



Exploring Radio Frequency-Based UAV Localization Techniques: A Comprehensive Review

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Abstract: UAVs (unmanned aerial vehicles) and WSNs (wireless sensor networks) are now two well-established technologies for monitoring, target tracking, event detection, and remote sensing. Typically, WSN is made up of thousands or even millions of tiny, battery-operated devices that measure, gather, and send information from their surroundings to a base station or sink. Within the realm of wireless positioning and communication, UAVs have garnered a lot of interest because of their remarkable mobility and simplistic deployment to tackle the problems of imprecise sensor placement, inadequate infrastructure coverage, and the massive quantity of sensing data that WSN collects. A crucial prerequisite for many position-based WSN applications is node location, or localization. The use of UAVs for localization is more preferable than permanent terrestrial anchor nodes due to their high accuracy and minimal implementation complexity. The possible interference or signal block in such an operating environment, however, might cause the Global Positioning System (GPS) to become ineffective or unobtainable. In these conditions, the need for innovative UAV-based sensor node location technologies has become essential. Radio frequency (RF)-based localization techniques are reviewed in the current paper. We examine the available RF features for localization and look into the current approaches that work well for unmanned vehicles. The most recent research on RF-based UAV localization is reviewed, along with potential avenues for future investigation.

Keywords: Unmanned Aerial Vehicles, Wireless Sensor Networks, Localization, Radio Frequency, GPS

1 Introduction and Overview

New developments in communication systems have made it possible to use tiny, inexpensive, energy-efficient, and multipurpose sensors. A wireless sensor network (WSN), which serves multiple purposes, is created by connecting numerous of these small sensors. Monitoring the environment is one of the uses of WSN, traffic management, military tracking, medical monitoring, industrial sensing, and so forth [1], [2]. The environment, houses, and buildings can be monitored and/or controlled by deploying a significant quantity of these sensors in the targeted area. The sensors are wirelessly linked to one another and can speak with one another within the range of their communication. These energy-efficient sensors possess the capacity to measure environmental phenomena, process data, and wirelessly transfer this data to other sensors. These sensors can measure or detect physical quantities, like humidity, temperature, or pressure, and they can transmit this data over short distances. Only when we know in advance where the wireless sensor nodes are located within the network can we make use of the sensed data [3], [4].

A mobile vehicle can be used as the point of contact between the WSN and the outside world, and sensors can be haphazardly placed throughout the target area to create the WSN. Therefore, sensors are initially blind to their location due to the random deployment. Since localization offers essential support for numerous location-aware protocols and applications, it is one of the most crucial tasks in a WSN [5]. The expectation is that individual sensors will not be GPS-enabled due to constraints in form factor, cost per unit, and energy budget. Numerous localization algorithms currently in use require a large number of fixed anchor points, or sensors whose locations are known in advance. The size of the deployment area increases both the quantity and expense of anchor point deployment. Furthermore, using anchor sensors in emergency situations is inappropriate because the anchor points need to be set up ahead of time [6], [7].

Data in a WSN are initially gathered by a local node, which then transmits the pertinent data to an infrastructure central to the deployment area but geographically remote from it [8]. Using an unmanned aerial vehicle (UAV) [9]

or mobile anchor sensor in place of fixed anchor sensors will reduce the setup costs of WSNs [6]. UAVs, commonly referred to as drones, have drawn more attention recently from the scientific and business communities. In this regard, UAVs are intended to replace traditional gateways in order to get around their drawbacks with regard to range, bandwidth, energy usage, as well as the requirement for tangible infrastructure. A UAV can swiftly travel to each and every WSN node and any point within the mission area [10]. The primary objective of the UAV in most real-world situations is to collect and share data from a collection of sensor nodes that have been placed throughout the mission area. When the UAV approaches the sensor node, it can function as a "smart and ubiquitous" local host and facilitate low-power, short-range data exchange. For instance, this could result in battery-operated sensor nodes for Industry 4.0 or Internet of Things (IoT) scenarios having a much longer lifespan, lasting months or even years [8], [11].

Range-free and range-based localization algorithms can be distinguished based on the method used to estimate the positions of the sensors. In the first scenario, no ranging measurements of any kind are used in the position estimation process. In the latter case, several characteristics of the communication signals, including the Received Signal Strength Indicator (RSSI) and the Time of Arrival (ToA), are used to infer the estimations [6], [12].

There have been a lot of recent and pertinent contributions made that deal with WSN or UAV technologies. These two subsystems lack efficiency in terms of data transfer, dependability, and self-sustained operation duration. Relying solely on ground sensors for communication would rapidly drain their batteries, and employing UAVs exclusively would be energy-inefficient. Therefore, a combination of these two agent types offers a better solution than the sum of its parts, whether it is stationary or mobile [6], [13].

There are already a lot of useful surveys available, but they don't offer a thorough and in-depth analysis of the most advanced localization systems. Most of the research only addresses a portion of the issues. The likelihood of a broadly sound solution is constrained by the more restricted perspectives. Certain surveys only offer a cursory overview and conceptualization of a localization system [14].

An updated survey paper that takes into account the most recent developments and trends in the localization industry is always needed. Additionally, a thorough investigation that covers the algorithms, various implementation details, and working principles is required. With the help of this survey, we hope to give researchers a comprehensive understanding of the localization issue so they can develop fresh ideas and advance the localization study [15].

The significant contributions contributed to the current state of peace of work are listed as follows:

- An extensive summary of the most recent RF-based

UAV localization systems is provided. Each system's benefits and drawbacks are analyzed to demonstrate how applicable they are and how challenging it is to place UAVs.

- A comprehensive survey and discussion are offered in order to assess the viability and feasibility of the current RF-based UAV localization technologies for accurate UAV location.

