This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2021.3074960, IEEE Communications Letters

Opportunistic fusion of ranges from different sources for indoor positioning

Carlos S. Alvarez-Merino*, Hao Qiang Luo-Chen*, Emil J. Khatib* and Raquel Barco*
*Dept. of Communication. University of Malaga . Campus de Teatinos s/n, 29071 Malaga, Spain.
Email: {cam, hao} @ic.uma.es; {emil, rbarco} @uma.es

***Abstract*—Ultra-Wide Band (UWB) technology stands out as one of the most promising technologies for locating the user in indoor scenarios for the new 5G mobile generation. As a drawback, it requires a dense infrastructure. For this study, a simulation of a real environment with UWB and Long Term Evolution (LTE) base stations for positioning users is presented, tracked by an Extended Kalman Filter (EKF). The proposed method uses information that is unusable with UWB alone, and combines it with LTE location, improving the precision for the latter and enabling sparse infrastructure deployments.**

***Index Terms*—UWB, Position control, Location fusion, Indoor positioning, Mobile network.**

I. Introduction

The forthcoming 5G will require a precise indoor localisation method in order to enrich end-user services [1]. As Augmented Reality (AR) and Virtual Reality (VR) applications become popular, a need for cheap and precise network based localisation emerges. Global Navigation Satellite Systems (GNSS) have settled as the reference localisation system for outdoor environments providing an accuracy down to the metre. Nevertheless, the positioning error inside indoor areas increases in GNSS due to the harsh reception conditions [2]. In some mobile networks, such as Long Term Evolution (LTE), the network may locate users by estimating the distance to each base station (BS). Indoor positioning is characterised by high multipath, attenuation and shadowing originated by phenomena such as signal reflections on obstacles and walls, Non-Line-of-Sight (NLoS) conditions, sudden temporal changes in presence of people or changes in the environment [3]. In the near future, UWB technology may become the standard for indoor location as described by ETSI [4]. Nevertheless, UWB data has not been included yet in the New Radio Positioning Protocol A (NRPPa). NRPPa transmits positioning information from 3GPP and non-3GPP technologies available in the User Equipment (UE) such as GNSS to outperform the accuracy of mobile network location. In certain limited areas where a precise location technology (such as UWB) is deployed, GNSS or LTE positioning can be complemented or replaced by the local technology. In these cases, there are transition regions in the borders of the deployment where the information of a reduced number of reference points is available but the local technology cannot perform location. In this work, we propose a method that benefits from isolated UWB reference points (also known as *anchors*) in LTE scenarios for enhancing the precision of network-based positioning. Moreover, we also study the extension of the area in which the UWB anchors become useful.

This work has been performed in the framework of the Horizon 2020 project LOCUS (grant agreement n. 871249), receiving funds from the European Union. This work has also been partially funded by Junta de Andalucia (project PY18-4647:PENTA)

Although there are many studies approaching location with radio-based technologies, there is no reference about fusing UWB and LTE for indoor positioning. In particular, both technologies have been studied separately, as seen in [5] and [6]. Indoor positioning is usually achieved with sources such as Wi-Fi, Bluetooth Low Energy (BLE) and pseudo-satellites, as described in [7]–[9]. In [8], different methodologies, such as fingerprinting or trilateration, which are the most commonly used location techniques, are applied. In some cases, location obtained with a single technology is combined with Inertial Measurement Units (IMU) in order to better track the movement of the user [10].

UWB systems give a centimetre-level accuracy over the area covered by the deployment [6]. The extremely wide bandwidth in UWB helps to deal with the multipath and fading effects on the signal, making it indispensable for indoor positioning. Therefore, some flagship smartphones are starting to integrate UWB chipsets, to provide an accurate positioning for the next generation of mobile applications. Nevertheless, deploying a mesh of UWB anchors has a very high cost, resulting in small, limited deployments. Conversely, LTE provides the user location with a large margin of error, but with a ubiquitous coverage [11]. A minimum of three ranging data items (reference coordinates and distances to the transmitters) are required at a single point in space to provide the location with trilateration. This limits the range of location below that of the simple addition of the coverage zones of the anchors, creating a zone in the border of the UWB network where energy is wasted. In this work, we fuse the ranging data of both LTE and UWB (low and high precise ranges, respectively) in zones where isolated UWB anchors do not provide location service but some ranging information is still available as shown in Figure 1.

