An Accurate Indoor User Position Estimator For Multiple Anchor UWB Localization

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***Abstract*—UWB-based positioning systems have been proven to provide a significant high level of accuracy hence offering a huge potential for a variety of indoor applications. However, the major challenges related to UWB localization are multipath effects, excess delay, clock drift, signal interferences and system computational time to estimate the user position. To compensate for these challenges, the UWB system uses multiple anchors in the experiment area and this gives accurate position results with minimum localization errors. However, the use of multiple anchors in the UWB system means processing large amounts of data in the system controller for localization, which leads to high computational time to estimate the current user position. To reduce the complexity of the UWB systems, we propose a position estimator for multiple anchor indoor localization, which uses the extended Kalman filter (EKF). The proposed UWB-EKF estimator was mathematically analysed and the simulation results were compared with classical localization algorithms considering the mean localization errors. In the simulation, three classical localization algorithms: linearized least square estimation (LLSE), weighted centroid estimation (WCE) and maximum likelihood estimation (MLE) were used for performance comparison. Thorough extensive simulation done in this study achieves results which demonstrate the effectiveness of the proposed UWB-EKF estimator for multiple anchor UWB indoor localization.**

***Index Terms*—Indoor localization, ultra-wide band (UWB), time of arrival (TOA), extended Kalman filter (EKF), least square estimation, weighted centroid estimation, maximum likelihood estimation.**

I. INTRODUCTION

The indoor localization systems using time information [1] for user position estimation give accurate position results as compared to other indoor position systems that use smartphone sensors [2], Wi-Fi received signal strength indication (RSSI) signals [3], and cameras [4]. The most common indoor positioning system that uses time information is the ultra-wide band (UWB) systems [5]. In UWB systems, the user position is estimated by anchor-tag communications. Multiple anchors are placed in the experiment area and the UWB tag sends pulses to the anchors. The anchors use the time of arrival (TOA) information and estimate the distances from each anchor using a TOA-distance model. The accuracy of a UWB system depends on the number of anchors used in the experiment area and multiple anchors provide a wide area of indoor localization with accurate user position results. However, the multiple anchors in the UWB system increase the system's computational time to estimate the current user position. Therefore, in UWB systems, it is necessary to reduce the computational time without affecting the localization accuracy. The computational time of a UWB system depends on the type of the localization algorithm used for position estimation. To reduce the UWB system computational time with minimum localization errors, we propose a UWB-extended Kalman filter (EKF) estimator for user position estimation. The conventional UWB systems use any of the linearized least square estimation (LLSE), weighted centroid estimation (WCE) and maximum likelihood estimation (MLE) approaches for UWB localization [6–8]. These mentioned conventional approaches give accurate position results when a small number of anchors is used [9]. However, by increasing the number of anchors in the UWB system, the conventional approaches exhibit a high system computational complexity due to the large number of distance values from multiple anchors and this computational complexity increases the localization error of the UWB system [10]. To improve the UWB system performance, we proposed an estimator, which uses an EKF algorithm for position estimation. The simulation results from proposed UWB-EKF estimator shows accurate indoor position results when we compared them to conventional UWB localization approaches such as LLSE, WCE and MLE.

To validate our proposed UWB-EKF estimator, we simulate an experiment scenario with multiple anchors for line of sight (LOS) and non-line of sight (NLOS) conditions. We implemented the LLSE, WCE, MLE and proposed UWB-EKF estimators for UWB localization and analysed the performance of each localization algorithm for multiple anchors for LOS and NLOS conditions. The analysis is based on the resulting localization error with respect to the number of anchors from proposed UWB-EKF estimator

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and conventional localization approaches. The positioning results from the proposed estimator outperform the conventional approaches in terms of localization accuracy.

The remaining sections of this paper are organized as follows; Section II presents the system model used for multiple anchor UWB localization. Simulation results and analysis are given in Section III. Finally, we conclude in Section IV.

II. System model for multiple anchor UWB localization

The UWB system consists of anchor-tag communication through the UWB indoor channel, calculation of distance values from each anchor using TOA information and position estimation using distance values. A UWB system model with multiple anchors is shown in Fig. 1.

In a UWB system based localization, the anchor nodes (ANs) are placed in the experiment area with known coordinates and the blind node (BN) is used to measure the TOA between BN and ANs. A TOA-distance model is used to estimate the tag distance from each anchor and the distance values are expressed as measurement matrix. The localization algorithms in the system controller use the measurement matrix for tag position estimation. In the system controller, the UWB system uses LLSE, WCE, MLE and UWB-EKF estimators for localization [11].