The arrangement of the current peace of work is shown as follows: in Section 2, we review the different localization schemes that have been put forth in the literature. In Section 3, the available radio frequency (RF) features are examined for localization and the approaches that are currently appropriate for unmanned vehicles, including time difference of arrival (TDOA), received signal strength (RSS), angle of arrival (AOA), time of arrival (TOA), and so on. We present various technologies. In Section 4, we emphasize wireless technologies that are useful for indoor positioning. The main topics we cover are WiFi, Bluetooth, and Zigbee. The main point of view during the conversation is localization, and we go over the benefits and drawbacks of each technology. Lastly, Section 5 concludes with a summary of the entire paper.

2 Models and Categorization of Localization

According to their goals, localization models often vary in a number of areas, including localization technique, anchor type, application area, deployment area, and localization processing. An overview of the localization models' goals may be seen in Figure 1. The next few sections will cover a few of these categorizations.

A. Range-Free vs. Range-Based Localization Techniques

Range-free models and range-based models are the two general categories into which localization techniques in WSNs fall. Methods based on ranges employ the length or angle of the communication link between the nodes to determine their positions. Time of Arrival (TOA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA), and Received Signal Strength Indicator (RSSI) are a few examples of this type of data. However, range-free approaches rely simply on the nodes' connection to some location-aware nodes, known as anchors. The UN is able to determine its geographical position through computations and the exchange of location data [16].

B. Distributed vs. Centralized Localization Processing

Within the framework of distributed algorithms, the UN establishes its localization by means of a single-hop or even multi-hop message exchange with its neighbors around it. Data transmitted between nodes is followed by the BS processing the localization prediction in the centralized method [16].

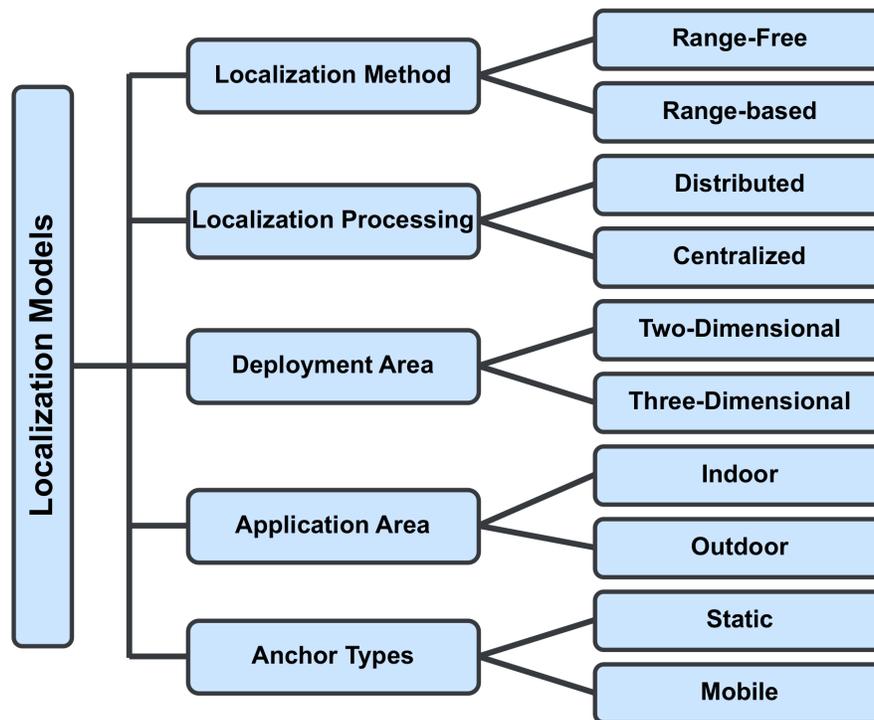


Figure 1. Localization type categorization in WSNs according to goals.

C. Two-dimensions versus Three-dimensions Deployment Area

Numerous studies are being suggested on localization in WSNs; however, they mostly concentrate on two-dimensional (2D) spaces. Sensor nodes are often placed on flat surfaces that include three-dimensional (3D) spaces in applications in the real world. These surfaces may be found in both outdoor and indoor settings, such as on doors, tables, walls, floors, and woods, hills, valleys, and mountains [16].

D. Outdoor vs. Indoor Area of Application

Physical barriers such as walls may hinder localization measures and precision in interior spaces. Such barriers can also be found in outdoor settings; thus, when using a localization approach, the application region needs to be carefully considered [17].

E. Mobile vs. Static Node Type and Anchor

There are four types of localization schemes that use anchor nodes: static anchors and static nodes, static anchors and mobile nodes, mobile anchors and static nodes, and mobile anchors and mobile nodes [16].

3 Related Work

Numerous surveys have been conducted in the localization field, addressing the subject from various angles. Among the first noteworthy publications to introduce the concept of using a GPS-equipped UAV as a beacon node.

In this instance, knowing the location is not required for the WSN node beforehand. GPS data and the RF communication's RSSI signal strength between the UAV and the node are combined for WSN node localization. A probability distribution function represents the position. Experiments demonstrate that the RSSI signal's standard deviation drops with increasing node and WSN distance. As a result, there is no need to filter the signal, and the positions are less susceptible to measurement errors [6].

The [18] discussed how to optimize for shorter UAV flight times during missions to gather data in support of ground sensor networks. The scenario assumes that the WSN deployment will be controlled in a straight line by the UAV during cruising or hovering. The aim is to optimize the sensor transmit power, UAV speed, and non-overlapping data collection intervals through the application of dynamic programming (DP). The primary result emphasizes how fast the UAV ought to be correlated with the sensors' energy states and the separation between sensors. Under the energy randomness assumptions, a number of scenarios are defined for evaluation, ground node localization, and data requirements. In contrast to hovering, it's been found that even though the nodes' data rate drops while cruising, the mission time reduction can make up for it. This works for small amounts of data; however, the hovering approach is better when the data reaches a certain threshold.