The contributions of this paper are listed as follows:

- Optimisation and extension of the coverage area of high precision location by fusing data from isolated UWB anchors with ranges obtained from cellular networks.
- Improvement of the cellular-based positioning accuracy in the border of UWB deployments by leveraging the unused

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2021.3074960, IEEE Communications Letters

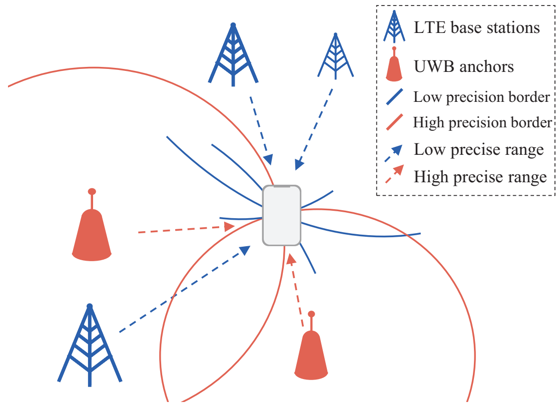

Fig. 1. Trilateration of a device fusing LTE (blue) + UWB (red).

data from edge anchors.

- A weighting scheme to prioritise ranging data depending on the technology and its precision.
- A modification of the NRRPa with the aim of including UWB into the standard to better benefit from the future availability of UWB chips in most smartphones.

Moreover, this method can be used to compensate missing LTE network elements that provide location with a sparse UWB deployment in some situations, such as in catastrophes.

The rest of this paper is organised as follows: Section II provides an explanation of the methodology. Section III shows the simulations that evaluate the proposed method. Finally, Section IV discusses the obtained results and the benefits of fusing the data in order to improve the indoor positioning areas.

II. Methodology

In this section, trilateration and EKF are described. Then, the fusion method for UWB and LTE is shown. Finally, a modification of the NRRPa to make use of the proposed method is introduced.

A. Trilateration and Iterative Weighted Least-Square

Trilateration is used for positioning a body with respect to a reference coordinate framework. To perform trilateration, the distance of the target to, at least, three reference points are required, as illustrated in Figure 1. Naïve trilateration in GNSS utilises the Time of Arrival (ToA) of the signal to estimate the distance to satellites whose positions are known beforehand; however, this method requires a very high precision in measuring time, forcing the need of atomic clocks. In [8] and [12], the range to the LTE BSs is estimated by means of the Received Signal Strength Indicator (RSSI) and propagation models that relate the RSSI with the distance. The main advantages of RSSI-based ranging are the simplicity and low cost for obtaining the received power from the BSs. As a drawback, LTE suffers from Inter-System Interference, fading and multipath, which modify the RSSI and add some ranging error. In contrast, UWB applies Two Way Ranging (TWR) protocol, which achieves centimetre-level precision in the range. Nevertheless, the lower coverage of a single UWB anchor implies that a much denser deployment is required in order to have all points in space covered with at least three signals. Each of the obtained ranges defines a circumference around its point of reference. In the ideal case where the distances are calculated without any error, the three circumferences will cut at the exact point where the target is located. In the more usual case where the ranges have some error and the circumferences do not cut at a single point, the system computes the Iterative Weighted Least-Square (IWLS) method in order to find the optimal solution as described in the next equations:

$$\begin{gathered} A = \|\mathbf{p} - \mathbf{bs}_i\|\,;\ \forall i \\ \mathbf{y} = \mathbf{p} - \hat{\mathbf{p}} \\ \delta\mathbf{p} = (A^\top W A)^{-1} A^\top W \mathbf{y} \\ \mathbf{p}^+ = \mathbf{p} + \delta\mathbf{p} \end{gathered} \tag{1}$$

where A is the euclidean distance matrix from the computed position ($\mathbf{p}$) defined in 2D and the coordinates of the different BSs ($\mathbf{bs}_i$). The innovation vector $\mathbf{y}$ is the difference between the computed position and the estimated position ($\hat{\mathbf{p}}$) until the variation ($\delta\mathbf{p}$) does not exceed an arbitrary threshold. The weighting matrix (W) is $diag\left(\ \sigma^{-1}_{UWB_1}, \sigma^{-1}_{UWB_2}, \sigma^{-1}_{LTE_1}, \ldots,\ \sigma^{-1}_{LTE_n}\ \right)$. A reasonable choice for the weight matrix is $W = Q_{yy}$, the variance–covariance matrix of the measurements [13]. The goal is to give more confidence to the more precise measurements. Finally, $\mathbf{p}^+$ is the updated position for the next time interval.

