# TWINS: Time-of-flight based Wireless Indoor Navigation System

Maurizio Rea
IMDEA Networks Institute
& University Carlos III of Madrid
Madrid, Spain
maurizio.rea@imdea.org

Héctor Cordobés
IMDEA Networks Institute
Madrid, Spain
hector.cordobes@imdea.org

Domenico Giustiniano
IMDEA Networks Institute
Madrid, Spain
domenico.giustiniano@imdea.org

## ABSTRACT

We introduce TWINS, Time-of-flight based Wireless Indoor Navigation System, that estimates the position of commercial off-the-shelf devices such as smartphones, tablets and laptops using pure commercial off-the-shelf WiFi Access Points in near real-time. TWINS is the result of several years of effort put into research and development. TWINS does not require any inertial sensors on the mobile devices, and it is based on a system that has participated in the 2014 and 2016 MSR Localization Competition editions.

## 1 INTRODUCTION

Systems based on Time-of-Flight (ToF) ranging are gaining momentum in WiFi networks as alternative to traditional SNR-based approaches [1]. These systems use two-way ranging, taking advantage of DATA/ACK traffic exchange. Yet, they come with the inherent difficulties to obtain accurate time measurements with commercial off-the-shelf (COTS) hardware [2, 3]. Work in the literature has also studied the combination of ToF with inertial sensors [4]. This has the drawback of requiring the active intervention of the mobile device (e.g. install an app). Other approaches circumvent time information noise in the estimation of the mobile device position by using time-differential-of-arrival (TDOA), and making the transmitter and the receiver hop across different bands [5]. However, current 802.11 protocols communicate in a single frequency band and TDOA requires a fine syncronization network mechanism.

## 2 TOF-BASED MOBILE TRACKING SYSTEM

In this work, we extend our previous ToF-based localization system that has already participated in the Microsoft Indoor Localization Competition at IEEE/ACM IPSN 2014 and 2016.

Our system is called TWINS, Time-of-flight based Wireless Indoor Navigation System. It uses COTS APs with customized firmware operating in the core of the 802.11 MAC state machine of a low-cost WiFi chipset. TWINS can estimate the position of 802.11 standard-compatible devices, with distance from each AP to mobile targets estimated with ToF ranging measurements and position estimates based on multi-lateration algorithm. The system presented at IEEE/ACM IPSN 2014 and IEEE/ACM IPSN 2016 Microsoft Indoor Localization Competition has been improved as follows:

- new ranging estimation technique;
- improved time scheduling and convergence time of positioning system;
- extensive and controlled tests conducted in the w.iLab.2 testbed[1] of H2020 Wishful Project with Turtlebot II Robotic Platforms acting as mobile nodes [6];
- enhanced backend infrastructure to store the system configuration and data of multiple mobile devices and several bugs fixed.

## 3 IMPLEMENTATION

The APs are equipped with Broadcom WiFi chipsets that run our customized version of the 802.11 openFWWF firmware [3]. Using only MAC-layer features of the 802.11 standard, we measure the ToF and pass the results to the open-source b43 driver running in the AP, where they are prefiltered, and sent to the Central Location Unit (CLU). The CLU computes the mobile position and connects to a database where the results are stored.

### 3.1 Ranging estimation

The ToF range is computed using regular 802.11 Probe Responses sent by the APs and acknowledged by the target device via 802.11 ACKs. We use Probe Responses rather than normal Data as we experimentally observe that the target device replies only to the Data of its associated AP, but not to other APs. In contrast, the target replies reliably to the short Probe Responses sent by any AP, which is a requirement of our positioning system. In this way, ToF ranges can be computed from multiple APs to estimate the mobile position.

In order to estimate the range to the target device on a given instant, we assume that, given $N$ measurements, some of them follows the Line of Sight (LOS) path (or the shortest NLOS path in case the LOS path does not exist), and others have one or more Non Line of Sight (NLOS) paths. For each

[1] http://doc.ilabt.imec.be/ilabt-documentation/

single path, the noise in the measurement is mainly due to the target device [7]. We consider a Gaussian distribution for the noise generated by the target replying with ACKs. Experimental observations of Gaussianity of the single path in controlled environments can be found in [3]. We model the sum of all these multipath components as a *Gaussian Mixture Model (GMM)* [8]. A key aspect of the model is to identify the number of dominant paths (clusters) $\kappa$, which is up to 5 in typical indoor environments [9]. However, as each round contains few ToF measurements per AP (N is in order of 20), fewer clusters are expected. This is confirmed by our experimental observations, where setting a maximum number of clusters equal to 5 increases the probability that the GMM identifies clusters without physical meaning. This, in turn, causes instability in the ranging estimates over time. Therefore, we limit the number of clusters to 3.