An effective cooperative sensor positioning and data



gathering approach for WSN facilitated by numerous UAVs is presented in [19]. In particular, one UAV is designated as the primary data collection vehicle, while additional UAVs are utilized as backup UAVs for TDoA sensor positioning. An uncertain sensor position presents a non-convex optimization problem involving mixed integers. By simultaneously optimizing the UAV trajectories, reducing the average positioning error of all sensors is the goal of the positioning observation points (POPs) and sensor transmission schedule.

“Weighted Energy-aware Trajectory with Adaptive Radius (WETAR)” is a novel drone trajectory planning technique that is presented in [20]. For trajectory planning, the suggested method makes use of linear programming (LP) when sensors obtained throughout a range-free pre-localization stage that have specific estimative regions are present.

The current work first maximizes altitude aloft, and then it uses this optimal height to define the node localization problem as a least squares optimization problem. It has been discovered that using optimization techniques for least square localization is a better option than multilateration based on the obtained signal strength indication, that leads to a significant localization error. Regarding this optimization issue, high accuracy can be attained through the powerful optimization technique known as the Artificial Bee Colony (ABC) algorithm, which was recently proposed. In order to minimize localization error, this paper’s objective is to create an ABC localization technique using UAV anchors [21].

The challenge of localizing these nodes with a mobile UAV that doesn’t know where it is addressed is addressed in this paper. Unlike previous works, this does not presuppose a UAV equipped with GPS. Every sensor node records an RSSI vector after receiving beacon packets sent by the UAV at random positions. Range is defined as the theoretical relationship between the L1 norm distance of two RSSI vectors, and the distance between two nodes is demonstrated to be linear. After that, target nodes are localized using an already-existing location estimator [22].

An approach called Low-Cost Physical Locations Discovery (LCPLD) is put forth in [23]. Both UAVs and mobile vehicles are employed in the LCPLD scheme to physically locate users on wireless sensor networks, a crucial part of smart cities’ use of the IoT. To further minimize expenses, they suggested the algorithm known as AUFPP, which stands for Adaptive UAV Flight Path Planning, to minimize UAV flight costs and a task application mechanism to minimize vehicle broadcasting costs. This paper proposed two algorithms that, in order to minimize localization error, employ UAV Same Position Broadcast Repeat (USPBR) and Large Error Rejection (LER).

In [24], a novel approach to obtain more precise range information is proposed. Unlike previous conven-

tional works, which rely on single-distance information, they employ multiple-range information. First, after a UAV sends beacon packets to them at random locations, sensor nodes log RSSI (Received Signal Strength Indicator) vectors. We may ascertain the distance between nodes by analyzing the RSSI vectors’ similarity. Subsequently, we calculate the separation between two nodes by contrasting their channel state information (CSI) with that of the UAV. Lastly, we fuse the two-range information using the Kalman filter. Additionally, we can obtain more precise range data for positioning.

Regarding UAVs assisting WSNs, [25] suggested a deep learning-based localization approach. The two components of the scheme are localization and ranging. As part of the range component, a UAV gathers data by measuring the distances between the ground sensor nodes. Using the range information, a localization convolutional neural network (CNN) is built and trained in the localization component to estimate the node coordinates.

In [26], the authors used a UAV for data collection and sensor localization, dividing the WSN into standard hexagon-shaped network cells (NCs). It is suggested to use received signal strength (RSS) for sensor localization. Additionally, the WSN per-node capacity and the sensor coordinates’ Cramer-Rao lower bound (CRLB) are determined.

Table I illustrates a comprehensive comparison of UAV-based WSN localization techniques for the literature.

4 Traditional Methods of Localization

In this part, RF-based UAV localization methods are described together with a thorough examination of the conventional localization methods, like fingerprint, TDOA, TOF/TOA, AOA, and RSS, etc. Additionally, at the conclusion of this section is a summary of each UAV placement, including its capabilities, applicability, and problems.

A. Received Signal Strength (RSS)

For anchor-based localization, one of the simplest methods is the received signal strength (RSS) approach. The RSS, which is expressed in milliwatts (mW), indicates the power level that the receiver received. A receiver (RX) and a transmitter (TX) engage in an indirect measurement known as the RSS. A higher RSS indicates a closer separation between RX and TX. The greater distance between TX and RX is indicated by the smaller RSS [27].

Using the measured RSS, it is easy to compute the transmission distance and the signal attenuation quantitatively and then apply the suitable model for the propagation of signals. The transmission distance can then be used to estimate position information using trilateration or multilateration. Equation 1 displays the propagation model, and Figure 2 clearly displays the conceptual design of the RSS-based localization process.



TABLE I. Comprehensive Comparison of UAV-based WSN Localization Techniques.