B. Extended Kalman Filter

For tracking the location of a moving target, the noise (that is, the positioning error) of the sensors (which may be devices such as IMU, GNSS receivers or UWB tags), creates an uncertainty in position increasing over time. Bayesian Filters can cancel this cumulative error with a probabilistic estimation in dynamic scenarios with ambiguous measurements. Extended Kalman Filter (EKF) is the most used algorithm in navigation systems [13]. EKF is a recursive method which allows to estimate the new position of the user according to the new measurements and the previous state (position and velocity) of the user [14]. This algorithm follows a Markov chain pattern, in which the system has memory, but it only takes into account the previous state $\hat{\mathbf{x}}_{k-1}$. This filter works in two steps:

1) Prediction: Using the previous state $\hat{\mathbf{x}}_{k-1}$ which includes the position and the velocity of the user, the system computes the predicted state $\hat{\mathbf{x}}_k^-$ and updates the covariance matrix of the prediction P as follows:

$$\hat{\mathbf{x}}_k^- = \begin{cases} \hat{\mathbf{x}}_k^- = F\hat{\mathbf{x}}_{k-1} \\ \hat{P} = FPF^\top + Q \end{cases} \tag{2}$$

where F is the state transition function and Q is the process covariance of the system.

2) Update: The update step consists in determining the position of the user with the compromise between the predicted state and the observation matrix $\mathbf{z}$. At this point, the Kalman Filter Gain (K) weights the measurements and the predicted

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2021.3074960, IEEE Communications Letters

state conforming to the quality of the observations. In case of inputs with poor quality, their weight will be low; otherwise, the input data will dominate over the prediction as shown in the next equation.

$$\begin{aligned} \mathbf{y} &= \mathbf{z} - H\hat{\mathbf{x}} \\ K &= \frac{\hat{P}H}{H\hat{P}H^{\top}+R} \\ \hat{\mathbf{x}}_k &= \hat{\mathbf{x}}_k^{-} + K\mathbf{y} \\ P &= (I - KH)\hat{P} \end{aligned} \tag{3}$$

where $\mathbf{y}$ is the residual vector between the prediction and the measurements, H is the measurement function, I is the identity matrix of $\mathbb{R}_{2x2}$ and R is the noise covariance matrix of the measurements.

C. Proposed fusion method

The proposed fusion method blends LTE and UWB ranges providing an over-determined system with more measurements than a technology in isolation. In this case, the trilateration algorithm uses ranges from different technologies as illustrated in Figure 1 in which LTE ranging data is complemented with data from UWB isolated anchors to improve the location accuracy. Figure 2 describes the algorithm divided in three steps. First, the ranging data is collected from the ranging devices (i.e. the LTE modem or the UWB tag). Second, trilateration is done using three UWB ranges if available. Otherwise, LTE ranges are used to complete the three required ranges. In this step, fusion is done between a precise technology with partial information (UWB) and an imprecise technology with ubiquitous coverage (LTE). Lastly, EKF updates the end-user position as described in the previous section.

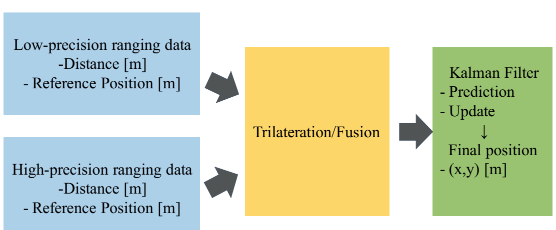

Fig. 2. Diagram of the fusion algorithm for positioning, step by step.

The proposed fusion achieves two things: in scenarios within an LTE network, a sparse UWB deployment can be used to improve location precision without reaching the density and cost required for a full UWB system; and a smooth transition with high precision is achieved between indoor and outdoor scenarios or between different location system areas as illustrated in Figure 3. The red zone is the area covered by UWB; throughout this area, all points have visibility of at least 3 UWB anchors. The yellow area is the zone where we apply the fusion algorithm. In this area, LTE location is complemented with the information from one or two anchors in the edge of the UWB deployment in order to improve the location accuracy. Finally, the rest of the scenario is covered only by LTE.

