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# A Distributed Antenna System for Indoor Accurate WiFi Localization

C. Loyez, M. Bocquet, C. Lethien, and N. Rolland

**Abstract**—Specific infrastructures are a key challenge for indoor geo-localization systems. In particular, an accurate narrowband localization technique using 802.11 g WiFi signals is proposed in this letter. The related system architecture is built on the basis of radio over fiber topology of distributed antennas systems that are increasingly deployed in buildings. In particular, the system proposed collects the microwave signals using remote and local access points linked by 62.5- $\mu\text{m}$  core diameter multimode fibers and enables to determine the location transmitter with an accuracy of less than 6.4 cm.

**Index Terms**—Localization, multimode fiber, radio over fiber.

## I. INTRODUCTION

THE geo-localization systems managed by GPS-based solutions are attractive but exhibit poor performance in indoor environment [1]. Numerous alternative technologies have been investigated but none of them can satisfy the system requirements of performance and cost [2]. For example, location accuracy in the order of a few centimeters using ultra wide band (UWB) signals has been demonstrated but the requirement of single mode fiber (SMF) backbone remains an expensive solution [3].

The combination of existing technologies as much as possible should improve the quality of positioning services. In particular, the radio over fiber topology (RoF) of distributed antennas systems (DAS) are increasingly deployed in buildings [4]. The characteristics of the hardware resources are narrowband multimode fiber (MMF) backbones exploiting 2.45 GHz 802.11 g WiFi signals. In particular, the feasibility of an original geo-localization solution using this technology is proposed in this letter. The principle of operation based on the time difference of arrival (TDOA method and dedicated hardware and software resources are depicted in Section II. Based on the architecture proposed, a proof-of-concept localization system is depicted in Section III. The experimental results are presented in Section IV and demonstrate a location accuracy better than 6.4 cm.

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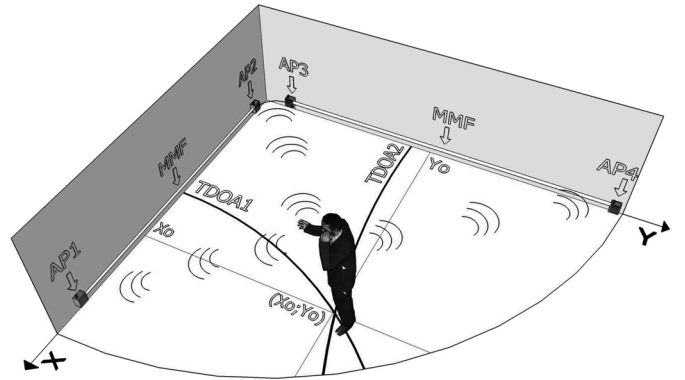


Fig. 1. Overall description of the MMF DAS localization system.

## II. HARDWARE AND SOFTWARE RESOURCES

### A. Localization system

The overall system architecture is given in Fig. 1. The proposed topology acts as a stereoscopic system including remote and local Access Points (APs) linked by 62.5- $\mu\text{m}$  core diameter MMFs [5], [6]. The use of the pre-installed MMF is an original solution to link optically four APs involved in a localization process and which are distributed around the sensing area.

In this configuration, the APs do not perform communications between them. Each AP collects 802.11 g WiFi signals from a transmitter to be localized incoming in the localization area. No synchronization is required between the transmitter and the APs. The APs are organized in two pairs (AP1; AP2) and (AP3; AP4) to determine two different TDOAs (TDOA1 and TDOA2, respectively). For each TDOA value, the locations of the transmitter describe a hyperbola. The estimated location of the transmitter ( $X_o; Y_o$ ) is the crossing of the two hyperbolas issued from the TDOA1 and TDOA2 measurements (Fig. 1). The method is based on the assumption that the first detected waveform results from the line of sight (LOS). Therefore, in contrast with RSS-based localization solutions, the multipath signal contribution can degrade the waveform but does not impact the localization accuracy based on the time of arrival of the first path [7], [8].