Ref	Technique	Description	Advantages	Disadvantages	Considerations	Future Directions
[6] 2019	RSSI-based localization	Uses a GPS-equipped UAV as a beacon node to estimate WSN node location based on the Received Signal Strength Indicator (RSSI) signal strength.	No prior knowledge of WSN node location needed -Simple implementation	-Accuracy decreases with distance due to signal propagation factors -Not suitable for large-scale deployments	-Requires calibration for different environments - Potential for incorporating machine learning for improved accuracy estimation	Explore integration with other localization techniques for enhanced robustness
[18] 2018	Dynamic programming for trajectory optimization	Optimizes the UAV flight path to minimize mission time for data collection from ground sensors using dynamic programming (DP).	Reduces mission time and resource consumption	- Assumes linear WSN deployment and static sensor locations - May not be efficient for complex network layouts	- Requires accurate initial estimates of sensor locations and data requirements - Consider incorporating real-time updates on sensor positions and data demands	Investigate adaptation to handle dynamic network environments
[19] 2023	Cooperative sensor positioning with multiple UAVs	Utilizes multiple UAVs for sensor positioning and data collection. One UAV acts as the primary data collector, while others serve as backups for Time Difference of Arrival (TDoA) based sensor positioning.	Improves localization accuracy and fault tolerance	- Requires complex optimization algorithms and coordination between UAVs - Increases operational cost and complexity	- Suitable for large-scale and critical deployments - Explore distributed and collaborative optimization approaches for better scalability	Investigate integration with edge computing for real-time data processing and decision making
[20] 2020	WETAR trajectory planning	Employs Linear Programming (LP) for trajectory planning based on pre-localized sensor estimates obtained during a range-free pre-localization stage.	Efficient for known sensor locations and predictable environments	- Not suitable for dynamic scenarios or real-time localization - Requires accurate pre-localization data	- Useful for initial deployment or static network monitoring - Explore integration with online learning algorithms to adapt to changing environments	Investigate incorporating environmental factors (e.g., wind) for more robust trajectory planning
[21] 2020	ABC algorithm for localization	Leverages the Artificial Bee Colony (ABC) algorithm for least squares based localization with UAV anchors.	Achieves high localization accuracy	Computationally expensive and requires significant processing power on the UAV	- Suitable for applications requiring high precision, but resource constraints need to be considered - Investigate hardware acceleration techniques or resource-efficient variants of the ABC algorithm	Explore federated learning approaches to distribute computational workloads across multiple UAVs

TABLE I – Continued on next page



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[22] 2019	Localization with mobile UAV	Localizes nodes using RSSI vectors and an existing location estimator without requiring a GPS-equipped UAV.	No GPS needed for the UAV, reduces cost and complexity	- Relies on the accuracy of the existing location estimator - May not be suitable for highly dynamic environments	- Useful for scenarios where GPS is unavailable or cost-prohibitive - Investigate incorporating alternative ranging techniques (e.g., Time of Arrival) for improved accuracy	Explore the use of lightweight and low-power location estimators suitable for deployment on WSN nodes
[23] 2021	LCPLD for low-cost localization	Combines UAVs and mobile vehicles with cost-minimizing algorithms (AUPPP and USPBR with LER) for user localization in WSNs, relevant for smart city applications.	Lowers operational cost compared to using only UAVs	Requires additional infrastructure (vehicles) and incurs maintenance costs	- Suitable for large-scale deployments in urban environments - Explore alternative cost-effective mobile platforms (e.g., ground robots)	Investigate integration with crowd-sourced localization data from mobile devices for enhanced coverage
[24] 2020	Multi-range information fusion	Improves range estimation and localization accuracy by combining RSSI and Channel State Information (CSI) data using a Kalman filter.	Provides more accurate range information compared to single-source methods	Requires complex data processing and may have higher computational demands	Beneficial for applications requiring high precision and reliable localization	Investigate advanced data fusion techniques (e.g., deep learning) for improved information extraction
[25] 2022	Deep learning-based localization	Employs a Convolutional Neural Network (CNN) trained on range data for sensor localization.	Has the potential for high accuracy, especially with large training datasets	Requires a significant amount of training data and computational resources on the UAV	Promising technique for future advancements, but practical implementation challenges exist	- Investigate federated learning approaches to train the CNN model collaboratively across multiple UAVs and WSN nodes, reducing individual resource requirements. - Explore lightweight and efficient CNN architectures specifically designed for resource-constrained UAV platforms.
[26] 2022	RSS-based localization in hexagonal WSNs	Utilizes received signal strength (RSS) for sensor localization in hexagonal network cells.	Simple and efficient to implement	Lower accuracy compared to other methods due to limitations of RSS-based techniques	May be suitable for preliminary localization or resource-constrained scenarios	- Investigate incorporating machine learning or statistical models to improve accuracy estimation based on RSS measurements. - Explore integration with other complementary localization techniques for enhanced robustness.

where:

$$P_d[dB] = P_0[dB] - 10\alpha \log_{10}(d/d_0) + X_\sigma[dB] + b[dB]d = \|X-S\| \tag{1}$$

- P_0 : power at the standard 1-meter reference distance, or d_0 , from the transmitter.
- P_d : obtained power at d distances from the source.
- X_σ : the shadowing effect, which is primarily Gaussian.
- α : The rate of power loss over distance is known as the path loss exponent, or PLE.
- b : bias error.

For the device-based localization (DBL) scenario, RSS-based localization necessitates trilateration or N-point lateration. This means that the device's RSS is utilized to determine the precise distance between the user's device and a minimum of three reference points. Subsequently, fundamental geometry and trigonometry are employed to determine the user's device's location in relation to the reference points. Comparably, the user device's position is determined in the monitor-based localization (MBL) scenario by using the RSS at the reference sites. The latter requires ad hoc communication between anchor points or a central controller to handle the entire RSS gathering and processing operation. However, in order to establish a geofence and determine the user's closeness to the anchoring node according to the approximate distance from the path loss, RSS-based proximity-based assistance (like sending marketing alerts to a user when they're near a retail store) needs only one reference node [28], [29].

UAV localization has previously made extensive use of RSS-based localization techniques.

A technique based on receiving signal strength measurements (RSS measurements) is used to find the location of RFID tags. In [30], an analysis was conducted utilizing Cramer-Rao bound expressions to determine how the configuration of the sensor network, which is distributed throughout the room, had an impact on how accurately RFID tags were located based on RSS measurements of the sensor network.

B. Angle of Arrival (AOA)

Using the angle at which the signal from this technique arrives, the transmitting node is utilized to determine the sensor node's location. The localization method uses the angle data captured by several receivers to determine position. As seen in Figure 3, UAV position can be estimated using triangulation using the antenna array's AOA data as well as anchor nodes' historical location data [31].

