Enhanced TOA Estimation Using OFDM over Wide-Band Transmission Based on a Simulated Model

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Abstract

This paper presents the advantages of using a wideband spectrum adopting multi-carrier to improve targets localization within a simulated indoor environment using the Time of Arrival (TOA) technique. The study investigates the effect of using various spectrum bandwidths and a different number of carriers on localization accuracy. Also, the paper considers the influence of the transmitters' positions in line-of-sight (LOS) and non-LOS propagation scenarios. It was found that the accuracy of the proposed method depends on the number of sub-carriers, the allocated bandwidth (BW), and the number of access points (AP). In the case of using large BW with a large number of subcarriers, the algorithm was effective to reduce localization errors compared to the conventional TOA technique. The performance degrades and becomes similar to the conventional TOA technique while using a small BW and a low number of subcarriers.

Keywords Indoor localization · OFDM · Time of arrival · Wideband spectrum

1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) has emerged in recent years as an effective digital modulation technique that is at the heart of all major wireless standards used or in development today, such as the 4G Long-Term Evolution (LTE), Wi-Fi IEEE 802.11a, WiMAX and in Digital Video Broadcasting (DVB) systems [1–3].

OFDM is utilized in several communication systems due to its robustness to multipath channels and high transmission rate in wireless communications networks. However, for

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reliable signal transmission, the OFDM technique requires precise timing and accurate frequency synchronization [4, 5]. Other key disadvantages of OFDM are Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) [6].

ICI often occurs as a result of the loss of synchronization caused by frequency offset and time offset between oscillators at the transmitter and receiver's end, which in effect results in the orthogonality, so the transmitted signal cannot be completely separated at the receiver. Thus, ICI decreases the signal-to-noise ratio (SNR) and increases error probability [7, 8].

Moreover, a large peak-to-average power ratio caused by the superposition of all subcarrier signals becomes a distortion problem [9]. The desirous advantages of OFDM have motivated its application for improved localization of targets, to provide accurate mobile station (MS) positioning within both outdoor and indoor environments.

Authors in [10] used the OFDM-Time of Arrival (TOA) algorithm for position estimation of a Long Term Evolution (LTE) signal. A similar algorithm was proposed to detect the arrival times of Wi-Fi signals [11, 12]. In [13], a simple OFDM-TOA-based algorithm is proposed to estimate the Direct Path (DP). Similar research was conducted in [14], by combining path detector to interference cancellation it becomes possible to distinguish low-power DP from the nearby interference.

TOA localization can be done using lateration [15]. Each time measurement between target and access point (APs) leads to a distance estimation, by having three or more APs, the target's location can be inferred [16]. Localization using TOA has the advantage of being highly accurate, however; it is sensitive to multipath and the existence of direct path [17]. Also, precise synchronization between APs is required and the availability of huge bandwidth (BW) is important for accurate estimations [18]. TOA detection techniques can be classified into four main categories: correlation-based techniques [19], maximum likelihood techniques [20], subspace techniques [21], and inverse Fourier transform techniques [19].

This paper introduces a coded OFDM system to be used in the application of localization systems and enhance the TOA estimation over the wideband transmission. The localization of objects within the indoor environment is investigated over a wide-band spectrum using the multi-carrier OFDM modulation technique. It is attended that the large bandwidth can support the time resolution required to estimate the localized positions of the objects. Of course with the advantages that have been added by the OFDM, the whole process can improve the estimation accuracy compared to conventional methods applied to similar applications [22–25]. In this study, a fractional spectrum of the lower Ultra-Wideband (UWB) was utilized to mitigate the effects of indoor channel propagations due to the high number of multipath, in which several carriers are spread over the bandwidth based on the impulse response of the channels using Wireless-InSite (WI) and then suitable estimations of time arrivals are applied, followed by a numerical technique to estimate the position of the hidden objects.

The organization of the paper is as follows: the second section presents a mathematical model for TOA estimation, while in the third section, the simulated model is illustrated. Results and discussion are introduced in Sect. 4, and finally, conclusions are drawn in Sect. 5.