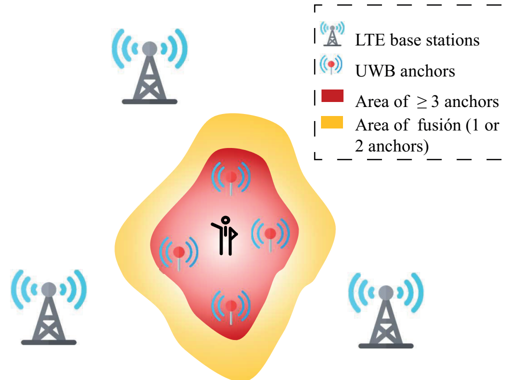

Fig. 3. Example of a LTE scenario with and UWB location area (red) and fusion location area (yellow)

D. NRPPa for UWB

Nowadays, 3GPP does not define any specification towards UWB. NRPPa establishes a mechanism by which the network may acquire a more precise location information from the UE. This precise location is obtained with GNSS receivers in the UEs. In this paper, we propose using procedures and messages similar to the existing NRPPa protocol for UWB such as those described in TR. 38.455 [15]. To allow fusing LTE ranges (that can be obtained by the mobile network) with UWB ranges (that can only be obtained in the UE), the following messages should be added as an extension to NRPPa:

- UE device unique identifier
- UWB anchor identifier
- UWB anchor location
- Timestamp
- Time of Flight (ToF)

Some optional fields could be used to transmit additional information that can be used to characterise the error of the UWB ranges, such as the frequency channel, LoS/NLoS conditions, etc.

III. EXPERIMENTAL SET-UP

This section presents the evaluation of the proposed fusion of LTE and UWB location. Furthermore, the performance of EKF with respect to a memoryless system is analysed. Then, the performance of the proposed fusion method compared to LTE-only location method inside the area within the range of some UWB anchors.

A. Environment setup

According to the density of LTE stations described in [16], four BSs have been deployed approximately 100 m from each other. In addition, an UWB deployment within the LTE network is emulated, with four UWB anchors placed tens of meters from each other, as described in [17]. Figure 4 shows the map of the simulated environment. LTE BSs are represented by the pink triangles and UWB anchors by the green triangles. Table I lists

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2021.3074960, IEEE Communications Letters

the main parameters of the simulation in which P_{tx} is the transmitted power from the BS, f is the frequency of the technology, h_b is the height of the BS and $P_{rx_{min}}$ is the sensitivity of the system for each technology. LTE follows the Okumura-Hata propagation model [18]. For simulation simplicity, this model is used both outdoors and indoors, adjusting the error of location to the typical LTE indoors location error. UWB, on the other hand, follows the log-normal propagation model described in [3].

TABLE I
PARAMETER CONFIGURATION OF THE BASE STATIONS

Source	P_{tx} [dBm]	f [MHz]	h_b [m]	$P_{rx_{min}}$ [dBm]
LTE	47.4	1800	30	-84
UWB	-68.28	6000	5	-132.98

B. Simulation and results

In the scenario described above, a Monte Carlo method is used in order to set up a simulation that provides statistically relevant results, generating a thousand random trajectories with a hundred points for each trajectory. The simulated points follow a straight line between two random points inside the scenario. We also include an Additive White Gaussian Noise (AWGN) in the LTE and UWB received signals.

1) Use of Extended Kalman Filter: the gain of using an EKF is determined comparing it to a non-memory system, a system that does not use the information from a previous time interval. Table II displays the relevant statistical results of the experiment i.e. the mean and the standard deviation of the error, and the 2σ parameter that contains the 95% of the sorted error compared with the ground truth in both cases: in a non-memory system and an EKF system. In order to be efficient, the rest of the simulations employ EKF due to the better performance of the system.

TABLE II
COMPARISON OF THE HORIZONTAL ERROR BETWEEN NON-MEMORY SYSTEM AND EKF SYSTEM.

System	Mean	Std. Deviation(σ)	2 σ
EKF	1.039	0.661	2.225
Non-Memory	1.489	1.036	3.529

2) Fusion location accuracy: Figure 4 shows the regions in which each technology acts. The scenario is composed of three different zones which follows the same distribution of Figure 3. The red dots are the points estimated only with UWB, while the blue dots are estimated by LTE. The yellow dots indicates the points where there are one or two UWB anchors visible and their ranges are fused with LTE ranges to provide location. In this area, the accuracy is expected to improve compared to LTE as long as we have more precise ranging information from UWB. Figure 5 shows the area where fusion (yellow) and UWB (red) are used independently. Figure 5 also shows the covariance error shapes (i.e. the confident contour). The error circumferences represent an outline of the Gaussian distribution