A. *Proposed UWB-EKF Estimator*

The proposed method follows an EKF algorithm for tag position estimation. The EKF algorithm is a non-linear state estimator with minimum localization error. As compared to conventional approaches, our proposed UWB-EKF estimator maintains the localization accuracy when we increase the number of anchors. The model presented in [12] is used for the EKF implementation. The state vector of the proposed estimator is expressed as

$$x_{t|t-1} = F_{t-1} + x_{t-1} + w_{t-1} \tag{1}$$

The following expressions define $x_{t|t-1}$, F_{t-1} and x_t values.

$$x_{t|t-1} = \begin{bmatrix} x_t \\ y_t \\ V_{xt} \\ V_{yt} \end{bmatrix} \tag{2}$$

$$F_{t-1} = \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$x_t = \begin{bmatrix} x_{t-1} \\ y_{t-1} \\ V_{xt-1} \\ V_{yt-1} \end{bmatrix} \tag{4}$$

where x_t and y_t are user x and y positions, V_{x_t} and V_{y_t} are user velocities and T is the sampling time. The system covariance of the Gaussian noise w_t is defined as Q_t. The non-linear observation matrix of the system model is expressed as

$$y_t = h\left(x_t\right) + v_t \tag{5}$$

The values of y_t and $h(x_t)$ are expressed in the following equations.

$$y_t = \begin{bmatrix} d_1 \\ d_2 \\ . \\ . \\ . \\ . \\ d_{10} \end{bmatrix} \tag{6}$$

$$h\left(x_t\right) = \begin{bmatrix} \left\{\left(x_t - x_t^1\right)^2 + \left(y_t - y_t^1\right)^2\right\}^{1/2} \\ \left\{\left(x_t - x_t^2\right)^2 + \left(y_t - y_t^2\right)^2\right\}^{1/2} \\ . \\ . \\ . \\ \left\{\left(x_t - x_t^{10}\right)^2 + \left(y_t - y_t^{10}\right)^2\right\}^{1/2} \end{bmatrix} + v_t \tag{7}$$

where the covariance of the Gaussian noise v_t is R and (x_t^n, y_t^n), $n \in [3, 10]$ is the coordinates of the nth anchors. The proposed UWB-EKF estimator consists of two parts and which is expressed as

Time-update:

$$\hat{x}_{t|t-1} = F_t \hat{x}_{t-1} \tag{8}$$

$$P_{t|t-1} = F_t P_{t-1} F_t^T + Q_t \tag{9}$$

Measurement-update:

$$K_t = P_{t|t-1} H_k^T \left(H_t P_{t|t-1} H_t^T + R_t\right)^{-1} \tag{10}$$

$$\hat{x}_t = \hat{x}_{t|t-1} + K_t \left\{y_t - h\left(\hat{x}_{t|t-1}\right)\right\} \tag{11}$$

$$P_t = \left(I - K_t H_t\right) P_{t|t-1} \tag{12}$$

where $H_t = \frac{\partial h(x_t)}{\partial x_t}|_{\hat{x}_t}$ is the Jacobian matrix, evaluated at the current state estimate. The variables used in the UWB-EKF estimator is summarized in Table I.

Table I: Variables used in the UWB-EKF estimator.

$\hat{x}_t$	state vector
P_t	state covariance matrix
K_t	Kalman gain matrix
H_t	Jacobian matrix
y_t	non-linear observation matrix
Q_t	system noise covariance matrix
R	measurement noise covariance matrix
I	identity matrix