2 Mathematical Model of OFDM for Time of Arrival Estimation

The idea is to use simple lateration localization, based on TOA; however, time is estimated based on analyzing the OFDM signal. Starting with the OFDM system, given that the input signal $g(t, \omega)$ is [6]:

$$g(t, \omega) = e^{j2\pi ft} \tag{1}$$

where f and t are frequency and time respectively. Assuming a linear time-invariant channel, the output can be simplified as:

$$s(t, \omega) = e^{j2\pi ft} \sum_{k=1}^{n} a_k e^{j\varphi_k} e^{-j2\pi f \tau_k} = e^{j2\pi ft} U(2\pi f) \tag{2}$$

where a_k, φ_k, τ_k and n are the kth multipath attenuation, phase shift, propagation delay, and the number of multipath rays, respectively. The spectrum bandwidth is divided by N sub-carriers, the jth frequency sample can be expressed by:

$$f_j = \frac{B}{2}\left(-1 + (j-1)\frac{2n}{N}\right) \tag{3}$$

And the jth uniform frequency sample of $U(2\pi f)$ is given by:

$$U(2\pi f_j) = \sum_{k=1}^{n} a_k e^{j\varphi_k} e^{-j2\pi f_j \tau_k} \tag{4}$$

The sampling time is given by:

$$\Delta t = \frac{1}{B} = \frac{1}{N \cdot \Delta f} \tag{5}$$

The challenge is how to utilize the benefits of using the OFDM system in localization. Before proceeding into this point, it's worth mentioning that we have extracted the channel information through simulations that were conducted in WI software at 5 GHz. We first extracted the arrival rays' corresponding information including phase, time delay, and received signal strength. This information is taken to a MATLAB code which has three functions.

Firstly, the code constructs the OFDM system based on Eqs. 1–5. The code allows the user to select N and BW. After that, the N-inverse transform of the received signal is estimated. The inverse fast Fourier transform (IFFT) translates frequency domain data to time-domain samples, i.e. from the discrete frequency domain we can have discrete time-domain samples.

By choosing a sufficient number of subcarriers and wider BW, it is possible to have more resolution on time (Δt is less than the time between multipath). We then mapped the high-resolution time with the output of the IFFT, after that we choose the time with the highest value of IFFT as the TOA, which is the second task of the code, in other words, the TOA is estimated based on the mapping between the discrete-time domain samples with the highest output of the IFFT.

In the third task, the code performs localization by using the lateration technique based on Eqs. 6–11.

For an electromagnetic wave, the elapsed time and travel distance are related by the speed of light, given the TOA, the distance between the transmitter and receiver is estimated.

Assuming we have several receiver points with known locations, and a transmitter with an unknown location, the TOA readings can be used to find the relative distances between the transmitter and each receiver, thus, by using lateration, it is possible to find the transmitter's location [20].

Lateration can be solved using the linear least square technique, which is helpful especially for Non-line-of-sight (NLOS) propagation [20]:

$$\frac{1}{R}\sum_{i=1}^{R} d_i^2 = \frac{1}{R}\sum_{i=1}^{R}\left[(\hat{x}-x_i)^2 + (\hat{y}-y_i)^2\right] \tag{6}$$

where d_i and R, are the distance between the ith receiver and transmitter and the number of receivers respectively, (x_i, y_i) is the ith receiver coordinates and $(\hat{x}, \hat{y})$ are the estimated transmitter coordinates. Rearranging Eq. 6 for the lth receiver:

$$\left[y_l - \frac{1}{R}\sum_{i=1}^{R} y_i\right]\hat{y} + \left[x_l - \frac{1}{R}\sum_{i=1}^{R} x_i\right]\hat{x}$$
$$= 0.5\left(\left[y_l^2 - \frac{1}{RR}\sum_{i=1}^{R} y_i^2\right] + \left[x_l^2 - \frac{1}{R}\sum_{i=1}^{R} x_i^2\right] - \left[d_l^2 - \frac{1}{R}\sum_{i=1}^{R} d_i^2\right]\right) \tag{7}$$

For all receivers, a matrix can be represented as $(Az = b)$ where $\left(z = \begin{bmatrix}\hat{y}\\\hat{x}\end{bmatrix}\right)$

$$A = \begin{pmatrix} y_1 - \frac{1}{R}\sum_{i=1}^{R} y_i x_1 - \frac{1}{R}\sum_{i=1}^{R} x_i \\ . \\ . \\ y_R - \frac{1}{R}\sum_{i=1}^{R} y_i x_R - \frac{1}{R}\sum_{i=1}^{R} x_i \end{pmatrix} \tag{8}$$

