidth is required. As an example, for a 16 cm baseline and 2 GHz bandwidth, the optimum value of τ_p is equal to 1283 ps to ensure at least one and a half period in the bandwidth.

As mentioned before, this work is in the context of indoor high data rate communication, where OFDM techniques are commonly applied. In order to mitigate multipath effects, OFDM based systems estimate the equivalent channel response using a cyclic-prefix, zero padding or Golay codes to perform an equalization [9]. Thus, the equivalent channel response is readily available in OFDM systems and our method can directly benefits from this data in order to estimate the TDOA. The added complexity remains therefore limited.

III. IMPLEMENTATION: INVERSE PROBLEM

The new proposed method is evaluated by performing simulations considering the IEEE 802.11.ad channel. It should be mentioned that communication aspects are not studied in this section and only the channel is explored to validate the proposed approach. In other words, the channel estimator of the OFDM scheme is supposed to be perfect. Simulation by ray tracing combined with the statistical definition of intra-cluster paths is used to generate the channel model [10]. A 2 GHz bandwidth, which corresponds to IEEE 802.11ad standard, and a conference room with a dimension of 10*10*3 m^3 are considered for simulations. The reference device is placed at the center of the room at a height of 1.5 m. Different positions for MD have been considered: 1 to 5 m range differences from the RD and an angle θ varying from 0 to 90° ($TDOA > 0$) and from 0 to $-90°$ ($TDOA < 0$), as shown in Fig. 2.

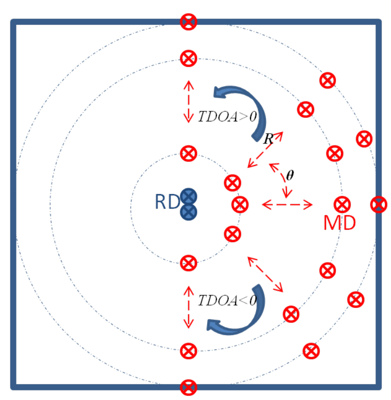
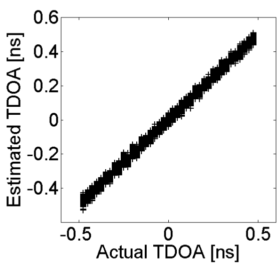


Fig. 2: RD at the center of room and schematic of different positions of MD.

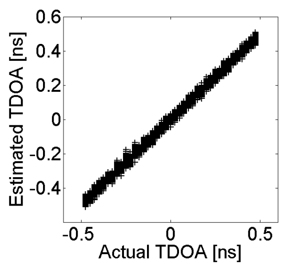
For each configuration, the channel impulse response between A_1 and MD is calculated, then the same calculation is done between MD and A_2 considering a delay shift in order to apply τ_p. Then the two channel impulse responses are added together and the frequency response of the whole MISO channel is calculated by applying the Fourier transformation. The envelope of the resulted channel is then fitted by applying the non linear least square (NLS) method. To solve the problem, the Levenberg-Marquardt algorithm is then used.

Simulations for different locations of MD are conducted. Throughout the simulation study, the baseline is set at 16 cm, $\tau_p = 1283$ ns is considered and an SNR of 10 dB is defined at the receiver by adding an additive white gaussian noise to the frequency response of the two added channels. Estimated TDOA are compared to actual ones that are geometrically determined. In Fig. 3, estimated TDOA values are compared to actual TDOA values. Results are ordered according to the radial distance R between RD and MD. Fig. 3a, 3b, and 3c show results for R=1 m , R=3 m, and R=5 m, respectively. The different TDOA values are obtained by varying the angle θ according to Fig. 2. For each location (so for each TDOA under consideration), 500 simulations are performed since noise and channel's clusters parameters follow statistical laws.

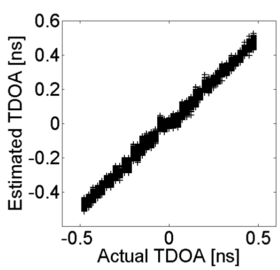
In Fig. 3a, estimated TDOA values are reasonably close to actual TDOA values.



(a) R=1 m.



(b) R=3 m.



(c) R=5 m.

Fig. 3: Estimation errors for different R, Baseline=16 cm.

Fig. 3b and Fig. 3c show approximately the same results for the TX-RX distance of R=3 and R=5 m, but with higher value of mean error and variance for the case of R=5 m. This is due to higher influence of multipaths for these positions that are closer to the walls. This assumption has been validated by calculating the Ricean factor K, and it has been found that the average K for R=5 m is 6.4 dB, whereas for R=1 m, it is 16.6 dB and for R=3 m it is 9.8 dB. The obtained values are summarized in Table. I.