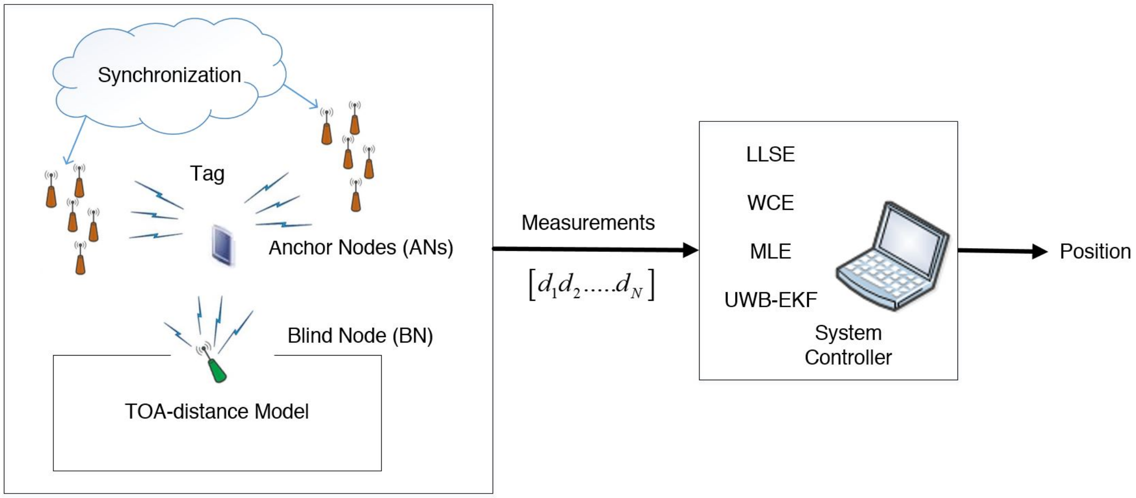


Fig. 1. System model for multiple anchor UWB localization.

III. Simulation Results and Analysis

To simulate the multiple anchor UWB system, we used the MATLAB R2019b simulation environment with all built in tools. We created a 2–dimensional $100 \times 100m$ simulation area and started our simulation with three anchors, which are placed in the simulation environment based on the UWB tag motion. The position of the anchors depends on the UWB tag motion and which covers the simulation environment. The remaining anchors from 4 to 10 are added to the simulation environment based on the user-predefined path. We placed the anchors in equal distance to cover the entire simulation area. The UWB tag communicates with all anchors and estimates the user distance information. In the simulation, we moved the UWB tag with a constant speed. We assumed that the user step length is $0.5m$ and we moved the UWB tag based on this assumption. We generated UWB Gaussian pulses in the transmitter side and passed through the UWB indoor channel [13]. We created IEEE 802.15 4a UWB channel model, which characterizes indoor office environment [14]. In the UWB receiver side, we used a correlator block to estimate the TOA of the signals. The TOA of the received signals is used to identify the UWB tag distance from anchors. Table II shows the simulation parameters used in the UWB indoor office environment for LOS and NLOS channel conditions.

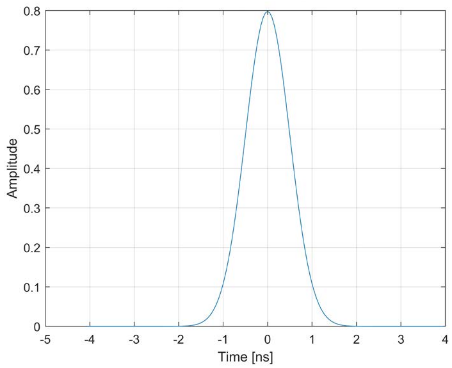
Table II: Simulation parameters used in UWB indoor office environment.

	LOS	NLOS
Pathloss		
n	1.63	3.07
σ_s	1.9	3.9
$PL_0[dB]$	35.4	57.9
A_{ant}	3 dB	3 dB
k	0.03	0.71
Power delay profile		
$\bar{L}$	5.4	1
$\Lambda[1/ns]$	0.016	NA
$\lambda_1, \lambda_2[1/ns], \beta$	0.19,2.97,0.0184	NA
$\Gamma[ns]$	14.6	NA
k_γ	0	NA
$\gamma_0[ns]$	6.4	NA
$\sigma_{\text{cluster}}[dB]$		NA
Small-scale fading		
m_0	0.42 dB	0.50dB
k_m	0	0
$\hat{m}_0$	0.31	0.25
$\hat{k}_m$	0	0
$\tilde{m}_0$		
χ	NA	0.86
γ_{rise}	NA	15.21
γ_1	NA	11.84

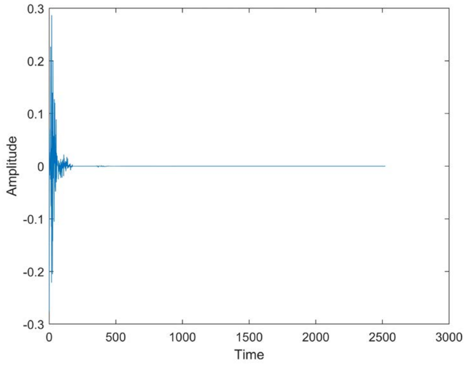
Using the Table II parameter values, we created the UWB simulation environment with UWB pulse and channel responses and which are demonstrated in Fig. 2.