$$b = \begin{pmatrix} 0.5\left(\left[y_1^2 - \frac{1}{R}\sum_{i=1}^{R} y_i^2\right] + \left[x_1^2 - \frac{1}{R}\sum_{i=1}^{R} x_i^2\right] - \left[d_1^2 - \frac{1}{R}\sum_{i=1}^{R} d_i^2\right]\right) \\ . \\ . \\ 0.5\left(\left[y_R^2 - \frac{1}{R}\sum_{i=1}^{R} y_i^2\right] + \left[x_R^2 - \frac{1}{R}\sum_{i=1}^{R} x_i^2\right] - \left[d_R^2 - \frac{1}{R}\sum_{i=1}^{R} d_i^2\right]\right) \end{pmatrix} \tag{9}$$

Then, the transmitter location can be estimated as:

$$Z = \left(A^T A\right)^{-1} A^T b \tag{10}$$

The position error is calculated by estimating the Euclidean distance [26]:

$$Error = \sqrt{(x-\hat{x})^2 + (y-\hat{y})^2} \tag{11}$$

where (x, y) is the transmitter's true coordinates.

3 Simulation Model

The scenario environments were created using WI software. WI is a site-specific radio propagation software that provides user-requested outputs for different indoor and outdoor environments and has the ability to provide efficient and accurate predictions of channel propagation characteristics like received signal strength, propagation paths, complex impulse response, delay spread, and time of arrival/departure, etc. [27]. The

software has been validated over the WLAN frequencies [28, 28]. The obtained channel response is to be used with the OFDM multi-subcarrier system for our proposed localization method.

The simulated model represents the 3rd floor of the Chesham building at the University of Bradford. The transmitter was placed in three locations.

Four receivers were distributed at fixed known locations and mounted 1.5 m above the floor. The transmitter was placed in both line-of-sight and NLOS with the receivers as were seen in Fig. 1. Coordinates of all transmitters and receivers are listed in Table 1. Transmitter and receivers' antennas used were omnidirectional and the operating frequency was 5 GHz with 2 GHz bandwidth. Settings for the Wireless InSite model are given in Table 2.

Table 3 shows the complex impulse response received at Rx-1 with 10 multipath over the desired band including the LOS path. By convolving the channel impulse response with the OFDM multi-subcarriers spread over the bandwidth, the proposed TOA is estimated by taking the inverse fast Fourier Transform (IFFT) of the convolution. The maximum TOA is used to infer the transmitter's location.

The conventional TOA simply uses the arrival times of the path which are the values in the "Time" column in Table 3 for distance estimations.

In this analysis, the range of the adopted bandwidth is (50 MHz, 100 MHz, 250 MHz, 500 MHz, 1 GHz, and 2 GHz) while the number of subcarriers ranges are (16, 32, 64, 256, 512, 1024, and 2048).

Fig. 1 The layout of all transmitters and receivers

Table 1 Access Points locations

Access Point	Coordinates (*x, y, z*) in meter
Rx-1	(4.5, 4.1, 1.5)
Rx-2	(12.65 9.99, 1.5)
Rx-3	(10, 14.86, 1.5)
Rx-4	(0.04, 14.13, 1.5)
Tx-1	(4.43, 12.25, 1.5)
Tx-2	(8.72, 6.11, 1.5)
Tx-3	(8.8, 10.64, 1.5)
Tx-4	(−0.97, 3.62, 1.5)

Table 2 Wireless InSite settings for the investigated scenario

Setting	Value
Transmitter antenna	Omnidirectional
Receiver antenna	Omnidirectional
Operating frequency	5 GHz
Bandwidth	2 GHz
Number of reflections	6
Number of transmissions	4
Number of diffractions	0
Ray-spacing	0.2^0
Maximum rendered paths	10
Ray-tracing method	Shooting-and-Bouncing-Rays (SBR)
Ray-tracing acceleration	Octree
Propagation model	full 3D

Table 3 Complex impulse response output

| Multipath No	Phase (°)	Time (s)	Power (dBm)
1	114.813	2.72E-08	−39.187
2	−150.495	2.80E-08	−41.601
3	−45.266	2.89E-08	−42.755
4	176.807	2.90E-08	−42.839
5	119.707	2.97E-08	−44.696
6	−16.269	2.98E-08	−44.875
7	−76.84	4.22E-08	−51.444
8	−80.377	4.33E-08	−51.991
9	74.659	4.27E-08	−52.404
10	169.951	4.34E-08	−53.459