We generate all the GMM models for each $\kappa \in \{1, \ldots, 5\}$, by using the iterative Expectation-Maximization (EM) algorithm initialized by a k-means++ run. We infer the optimal $\kappa$ for the GMM statistical model selecting the model with the lowest Akaike Information Criterion (AIC) for the $N$ measurements [10]. We finally consider the mean of each of the $k$ paths. Our estimator rejects the paths with negative means, as they do not correspond to a physical propagation path, and uses the *path with the least positive mean* as ranging estimate.

### 3.2 Position estimation

The system is orchestrated by the CLU, that manages the APs and generates traffic towards target devices. The CLU computes the ranges and positions, and makes data available to location-based applications through a database. The CLU issues measurement rounds to the APs. As APs operate in the same radio channel, measurements are scheduled using a time division approach to minimize network collisions and hidden nodes. This also allows to have a better control of the time slot allocated to the AP. In TWINS, only one AP at each time can measure the ToF to the target devices. A final slot is allocated to drain the measurement queue of all APs.

Measurements are performed by each AP using a modified OpenFWWF firmware. These measurements may be related to different targets, as the system allows the continuous tracking of multiple targets. The CLU receives raw ToF measurements from the APs. After this set of measurements is received, the CLU estimates the distance from each AP to each intended target as explained in Section 3.1. Using the estimated distances, a position-wise suboptimal but computationally efficient Linear Least Squares (LLS) multi-lateration algorithm is used to make an inital position estimate. Then the algorithm makes use the Weighted Non-Linear Least Squares (NLLS) technique to compute the position from this initial value.

The NLSS algorithm is implemented using the Newton-Gauss method with line-search for the step-size. Our implementation takes also into account that as a result of quantization errors in the range estimation divergence problems may occur in the Newton-Gauss method. As such, we perform pre-filtering of the data to remove the side effects of quantization.

## 4 CONTEST SETUP

The APs and the mobile device to be tracked run exclusively on commodity hardware. For the contest, we will deploy our own 802.11 APs which are net5501 embedded machines from Soekris. We will demonstrate the tracking of a mobile device with off-the-shelf components. Experiments are conducted using the 802.11b/g standard in the 2.4 GHz ISM band. The targets can move freely along the exhibition space and remain tracked as long as at least four APs are able to perform ToF measurements to the targets. The installation of the system at the exhibition requires only the placement of the APs at fixed locations.


## ACKNOWLEDGEMENTS

We thank Aymen Fakhreddine for the simulation studies. This work has been funded in part by the European Commission in the framework of the H2020 project WiSHFUL (Grant agreement no. 645274), and in part by the Madrid Regional Government through the TIGRE5-CM program (S2013/ICE-2919)


## REFERENCES


[1] A. Goswami, L. E. Ortiz, and S. R. Das, "Wigem: A learning-based approach for indoor localization," in *CoNEXT '11*. ACM, 2011, pp. 3:1–3:12.

[2] D. Giustiniano and S. Mangold, "CAESAR: Carrier sense-based ranging in off-the-shelf 802.11 wireless lan," in *CoNEXT '11*. ACM, 2011, pp. 10:1–10:12.

[3] M. Rea, A. Fakhreddine, D. Giustiniano, and V. Lenders, "Filtering noisy 802.11 time-of-flight ranging measurements from commoditized wifi radios," *IEEE/ACM Transactions on Networking*, vol. 25, no. 4, pp. 2514–2527, Aug 2017.

[4] A. T. Mariakakis, S. Sen, J. Lee, and K.-H. Kim, "Sail: Single access point-based indoor localization," in *MobiSys '14*. ACM, 2014, pp. 315–328.

[5] J. Xiong, K. Sundaresan, and K. Jamieson, "Tonetrack: Leveraging frequency-agile radios for time-based indoor wireless localization," in *MobiCom '15*. ACM, 2015, pp. 537–549.

[6] "H2020 WiSHFUL project," http://www.wishful-project.eu.

[7] D. Giustiniano, T. Bourchas, M. Bednarek, and V. Lenders, "Deep inspection of the noise in wifi time-of-flight echo techniques," in *MSWiM '15*, 2015, pp. 5–12.

[8] A. Fakhreddine, D. Giustiniano, and V. Lenders, "Data fusion for hybrid and autonomous time-of-flight positioning," in *IPSN*. ACM, 2018.

[9] M. Kotaru, K. Joshi, D. Bharadia, and S. Katti, "Spotfi: Decimeter level localization using wifi," ser. SIGCOMM '15. ACM, 2015, pp. 269–282.

[10] S. Konishi and G. Kitagawa, *Information criteria and statistical modeling*. Springer Science & Business Media, 2008.