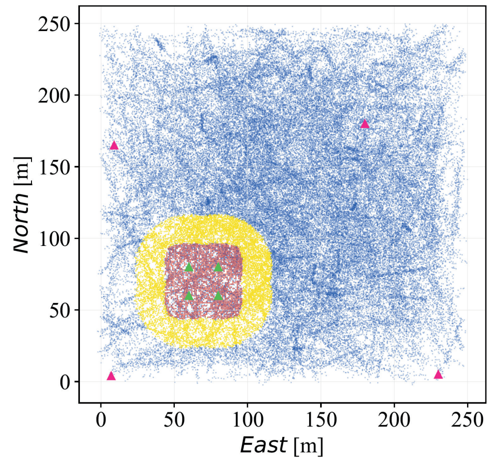

Fig. 4. Position tracked in LTE (blue), fusion (yellow) and UWB (red) over a Monte Carlo simulation.

and they contain the 99% of the points of each distribution. The shapes are typically ellipsoids, however, the square-shaped distribution of the UWB stations leads to this circular shape. This distribution was considered as the best option in order to better represent the improvement of the coverage area. The inner circle (green) separates the UWB coverage area (red). The outer circle (pink) wraps the points where LTE location has been improved with fusion with the available UWB information (yellow). The fusion radius is 50m compared with the UWB radius of 25m by using information that normally has been dropped, therefore, a noticeable increase in the area with high accuracy is observed.

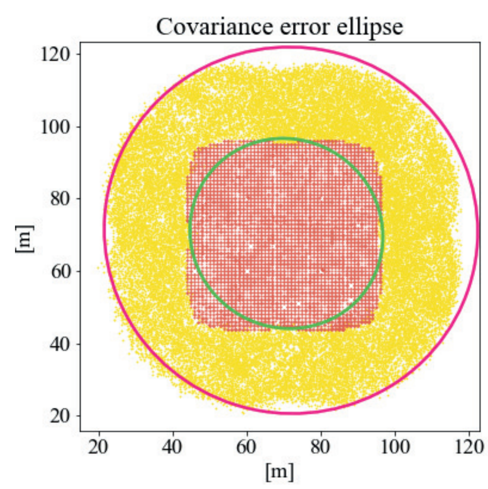

Fig. 5. Confidence circumferences of the position points in fusion (outer circle) and UWB (inner circle)

Figure 6 represents the cumulative distribution function (*cdf*) of the horizontal position error in LTE (blue), fusion (yellow) and weighted fusion (red) with respect to the ground truth in the yellow area or the transitional area between the only LTE to only

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2021.3074960, IEEE Communications Letters

UWB. It can be observed that fusing incomplete information from UWB anchors with LTE ranges reduces the error with respect to using only LTE ranges. The green line represents 90% sample line, and the error for this point is reduced by 60cm and 90cm for fusion and weighted fusion, respectively.

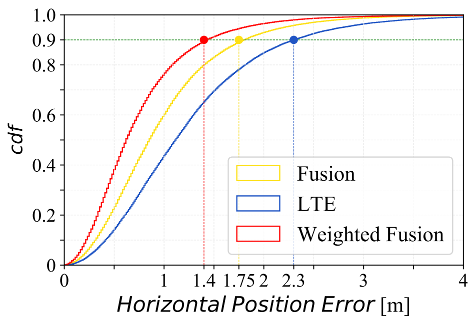

Fig. 6. Horizontal Position Error of LTE (blue), fusion (yellow) and weighted fusion (red).

The error distribution clearly follows a log-normal distribution. Table III shows the parameters to characterise the error of all the cases by their mean and standard deviation (σ) and the 2σ parameter which includes the 95% of the error. By using the remaining information of UWB anchors that were not used in the single-technology scenario, an overall enhancement of the system is achieved. In addition, giving more confidence to the UWB ranges by using a higher weight also improves the performance.

TABLE III
COMPARISON OF BETWEEN LTE, FUSION AND WEIGHTED FUSION HORIZONTAL ERROR.