	R=1 m	**R=5 m**
Average error in time domain	4.3 ps	10 ps
Spatial domain RMSE	3.8 cm	23 cm

TABLE I: Average error in time domain and spatial domain.

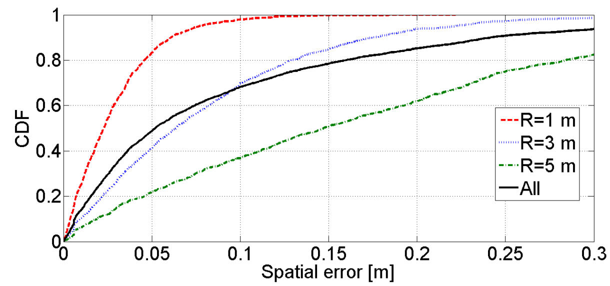


Fig. 4: CDF of estimation errors in spatial domain for different R, Baseline=16 cm, $\tau_p = 1283$ ns.

The cumulative distribution functions (CDF) of estimation errors in spatial domain are presented in Fig. 4 for R=1 m, R=3 m, R=5 m, and all R values respectively. The CDF represents the probability that the spatial error is less than the given threshold presented in x-axis. To obtain these results, the spatial locations considered in Fig. 3 are taken into account. As shown in Fig. 4, for R=1 m, the spatial error is below 10 cm for 97 % of cases whereas cases with R=3 and R=5 show higher values of errors. For R=3 m and R=5 m, errors are less than 15 cm and 30 cm for 80 % of cases respectively. Consequently, it can be seen that the proposed method allows performing localization with a decent accuracy. The CDF of all spatial errors for all R values is also presented in Fig. 4. It is shown that for 80 % of the cases (considering different R from 1 m to 5 m), the spatial error is less than 17.5 cm.

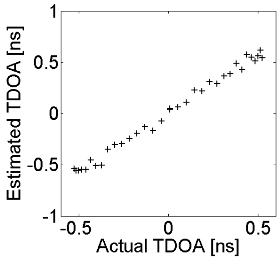
IV. Experimental measurements

To validate the theory and simulation results, measurements using a VNA are conducted as illustrated in Fig. 5. A 2 GHz bandwidth is considered at 60 GHz. To be able to use longer cables to cover distances up to 2.5 m, RD and MD are connected to a Rohde Schwarz ZVA24 via a frequency extension to measure the forward transmission scattering parameters (S21). A special configuration is considered to obtain the output at 60 GHz, as mentioned in [11].

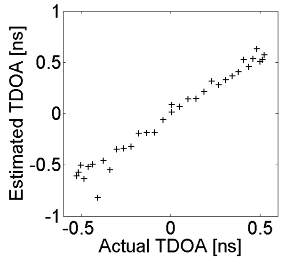
Different positions of the mobile device are considered in a lobby. 256 points are recorded in the 2 GHz bandwidth for each measurement.

Fig. 6 shows estimated TDOA value results, considering $\tau_p = 1300$ ps and changing the position of MD from RD with

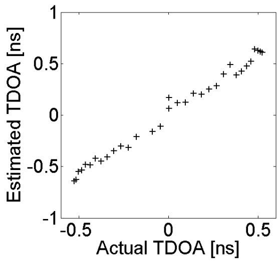
Fig. 5: VNA-based measurement set-up.



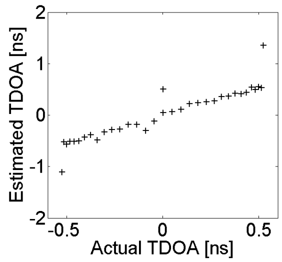
(a) R=1 m.



(b) R=1.5 m.



(c) R=2 m.



(d) R=2.5 m.

Fig. 6: VNA measurements results, baseline=16 cm.

	R=1 m	**R=1.5 m**	**R=2 m**	**R=2.5 m**
Average error	0.18 m	0.31 m	0.44 m	0.61 m
RMSE	0.25 m	0.44 m	0.6 m	1.14 m

TABLE II: Average error in spatial domain and RMSE.

range differences of 1 m and 2.5 m and with θ varying from $-90°$ to $90°$ for each case. Obtained results are summarized in Table II and follow a similar behavior than simulation ones, errors being larger when R is larger. However, positioning accuracy is less than in simulation. Additional errors are due to the mixer phase noise, non-linearity of the amplifiers, etc. Also, the reference positions are a source of errors as they have been measured manually while changing the position of the MD. At the largest distance R = 2.5 m, the average error is 61 cm. From the RD point of view, that corresponds to an angle of about $14°$. So when beamforming occurs at the RD after the localization process, if the beamwidth were of that order or less, this accuracy would not be acceptable. At 60 GHz, arrays can reach high directivity with a limited physical size. For instance in [12], a 16x16-element array exhibits a beamwidth of $4°$ and a 30 dB gain with a size of approximately 6x7 cm^2. Consequently, although the proposed approach is interesting to offer a localization functionality with a limited added complexity, it could be limited to moderate directivity antenna systems only (such as the $30°$-aperture 15 dB-gain 4x4 array presented in [13]), unless some appropriate post-processing could significantly increase the accuracy.