4 Results and Discussion

In general, the accuracy of the TOA localization depends greatly on the available BW and the number of receivers. The accuracy of the proposed method depends on the number of sub-carriers and the allocated BW. Comparing to the conventional TOA (the first

Table 4 Transmitter at the 3rd location (Tx-3) LE in meters using the proposed approach with a different number of receivers

BW (MHz)	No. of subcarriers	Receivers (1, 2, 3, 4)	Receivers (1, 2, 3)	Receivers (1, 2, 4)	Receivers (2, 3, 4)	Receivers (1, 3, 4)
2000	2048	0.97	3.32	1.56	2.99	0.02
	1024	0.97	3.31	1.56	2.98	0.03
	512	0.96	3.3	1.56	2.96	0.03
	256	0.95	3.27	1.56	2.92	0.05
	128	0.74	10.55	4.94	9.61	0.35
	64	7.7	8.72	7.29	9.28	7.53
	32	6.13	7.03	5.71	7.68	6.01
	16	6.53	7.17	6.21	7.7	6.45
1000	1024	1.01	3.91	1.89	3.53	0.26
	512	1.06	3.67	1.89	3.16	0.28
	256	0.99	3.41	1.56	3.12	0.06
	128	0.97	3.35	1.56	3.03	0.02
	64	0.94	3.23	1.57	2.86	0.1
	32	7.57	8.56	7.16	9.12	7.4
	16	5.98	6.66	5.64	7.2	5.9
500	512	0.62	2.94	1.18	2.94	0.32
	256	0.61	2.91	1.19	2.89	0.31
	128	0.59	2.85	1.2	2.81	0.31
	64	0.98	4.19	1.89	3.95	0.33
	32	0.94	3.93	1.93	3.58	0.44
	16	7.45	8.48	7.02	9.09	7.29
250	256	1.33	4.4	1.95	4.06	0.22
	128	1.3	4.33	1.95	3.97	0.17
	64	1.25	4.19	1.95	3.78	0.09
	32	1.18	3.93	1.96	3.41	0.17
	16	0.67	2.67	0.69	3.05	0.69
100	128	1.92	1.51	2.41	3.9	3.2
	64	1.83	1.56	2.28	3.93	3.11
	32	2.03	2.1	2.02	2.11	2.02
	16	1.52	1.53	1.52	1.53	1.52
50	64	5.39	7.21	3.36	11.56	6.66
	32	5.38	7.21	3.39	11.41	6.57
	16	5.37	7.21	3.46	11.14	6.41
Conventional TOA	6.57	7.20	6.24	7.75	6.49	

Fig. 2 The estimated position of Tx-1, using 2 GHz and BW = 256 subcarriers
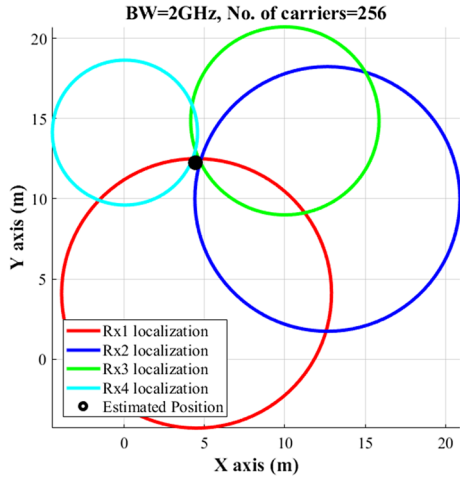
Fig. 3 The estimated position of Tx-2, using 1 GHz and BW = 512 subcarriers
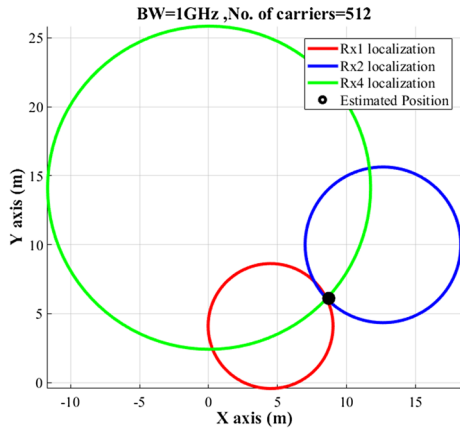
path arrival time), this approach minimized the error to centimeters.