### B. Localization Algorithm

The localization algorithm is detailed as follows:

#### Step 1) TDOAs determination

Autocorrelation  $C_{XX}(k)$  performed on the signal issued from a local AP and cross-correlation  $C_{XY}(k)$  involving the local and remote received

signals are calculated according to relations (1) and (2) respectively

$$C_{XX}(k) = \begin{cases} \frac{1}{N} \sum_{n=0}^{N-1-k} x(n) \cdot x(n+k) & 0 \leq k \leq L \\ \frac{1}{N} \sum_{n=0}^{N-1-|k|} x(n) \cdot x(n+k) & -L \leq k < 0 \end{cases} \quad (1)$$

$$C_{XY}(k) = \begin{cases} \frac{1}{N} \sum_{n=0}^{N-1-k} x(n) \cdot y(n+k) & 0 \leq k \leq L \\ \frac{1}{N} \sum_{n=0}^{N-1-|k|} x(n) \cdot y(n+k) & -L \leq k < 0 \end{cases} \quad (2)$$

where  $N$  denotes the number of input samples and  $L$  the number of samples involved in the lag considered between  $X$  (signal received by the local AP) and  $Y$  (signal received by the remote AP), assuming that the maximum value of the TDOA is less than the resulting lag value.

The time difference observed between the maxima of these two correlations, equal to the TDOA value, is given by

$$\text{TDOA} = \text{Delay} [\text{Max}(C_{XX}), \text{Max}(C_{XY})]. \quad (3)$$

#### Step 2) Localization determination

The transmitter is localized using a hyperbolic TDOA algorithm [9].  $R_i$  ( $i = 1, \dots, 4$ ) are the four distances between the transmitter ( $X, Y, Z$ ) and the access points  $AP_i$  ( $X_i, Y_i, Z_i$ ) ( $i = 1, \dots, 4$ ), the estimated coordinates of the transmitter ( $X_0, Y_0$ ) are obtained by solving (4) and (5) assuming a 2D localization process ( $Z_0 = Z_1 = Z_2 = Z_3$ ).

$$\begin{bmatrix} X_0 \\ Y_0 \end{bmatrix} = \begin{bmatrix} X_{2,1} & Y_{2,1} \\ X_{3,4} & Y_{3,4} \end{bmatrix}^{-1} \cdot \left( \begin{bmatrix} R_{2,1} \\ R_{4,3} \end{bmatrix} \cdot R_1 + \frac{1}{2} \begin{bmatrix} R_{2,1}^2 - K_2 + K_1 \\ R_{4,3}^2 - K_4 + K_3 \end{bmatrix} \right) \quad (4)$$

$$R_{i,1}^2 + R_{i,1} \cdot R_1 = K_i - K_1 - 2 \cdot X_{i,1} \cdot X - 2 \cdot Y_{i,1} \cdot Y \quad i=2, 3, 4 \quad (5)$$

with  $K_i = X_i^2 + Y_i^2$   $i = 1, \dots, 4$ ,  $X_{2,1} = X_2 - X_1$ ;  $X_{3,4} = X_3 - X_4$ ;  $Y_{2,1} = Y_2 - Y_1$ ;  $Y_{3,4} = Y_3 - Y_4$   
 $R_{2,1} = R_2 - R_1 = \frac{\text{TDOA}_1}{c}$ ;  $R_{4,3} = R_4 - R_3 = \frac{\text{TDOA}_2}{c}$  where  $c$  denotes the speed of light.