V. Conclusion

In this paper, a new method for estimating the TDOA particularly well suited for communication systems in indoor applications operating at 60 GHz and using UWB OFDM signals is presented. It is shown that even by considering the IEEE.802.11ad channel in the hypothesis of LOS scenario, it is possible to estimate a 1D position of a mobile device using the new proposed approach. Only one reference device is used and interferometry technique is applied to estimate the TDOA. To obtain an estimation with a good precision, NLS method is used. This technique, contrary to classic TDOA measurements, has the advantage of implementing the localization and the communication in a simultaneous way. For future works, the same approach may be explored in outdoor environment regarding the recent advance in 5G mobile networks, where beamforming is considered for millimeter-wave communications in small cells. Low complexity positioning techniques would be valuable to determine beam's directions.

References

[1] C.J. Hansen; Wigig: "Multi-gigabit wireless communications in the 60 GHz band", IEEE Wireless Communications, vol. 18, no. 6, pp. 6-7, 2011.

[2] T. Baykas, Chin-Sean Sum, Zhou Lan, Junyi Wang, M.A. Rahman, H. Harada, and S. Kato; "IEEE 802.15.3c: the first IEEE wireless standard for data rates over 1 gb/s", IEEE Communications Magazine, vol. 49, no. 7, pp. 114-121, July 2011.

[3] S. Yong and C. Chong; "An overview of multigigabit wireless through millimeter wave technology: Potentials and technical challenges", EURASIP Journal on Wireless Communications and Networking, 2007(1):078907, 2007.

[4] M. Bocquet, C. Loyez, and A. Benlarbi-Delai; "Using Enhanced-TDOA measurement for indoor positioning", IEEE Microwave and Wireless Components Letters, Vol. 15, no. 10, pp. 61-614, 2005.

[5] K. Panta and J. Armstrong; "Indoor localisation using white leds", Electronics Letters, vol. 48, no. 4, pp. 228-230, 2012.

[6] A. Jafari, L. Petrillo, J. Sarrazin, D. Lautru, P. De Doncker, and A. Benlarbi-Delai; "TDOA estimation method using 60 GHz OFDM spectrum", *International Journal of Microwave and Wireless Technologies*, vol. 7, pp. 31–35, 2 2015.

[7] A. Jafari, J. Sarrazin, D. Lautru, A. Benlarbi-Delai, L. Petrillo, P. De Doncker; "Simultaneous communication and localization for 60 GHz UWB OFDM systems", IEEE Antennas and Propagation Society International Symposium (APSURSI), pp.1948,1949, 7-13 July 2013.

[8] F.P Fontan and P.M Espineira; "Modelling the wireless propagation channel: a simulation approach with MATLAB". Vol. 5. John Wiley and Sons, 2008.

[9] M. Ghosh; "Improved Equalization For Coded, Zero-Padded OFDM (ZP-OFDM) Systems", 2007. ICC '07. IEEE International Conference on communications, pp.4263,4268, 24-28 June 2007.

[10] T. Mavridis, L. Petrillo, P. De Doncker, J. Sarrazin, D. Lautru, A. Benlarbi-Delai; "A 60 GHz Off-Body channel implementation", IEEE Antennas and Propagation Society International Symposium (APSURSI), pp.1786,1787, 7-13 July 2013.

[11] R. Felbecker, W. Keusgen, M. Peter; "Estimation of permitivitty and loss tangent of high frequency materials in the millimeter wave band using a hemispherical open resonator", IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS), pp.1,8, 7-9 Nov. 2011.

[12] Y. Li, K.-M. L., 60-GHz Substrate Integrated Waveguide Fed Cavity-Backed Aperture-Coupled Microstrip Patch Antenna Arrays, IEEE Transactions on Antennas and Propagation, vol.63, no.3, pp.1075-1085, March 2015.

[13] W. Yang, K. Ma, K. Yeo, W. Lim, A Compact High-Performance Patch Antenna Array for 60-GHz Applications, IEEE Antennas and Wireless Propagation Letters, vol.PP, no.99, pp.1-1.