The most popular method for determining the angle of arrival signal to measure is to set up antenna arrays on the

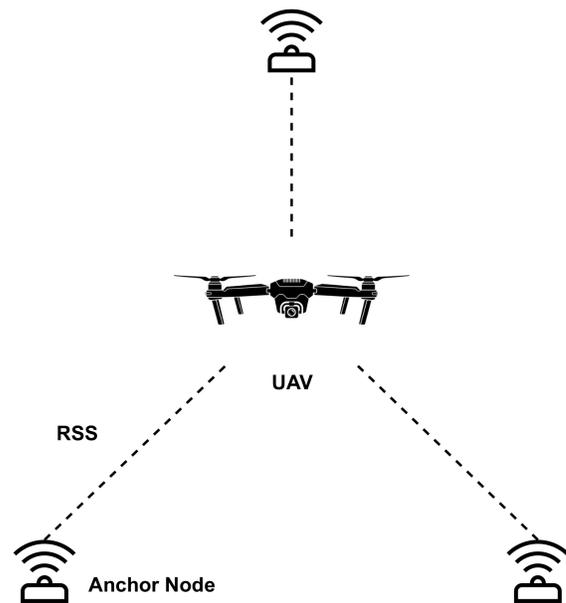


Figure 2. RSS based localization mechanism.

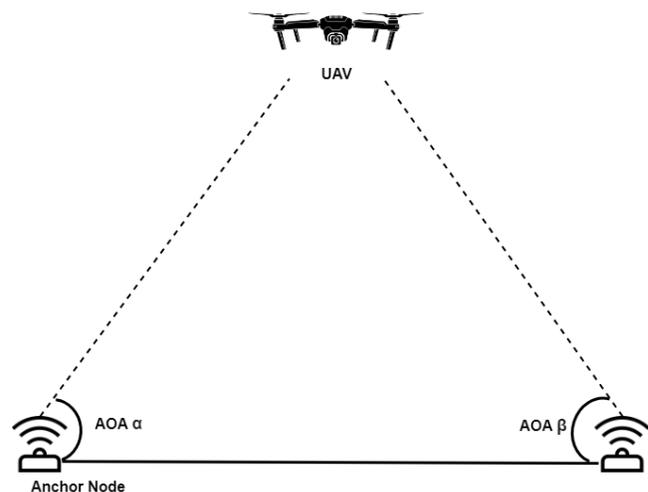


Figure 3. AOA based localization mechanism.

sensor node. The measurement is made of the difference in the TOA of the signal from different antennas because the arrays are placed independently at known positions. The alternative is to employ directional antennas, which are mounted on the sensor nodes and are utilized for both signal transmission and reception. The directional antenna is rotated around its axis to transmit or receive in all directions, serving multiple nodes. High precision is attained, but sophisticated hardware is required. Additionally, accuracy will be impacted by shadowing and multipath fading [31].

In situations where there is no multipath effect, the anchor position can be accurately estimated using the AOA-based approach. The localization accuracy typically decreases when multiple agents are working within [27], [32].

However, a number of recently suggested high-accuracy localization systems based on AOA have also been examined in [33]. The wireless sensor network's AoA measurements can be used to pinpoint where the unidentified UAV that was serving as a radio source was located. A dynamic system with discrete-time switching is used as a model to explain the movement of a maneuvering UAV. The switching variable's values dictate the kind of movement the UAV makes. The extended process's Markov property is utilized in the construction of trajectory filtering algorithms, which are composed of a switching variable and a vector of UAV movement parameters. For determining the posteriori probability density function of an extended process, a recurrent technique is described by the ideal trajectory filtering technique. An ideal filtering device would include many channels and inter-channel feedback.

In [33] the algorithm, which is developed as data from additional pairs of sensors is received, the location of radio sources in a rectangular coordinate system can be repeatedly determined utilizing the Kalman filtering mathematical apparatus. One pair of sensors determines the location of the sources, which is used to form the initial conditions.

Even though AOA-based techniques offer many more benefits, there are still a lot of variables that could affect how well localization works. Due to the intrinsic characteristics of triangulation, the proper operating range of UAVs can be limited by even a tiny measurement error, which can have a substantial impact on localization accuracy as transmission distance increases. In addition, because of the additional complex hardware, the UAV's payload, energy consumption, and system cost will all increase. Most importantly, the estimates of AOA are typically skewed in a dense multipath environment. Therefore, more study is still required to fully understand the AOA-based localization mechanism for UAV positioning [19], [34].

C. Time of Arrival (TOA)

The Time-Of-Arrival (TOA) technique is multiplied to find the duration of an RF signal. The speed of the signal in the medium, which is typically the same as the expedition at which light propagates, can be used from transmitter to receiver. It is thus possible to infer the scope. Provided there is a line-of-sight (LOS) path and strict clock synchronization between the transmitters and receivers, TOA is more accurate than RSS. The wave's speed is not greatly impacted by the obstruction [35].

Trilateration or multilateration can be used to realize UAV positioning given the range information. When compared to the RSS and AOA, the TOA can perform with higher accuracy and requires no additional apparatus, which

is important for UAV positioning. Figure 4 makes it evident, nevertheless, that all of the network's sensor nodes must synchronize their clocks [19], [36].

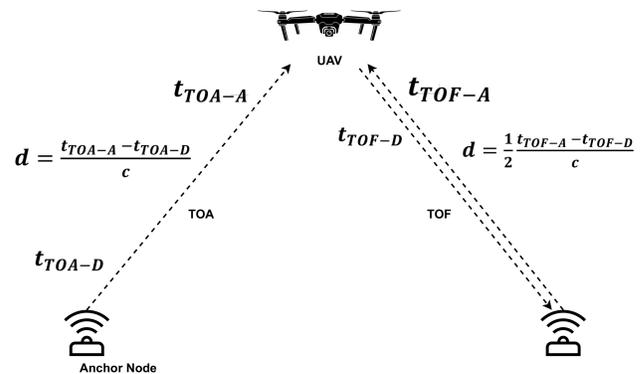


Figure 4. TOA based localization mechanism.