Source	Mean	Std. Deviation(σ)	2 σ
LTE	1.015	0.637	2.196
Fusion	0.908	0.586	1.997
Weighted Fusion	0.763	0.553	1.997

IV. CONCLUSIONS

In this paper, the fusion of LTE and UWB data is proposed for enhancing cellular-based location. A modification of NRPPa is also proposed due to the role that UWB will take in the upcoming future thanks to its inclusion in the latest flagship smartphones. The use of this novel fusion in the trilateration algorithm noticeably extends the precise coverage area beyond what an UWB deployment can offer on its own. Furthermore, this technique does not require any additional hardware apart from UWB and LTE receivers. This allows a reduction of costs in network deployments oriented at providing location. Firstly, with this setup, a smaller number of UWB anchors is required to provide an accurate and precise location in a planned area. Secondly, in cases where an LTE network already provides location information, but an increase in precision is required, a sparse UWB network can be deployed such that at each point, one or two anchors are visible to use fusion.

REFERENCES

[1] 3GPP, "Feasibility study on new services and markets technology enablers for critical communications; Stage 1," 3rd Generation Partnership Project (3GPP), Technical report (TR) 22.862, 10 2016, version 14.1.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3014

[2] D. Medina, H. Li, J. Vilà-Valls, and P. Closas, "Robust statistics for gnss positioning under harsh conditions: A useful tool?" *Sensors*, vol. 19, no. 24, p. 5402, 2019.

[3] R. Mautz, "Indoor positioning technologies," Ph.D. dissertation, DETH Zurich, Department of Civil, Environmental and Geomatic Engineering ..., February 2012.

[4] E. T. S. I. (ETSI), "Ultra Wide Band," 2020, https://www.etsi.org/technologies/ultra-wide-band?jjj=1596015945046.

[5] T. Wigren, I. Siomina, and M. Anderson, "Estimation of prior positioning method performance in lte," in *2011 IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE, 2011, pp. 1279–1283.

[6] M. Yavari and B. G. Nickerson, "Ultra wideband wireless positioning systems," *Dept. Faculty Comput. Sci., Univ. New Brunswick, Fredericton, NB, Canada, Tech. Rep. TR14-230*, 2014.

[7] H.-H. Liu and Y.-N. Yang, "Wifi-based indoor positioning for multi-floor environment," in *TENCON 2011-2011 IEEE Region 10 Conference*. IEEE, 2011, pp. 597–601.

[8] A. Tahat, G. Kaddoum, S. Yousefi, S. Valaee, and F. Gagnon, "A look at the recent wireless positioning techniques with a focus on algorithms for moving receivers," *IEEE Access*, vol. 4, pp. 6652–6680, 2016.

[9] J. Barnes, C. Rizos, J. Wang, D. Small, G. Voigt, and N. Gambale, "Locata: A new positioning technology for high precision indoor and outdoor positioning," in *Proceedings 2003 International Symposium on GPS\GNSS*, 2003, pp. 9–18.

[10] J. Li, Y. Bi, K. Li, K. Wang, F. Lin, and B. M. Chen, "Accurate 3d localization for mav swarms by uwb and imu fusion," in *2018 IEEE 14th International Conference on Control and Automation (ICCA)*. IEEE, 2018, pp. 100–105.

[11] A. Roxin, J. Gaber, M. Wack, and A. Nait-Sidi-Moh, "Survey of wireless geolocation techniques," in *2007 IEEE Globecom Workshops*. IEEE, 2007, pp. 1–9.

[12] D. Wu, R. Li, R. Li, H. Liang, and J. Luo, "Localization in uwb sensor networks for agriculture environment," in *2008 4th International Conference on Wireless Communications, Networking and Mobile Computing*. IEEE, 2008, pp. 1–4.

[13] P. Teunissen and O. Montenbruck, *Springer handbook of global navigation satellite systems*. Springer, 2017.

[14] R. Labbe, "Kalman and bayesian filters in python," 2015.

[15] 3GPP, "5G;NG-RAN;NR Positioning Protocol A (NRPPa)," 3rd Generation Partnership Project (3GPP), Technical report (TR) 38.455, 07 2018, version 15.0.0. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138400_138499/138455/15.00.00_60/ts_138455v150000p.pdf

[16] L. Chiaraviglio, F. Cuomo, M. Maisto, A. Gigli, J. Lorincz, Y. Zhou, Z. Zhao, C. Qi, and H. Zhang, "What is the best spatial distribution to model base station density? a deep dive into two european mobile networks," *IEEE Access*, vol. 4, pp. 1434–1443, 2016.

[17] I. SM, "Characteristics of ultra-wideband technology," 1755.

[18] P. Kumar, B. Patil, and S. Ram, "Selection of radio propagation model for long term evolution (lte) network," *International Journal of Engineering Research and General Science*, vol. 3, no. 1, pp. 373–379, 2015.