### III. EXPERIMENTAL SYSTEM AND CONFIGURATION

#### A. Experimental Localization Platform

A proof-of-concept localization platform based on the MMF DAS localization system has been developed (Fig. 2). Only commercial off-the-shelf (COTS) components are used to develop the remote and local APs specific to our localization technique. In this configuration, each remote AP consists of a dipole antenna followed by a Minicircuits 2.4-GHz low noise amplifier (LNA) associated with a 850-nm receptacle multimode vertical-cavity surface-emitting laser (VCSEL) manufactured by ULM Photonics GmbH. The LNA has a 35-dB gain and a 1-dB noise figure. The VCSEL is biased at 10 mA and its 3-dB bandwidth is equal to 3 GHz: it performs the electrical/optical conversion

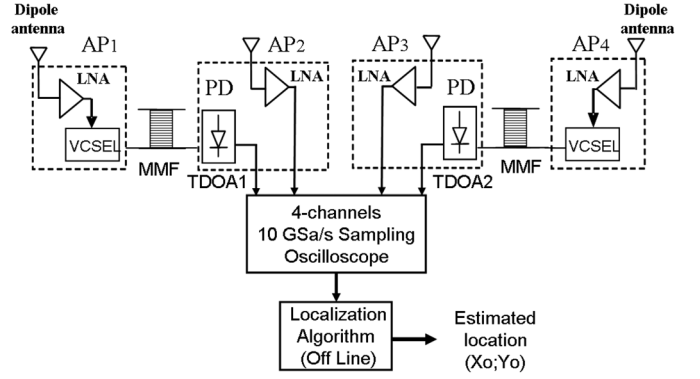


Fig. 2. Topology of the MMF DAS localization system.

of the received RF signals which are amplified by the LNA before to be transmitted over a MMF using the intensity modulation–direct detection technique. The optical signal, which has a power of  $-2$  dBm, is then transmitted through a  $62.5\text{-}\mu\text{m}$ -core MMF (length = 100 m). This MMF has a spectral attenuation of 2.7 dB/km and a bandwidth-length product equal to 200 MHz.km at 850 nm. The optical signal is then collected by a  $62.5\text{-}\mu\text{m}$ -core matched receptacle Thorlabs photodiode (PD). Such a PD is included within each local AP which is also composed by a dipole antenna and another LNA. The RoF transmissions of 802.11 g WiFi signals are performed without significant impacts on the signal quality and the error vector magnitude (EVM) is still below 8%. An Keysight arbitrary waveform generator has been used to generate the 802.11 g frame with mean power output equal to 10 dBm. In this configuration, the same sequence has been used for all the transmitter positions. The SNR of the received signals from local and remote APs are better than 10 dB. The signals provided by the local and remote APs are acquired in a parallel configuration by a Keysight four-channel 10 GSa/s sampling oscilloscope.

#### B. System Configuration

WiFi localization systems usually estimate the transmitter position using radio beacons involving several antennas and measuring the power of received signals [10]–[12]. Such systems exhibit location errors which can reach several meters in indoor environment. To enhance their performance, one way is to use a TDOA-based algorithm but compact RF systems including several antennas are limited by the geometric dilution of precision. Fig. 3(a) describes this limitation which is due to weak separations (a few wavelengths) between the different antennas in a conventional system. To overcome this limitation, a large distance between APs, set to 9 m, enables to focus the TDOA crossing, as depicted Fig. 3(b). The proposed MMF DAS owns an intrinsic accuracy which can address applications such as high-speed optical wireless communication with a mobility feature [13] or energy-efficient broadcasting in wireless multi-hop wireless networks [14].

#### C. Impact of the Frequency Sampling and Bit Resolution

The acquisition technique is based on triggered records of four delayed waveforms. The recording time is set to 500 ns resulting in a number of samples equal to 50,000 per waveform that are processed offline. The sampling frequency  $f_s$  and the

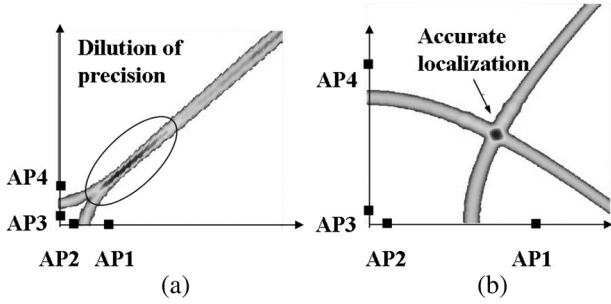


Fig. 3. Hyperbolas issued from TDOA measurements with (a) compact RF system and (b) the MMF DAS-based localization system.