Many strategies have been put forth to reduce the influence of clock differences, in [37]. In an effort to lower the influence of clock differences, in mixed line-of-sight (LOS)/NLOS scenarios, the cooperative localization problem based on time of arrival (TOA) is addressed, along with the NLOS errors. A cooperative localization algorithm based on the topological unit is proposed for TOA NLOS mitigation, by examining the topological relationship between nodes. The framework of classical multidimensional scaling is used to implement this algorithm.

The authors in [38] suggested $T1A_a$, a hybrid algorithm for TOA/AOA localization, in order to reduce the agents' complexity. Only TOA-ranging and azimuth angle estimation are combined in $T1A_a$. Agents can therefore operate with less complex signal processing, a 1-D antenna array, and less power.

There are two types involved in this technique:

- 1) One-Way Time of Arrival: This method uses the distinction between the beacon node's and the dumb node's acquired times to estimate the position, respectively. Since the receiver node determines its location without disclosing it to the beacon node, it is also known as passive arrival localization time. Typically, one uses either an ultrasonic pulse or an RF signal to determine distance. The primary drawback of this method is that it necessitates synchronization between the transmitting and receiving times. A tiny variation in the timing causes a significant inaccuracy in the estimation of position and distance. An extremely tiny synchronization error of roughly 1 ns at the speed of light causes an approximate 0.3 m error in distance estimation. As a result, in order to attain synchronization, the sensor nodes must be equipped with additional circuitry,



such as highly accurate clocks, which raises their weight and cost [39].

- 2) Two-Way Time Of Arrival: With this method, the receiver returns the signal to the transmitter. The time it takes to travel both ways between the dumb nodes and the beacon is used to estimate the distance. Since the transmitting sensor node uses the same clock to measure the time difference, synchronization is not necessary. The mistake arises when the dumb node needs extra time to handle, process, and relay the signal back to the beacon node [33], [40].

D. Time Difference of Arrival (TDOA)

The TDOA technique takes advantage of the variation in signal traveling time that is measured at the receiver device and is produced by several transmitters. Compared to the straightforward TOF-based approach, this one is better [27].

The TDOA-based localization mechanism can significantly reduce localization latency and energy usage when compared to the TOA, as precise positioning only needs to know how much time each sensor node is apart. This can significantly enhance the UAV's timing and stability [19].

In [41] to enhance the precision of target localization, the combined time difference of arrival (TDOA) and frequency difference of arrival (FDOA) localization technique is improved in this paper by the addition of information on phase difference of arrival (PDOA). First, a multi-station precise phase synchronization approach using joint TDOA, FDOA, and PDOA localization is derived, yielding the Cramer-Rao lower bound (CRLB).

Two sensor network configurations are examined, each having a distinct quantity of sensors distributed equally around a circle. The methods' operability is guaranteed by the sensor network's initial configuration, which has the fewest possible sensors. The location of a specific range's radio source in any direction can be found with the same accuracy using the sensor network's second configuration. By combining the accuracy of the sensor network's measurements using TDOA, RSS, and AOA, the radio source's location is analyzed [42], [43].

When comparing the TDOA method to the TOF-based method, the primary benefit of the TDOA method is that it eliminates the need for costly atomic clocks on the receiver side. The new agent does not require any prior knowledge of the precise time, and the hard synchronization issue is solely related to infrastructure. Thus, the initial installation cost of the TDOA method is high. It's extremely inexpensive for a new agent to come after. However, this approach has the same issue as the TOF method. There will be a noticeable decrease in accuracy and generalization when there are obstacles. The TDOA method continues to be regarded as simple in terms of computational and system complexity. The TODA's affordability and ease of use have made it the most popular approach [27].

Table II provides an overview and discussion of the benefits and drawbacks of using RF-based localization systems in place of traditional localization processes for UAV locations. Because of their great localization accuracy, time-based localization techniques like TOA/TOF and TDOA are highly sought after. Furthermore, our study indicates that several studies have been conducted on RSS-based localization methods, taking into account their ease of installation and cost-effectiveness. but mostly concentrated on the utilization in open environments.

5 RF-based UAV Localization Systems

The crucial integration work for large-scale UAV-WSN monitoring systems is carried out by data communication [48]. Because of the possible future applications of UAV localization, several state-of-the-art radio frequency (RF) localization systems have been reviewed that are able to achieve decimeter-level localization accuracy. The following subsections go into great detail about radio communication technologies, as illustrated in Figure 4, including Bluetooth, Wi-Fi, Zig-bee, RFID, and UWB-based localization systems [48].

A. Wi-Fi based Localization System

An international standard known as IEEE 802.11 describes the characteristics of a wireless local area network (WLAN). Originally, WiFi stands for Wireless Fidelity, and the WiFi Alliance has awarded a certification with that same name (formerly WECA, or Wireless Ethernet Compatibility Alliance), the group in charge of ensuring that devices that are 802.11 compliant can communicate with one another [37], [49].

In [50] in addition to new technological directions and developments being highlighted, consolidated mathematical models of lateration and location fingerprinting are presented and evaluated. The case studies' findings show that Wi-Fi is capable of continuously localizing users even in dynamic settings and in kinematic mode, where users walk at a regular pace. However, in order to reduce the variance issues brought on by the heterogeneity of the devices, calibration of the devices is required to obtain a satisfactory level of localization accuracy.

In [51] in order to enhance precision and resilience the paper proposed a positioning system named CCPos (CADE-CNN Positioning) as an application of indoor WiFi fingerprint localization technology. This system is built around a convolutional neural network (CNN) and a convolutional denoising autoencoder (CDAE). During the offline phase, the K-means algorithm is used to extract the validation set from the whole training set. The RSSI is first denoised in the online stage, after which the CDAE extracts important features. The CNN then outputs the location estimate.

B. Bluetooth based Localization System

Through the use of Bluetooth, devices within a certain proximity can communicate wirelessly and share data



TABLE II. A comparative analysis of current RF-based UAV localization systems with traditional methods.