As seen in Table 4, when we used 4-receivers with 2 GHz BW and 2048 sub-carriers, the localization error (LE) was 0.97 m. Using the same settings with 3 receivers, LE was 3.32 m. Those results are still better than the conventional TOA results, where LE were 6.67 m using four receivers and 7.2 m using receivers. As seen, LE using the proposed algorithm was reduced compared to the conventional TOA approach.

In most cases, the average localization error using the proposed method was decreased to around 2 m for Tx-1, 3.32 m for Tx-2, and 4.03 m for Tx-3, while utilizing different sets of bandwidths and subcarriers. However, at low bandwidth and low number of subcarriers, the error increases to become approximately the same value as the conventional TOA approach as presented in Table 4.

Figure 2 shows the estimated position of Tx-1 using 4-receivers with 2 GHz BW and 256 subcarriers. In this case, LE was 0.354 m which is 2 m less than the conventional TOA LE. Figure 3 presents Tx-2 localization using 3- receivers (Rx-1, Rx-2, Rx-3) with 1 GHz BW and 512 subcarriers where the LE was 0.1555 m.

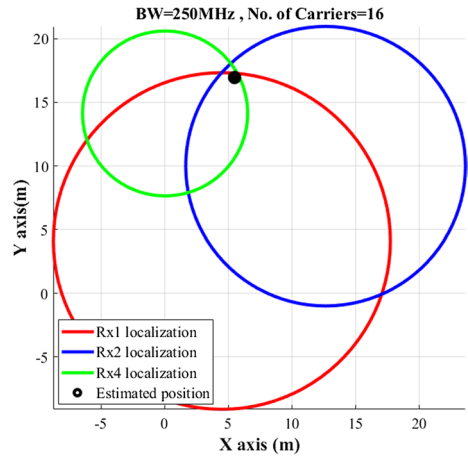**Fig. 4** The estimated position of Tx-3, using 250 MHz and BW = 16 subcarriers

Figure 4 demonstrates the estimated position of Tx-3 using 3- receivers (Rx-1, Rx-2, Rx-4) with 250 MHz BW and 16 sub-carriers. The LE was 0.6946 m which is 5.5 m less than the conventional TOA localization error.

Figure 5 shows the LE values when estimating transmitter at location 1 using 2 GHz BW and various subcarriers. As seen, most LEs of the proposed algorithm are less than the minimum conventional TOA LE except for the 16 carriers case. The maximum LE values in the proposed method occurred when the number of subcarriers was 16, however; it remains less than the maximum value of the LE of the traditional method.

5 Conclusions

This paper describes the OFDM technique for wireless communications and desirous advantages of OFDM to improve the localization of targets, in order to provide accurate mobile station (MS) positioning within indoor environments, and provided an overview of different delimiting factors that affect the performance and capability of OFDM. The causes and effects of these drawbacks and the various methods to deal with these problems for improved performance of OFDM systems are covered in the paper.

The localization of objects within the indoor environment over a wideband spectrum adopting multi-carrier has been presented. The utilized proposed algorithm to estimate

Fig. 5 The error values of the estimated Tx-1 position using the proposed algorithm
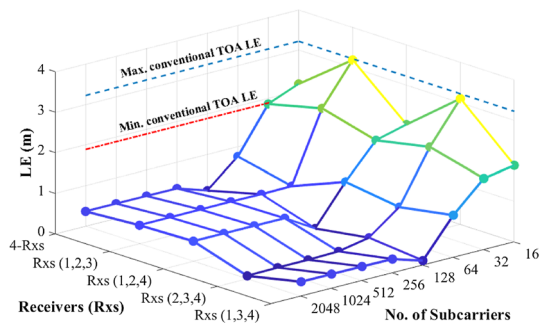
the position of several transmitter positions was also presented. The method was based on the TOA for various spectrum bandwidths and the number of carriers covering the LOS and the NLOS positions of the transmitter's positions. The method adopted the impulse response of the channel to estimate the transmitter position. It was concluded that the TOA approach over several wide bandwidths and different subcarriers was effective to reduce the localization errors compared to the typical TOA technique.

Declarations

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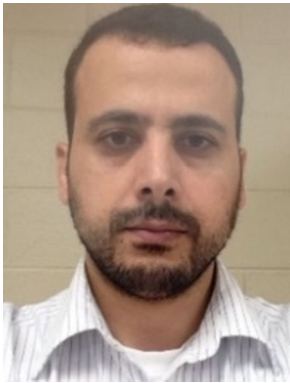
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