The peak detector in the UWB receiver uses the correlator outputs and identify the peaks of the receiving signals. The peak detector gives the TOA of the signals and TOA-distance model estimates the UWB tag distances from all anchors. The localization algorithms utilize UWB tag distances from anchors and estimate the current tag position. In the simulation, we analyze the performance of conventional UWB localization algorithms such as LLSE, WCE and MLE and compare the localization results with proposed UWB-EKF estimator. A comparative analysis of localization error with number of anchors from conventional approaches and proposed estimator is shown in Fig. 3.

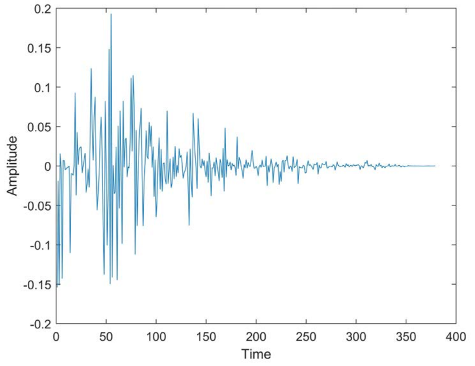
From Fig. 3, it is clear that the proposed estimator shows best performance for UWB localization using multiple anchors. In the case of conventional UWB localization approaches, the LLSE algorithm outperforms the MLE and WCE algorithms and gives high position accuracy



(a) UWB pulse



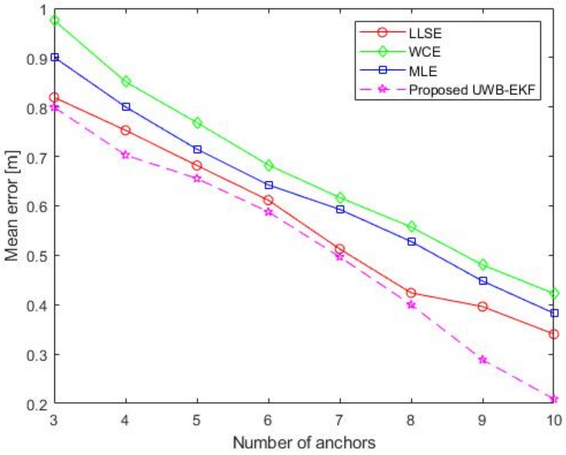
(b) LOS channel response



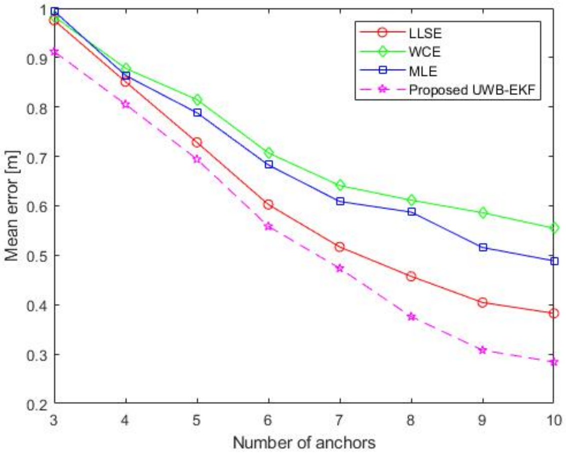
(c) NLOS channel response

Fig. 2. UWB simulation environment.

for UWB multiple anchor localization. The MLE algorithm is better than WCE algorithm and shows better localization performance than WCE position results. The WCE algorithm is not suitable for multiple anchor UWB localization due to the weight calculation between tag and each anchor in the algorithm and poor localization accuracy. From our simulation results and analysis, we demonstrate the significance of the proposed estimator for UWB localization.



(a) LOS



(b) NLOS

Fig. 3. Performance of the UWB localization algorithms.

IV. CONCLUSION

This paper proposed a position estimator for multiple anchor UWB indoor localization. The simulation results show that the proposed UWB-EKF estimator has better results for multiple anchor UWB localization. The proposed system reduced the system complexity when the number of anchors was increased. The position estimation results show that the proposed estimator gives accurate measurements with minimum localization error. In the case of conventional approaches, the LLSE localization algorithm shows better performance than WCE and MLE algorithms. When the number of anchors increases in the experimental area, the position accuracy increases gradually. However, the average computation time for multiple anchors is increasing with respect to the number of anchors. From all the simulation results and analysis, it is clear that the proposed UWB-EKF estimator is a better choice for multiple anchor UWB localization than conventional UWB localization approaches.

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