Ref.	Method	Drawbacks	Benefits
[44]	the RSS and AOA of the signal from the suspect emitter	does not address the trajectory planning for the legitimate UAV to track the suspicious UAVs	maximizes the number of eavesdropped packets, enhancing the effectiveness of wireless surveillance, improving the tracking accuracy of the UAVs' trajectory.
[30]	RSS measurements of the sensor network.	it focused specifically on the influence of sensor network configuration on the precision of using RSS measurements to determine the location of RFID tags. Other factors that may affect accuracy, such as environmental conditions or interference, were not considered in this analysis.	ability to mitigate multipath impairment, robustness against environmental conditions such as dust, more precise tracking and localization of RFID tags.
[45]	Unmanned aerial vehicles (UAVs) based on AOA-measurement sensor networks.	The real-time implementation of the optimal algorithm described in the paper is difficult due to its non-linear character and the form of the measurement equations.	reduce the UAV location error compared to the error Using the AOA method alone, two to three times, provides a high probability of identifying different kinds of UAV movement.
[46]	Angle of Arrival (AoA) method based on MIMO technology.	does not mention any limitations or potential sources of error in the measurement equation or the model used for state vector estimation done recursively using the Kalman filter.	The AoA method is known for its simplicity and wide practical application, making it a suitable choice for figuring out where a radio source is.
[47]	TOA NLOS mitigation cooperative localization algorithm based on the topological unit	does not address the potential impact of measurement noise or uncertainties in the localization process.	improved NLOS mitigation in cooperative localization, better localization performance.
[38]	Hybrid TOA/AOA localization method	it requires elevation AOA estimations, which may not always be available or accurate in certain scenarios.	it reduces the complexity of the agents by only requiring elevation estimations of AOA to complement TOA measures, lower computational complexity.
[41]	joint time difference of arrival (TDOA), frequency difference of arrival (FDOA), and phase difference of arrival (PDOA) localization approaches.	does not discuss the limitations of the assumptions made in the localization equations or the impact of measurement errors on the accuracy of the localization results.	improves target localization accuracy, enhances localization performance in different scenarios.
[42]	TDOA (Time Difference of Arrival), RSS (Received Signal Strength), and AOA (Angle of Arrival) measurements of a sensor network.	the presence of anomalous measurement errors, which can lead to divergence of conventional Kalman filtration algorithms to estimate parameters related to radio source movement, the sensitivity of the source location estimates to random noise in the known sensor positions.	reduce the loss in source localization accuracy due to uncertainties in sensor positions, improve the accuracy of positioning.

within a personal network. It can be said that Bluetooth was the first WPAN to be designed and specified [37].

The frequency hopping technique, employed by Bluetooth minimizes interference with other systems coexisting in this popular band and prevents frequency fading by employing different carriers one after the other in a pseudo-random sequence [37]. Numerous localization systems based on Bluetooth have already been created with UAV positioning in mind.

In [52], the authors created BloothAir, a safe aerial relay mechanism with multiple hops built on self-contained drones with Bluetooth Low Energy (BLE) connections. For BloothAir, a channel-based technique for the generation of secret keys is suggested to encrypt BLE communications. In order to generate the secret keys, the ground devices and drones quantize the received signal strength.

[53] provided a practical and affordable indoor navigation system that can be used to guide people through

big, intelligent buildings. Utilizing Bluetooth Low Energy (BLE), an upcoming short-range wireless communication technology based on the Internet of Things, the solution provides mobile users with smartphone navigational guidance. Our work primarily contributes to science with A brand-new proximity-based GPS system that uses beacon data to determine the user's position, processes the optimal Using the edge computing infrastructure's indoor navigation path, the user receives the results on their smartphone.

In [54], the authors highlighted the need for ubiquitous bike identification to enhance situational awareness and suggest AV-mounted Bluetooth receivers as a means of locating and identifying a pedalcyclist's "beaconing" Bluetooth device, such as an already-existing, reasonably priced performance monitoring system, as a potential solution. Using the Received Signal Strength Indicator (RSSI) of the receivers, this method calculates the distance to the bicycle.

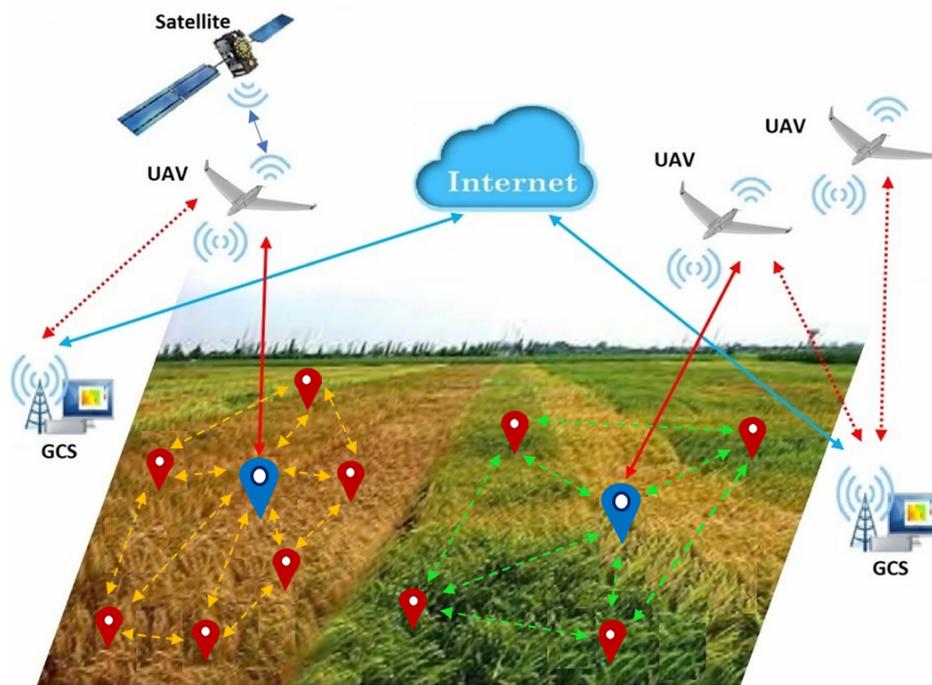


Figure 5. The idea of a WSN-UAV integrated system.