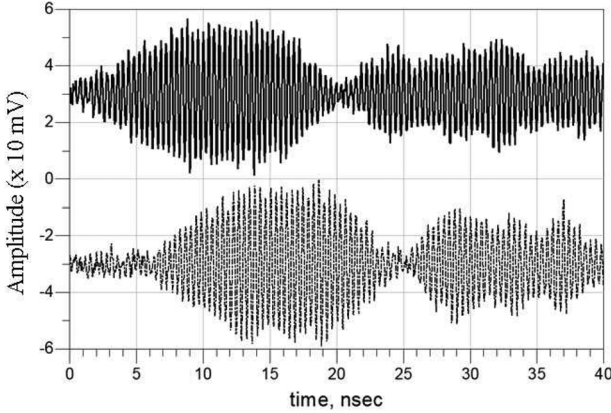


Fig. 4. Illustration of 802.11 g received signals by the local AP (solid line) and the remote AP (dot line) –TDOA = 4.65 ns.

signal-to-noise ratio (SNR) of the system are the key parameters determining the performance since the time resolution of the digitized signals impacts directly the location error. The variance error is described by the Cramer–Rao lower bound [15] by

$$\sigma_{\text{TDOA}}^2 = \sigma_{\text{TDOA1}}^2 + \sigma_{\text{TDOA2}}^2 \quad (6)$$

$$\text{with } \sigma_{\text{TDOA}i} = \frac{2 \cdot c}{f_s \cdot \sqrt{\text{SNR}}}. \quad (7)$$

The SNR and distortion ratio (DR) called SINAD are related to the effective number of bits (ENOB) by the following relationship:

$$\text{SINAD} = 6.02 \cdot \text{ENOB} + 1.76 \text{ with ENOB} = 8. \quad (8)$$

The resulting SINAD is on the order of 50 dB in the best case and allows to appreciate the dynamic performance of the analog-to-digital converters (ADCs) of the sampling scope. Nevertheless, the SNR is limited by the thermal noise of the receiver affects and can be degraded up to 10 dB for the tested transmitter positions. In the present study, a maximum sampling of 10 GSa/s is considered by using a high-performance oscilloscope that leads to a theoretical limitation of the location accuracy  $\sigma_{\text{TDOA}} = 2.7$  cm for a SNR = 10 dB. As ultra-high-speed ADC of tens of GSa/s remains a cutting-edge technology, the constraint on the expected spatial resolution should be released in order to reduce the cost of the system.

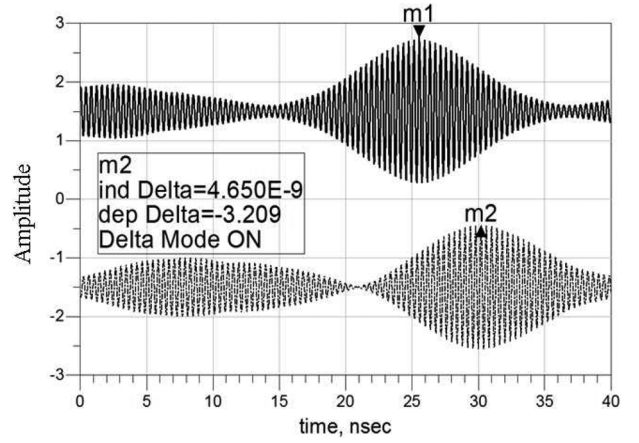


Fig. 5. Illustration of  $C_{xx}$  (solid line) and  $C_{xy}$  (dot line) in time domain TDOA = 4.65 ns;  $N = 512$ ;  $L = 1024$  (not normalized).

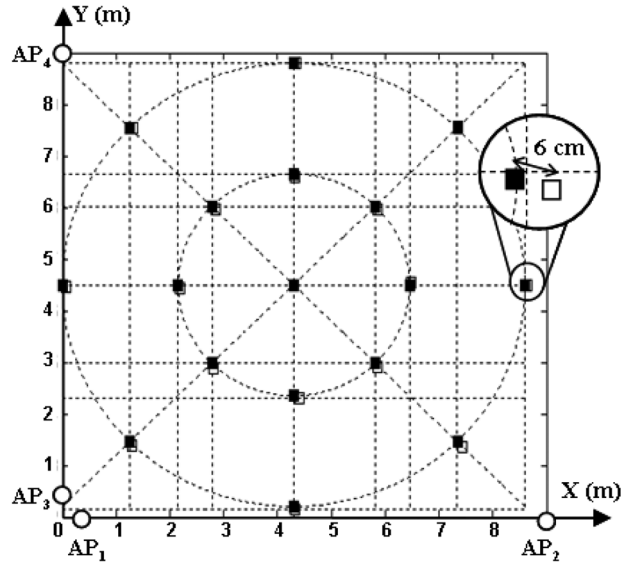


Fig. 6. Comparison between the true and estimated positions of the transmitter.

## IV. MEASUREMENT PERFORMANCE

### A. Measured Waveforms and TDOA Determination

The localization process described previously has been tested in indoor conditions considering a typical large furnished room ( $10 \times 11$  m<sup>2</sup>). The power of the transmitted 2.45 GHz 802.11 g signals is set to 10 dBm. Illustrations of 802.11 g signals received by the local and remote APs are given in Fig. 4 for a measured TDOA value equal to 4.65 ns. The related autocorrelation  $C_{xx}$  and cross-correlation  $C_{xy}$  are given in Fig. 5 and the TDOA value is determined by the difference between the  $C_{xx}$  and  $C_{xy}$  maxima. (m1 and m2 markers, respectively).

In order to validate the performance of the overall system with a statistic approach, a large number of transmitter positions have been considered (> 500). A few examples of these tests are illustrated in Fig. 6. The true and estimated locations are respectively represented by black and white squares.

We can note that the error location is in the order of few centimeters whatever the transmitter position is. In order to clearly

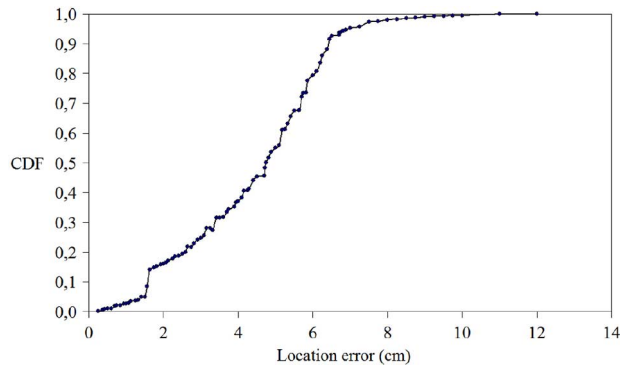


Fig. 7. Cumulative distribution function of the location errors.

TABLE I  
LOCATION ERRORS ANALYSIS

Metrics	Mean Error	50% Error	90% Error
Value (cm)	5.3	4.75	6.4

summarize all the measurements, Fig. 7 shows the cumulative distribution function (CDF) of experimental location errors.

The statistics of location errors are summarized in Table I.

The error distribution demonstrates that the error value resulting from this localization process is typically better than 6.4 cm in most of the cases: the mean location error is equal to 5.3 cm considering more than 500 transmitter positions. To the authors' knowledge, such accuracy cannot be reached with the reported WiFi localization systems [10]–[12], [16], [17] which exhibit location error of several meters.

## V. CONCLUSION

We have presented a new class of application for DAS based on RoF technology. In addition to transmit standard RF signals, multimode fibers can be used for applications of accurate localization. The already demonstrated multi-services concept on MMF [18] could be used to transmit simultaneously Ethernet and radio signals for both communication and localization applications. The growth of the DAS market strengthens the potential interest of this original solution. Such a localization system involved in a study of DAS energy efficiency is another interesting challenge for future works [19].

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