Still, more investigation is needed, particularly to address the issue of limited localization coverage and susceptibility to NLOS paths.

C. Zigbee based Localization System

Zigbee, specified by IEEE 802.15.4, is one of these WSN technologies. Zigbee works well in a variety of industries, including the industrial sector, home automation, and medical and healthcare sectors, as a well-liked wireless sensor network technology due to its many benefits, including low latency, low power consumption, substantial scalability, affordability, and flexible topology [38].

Zigbee is still susceptible due to NLOS's influence paths, and low data rates can result in high localization latency, which is incompatible with UAV requirements. Based on our investigation, there is currently a single scientific publication that uses a Zigbee-based UAV localization system.

In [55], an APM 2.0 automated quadrotor was used to test a proposed UAV localization system that combined Zigbee and INS to achieve an absolute accuracy of 20 cm. The system's performance was only evaluated in an open space; thus, the NLOS path's influence was disregarded. Just a rate of sampling for localization was configured on the simulation platform at 1s; the localization latency was left out.

D. UWB based Localization System

In the short-range communication space, ultra-wide band technology (UWB) provides the advantages of strong immunity to interference and adaptable data rates with minimal power usage. Because of its fine-grained ranging/localization accuracy, obstacle penetration capability, and high resolution in time and space, UWB outperforms other ranging techniques when it comes to indoor localization and positioning [41].

With UWB's obvious features, it has become a dependable and practical localization technology that has garnered many interests for the placement of UAVs in the past few years. In [62], in order to increase the robustness and accuracy, suggest an IPS, or integrated indoor positioning system, that combines UWB and IMU by utilizing the extended (EKF) and unscented (UKF) Kalman filters.

The authors of [63] introduced SnapLoc, an indoor localization system based on UWB that enables an infinite number of tags to self-localize at a $2.3kHz$ theoretical upper bound. A tag in SnapLoc receives responses from several anchors at once. The tag determines its position and the time difference between anchors based on these signals. As a result, SnapLoc only needs tags to receive a single message, rather than actively transmit packets. This guarantees that SnapLoc's performance does not suffer at high node densities and permits tags to passively localize themselves.



TABLE III. Description of Various Wireless Methods for Localization.

Technique	Maximum distance	Throughput maximization	Energy usage	Benefits	Drawbacks
IEEE802.11 n IEEE802.11 ac IEEE802.11 ad	250M outdoor 35M indoor few meters	600Mbps few 1.3Gbps 4.6Mbps	Average	Good precision, widely accessible, and without any complicated additional hardware	noisy by nature and necessitates intricate processing methods
UWB	10-20M	460Mbps	Average	interference-free, offers excellent precision	Reduced range, more expensive, and requiring additional hardware for many consumer devices
Bluetooth	100M	24Mbps	Low	Minimal energy usage, wide receiving range, and significant throughput	Poor localization precision and noise vulnerability
RFID	200M	1.67Gbps	Low	minimal power consumption and broad range	The precision of localization is poor.
LoRA	15km	37.5Kbps	Very low	Minimal energy usage and a large receiving range	Extended distance from the device and base station, severe signal attenuation from outside to inside owing to building walls

A review of the various wireless technologies from the standpoint of localization is given in Table III. Here is a summary of the energy usage, throughput, maximum range, benefits, and drawbacks of employing certain technologies for localization [64], [65].

Table IV provides a summary and analysis of the benefits and drawbacks of the current RF-based UAV localization methods using various radio communication methods.

6 Challenges and Open Problems

There are several ways in which a localization scheme could appear weak. Algorithmic or hardware-related issues might cause failures. The first category comprises failure scenarios brought about by the limitations of the current algorithms, such as challenges managing excessively dynamic or severe situations. The last category comprises sensor degradation-related failures, such as mechanical LIDAR failures [66].

The data association is among the main reasons algorithmic errors occur. The backend optimization procedure cannot produce satisfactory results if there are false positives or false negatives due to incorrect data association. Unmodeled processes in the environment have the potential to exacerbate the issue. The world stays the same while the UAV flies across it, which is a very typical assumption in the present localization technique. In actuality, though, there may be variations in the weather, lighting, etc. It stops the system from operating in the intended manner.

Another group of issues that might lead to system failure is sensor deterioration. Dust particles on the lens of

autonomous UAVs operating in dusty environments cause incorrect associations. Long-term use will undoubtedly cause certain sensors to fail. The topic of how to design a system that can withstand several types of failure remains unanswered.

Although most successful demonstrations of contemporary localization algorithms have taken place in interior building-scale environments, many application initiatives require UAVs to operate across longer distances for lengthy periods of time. The amount of memory needed to retain previously recognized landmark features will increase dramatically. While outdoor uses GPS for localization, drift or posture tracking loss may still occur while switching paradigms.

Here are some more recent challenges and open problems in UAV localization:

- **Urban Environments:** As UAVs are increasingly used in urban environments for tasks like surveillance, delivery, and transportation, navigating through complex and dynamic urban landscapes poses significant challenges. The presence of tall buildings, signal reflections, and signal blockages can impact the accuracy of localization systems.
- **Edge Cases and Uncommon Environments:** Localization systems may struggle in unconventional or extreme environments, such as dense forests, caves, or areas with significant electromagnetic interference. Developing robust algorithms that can handle these edge cases is an ongoing challenge.
- **Interference and Security:** As the number of UAVs in the airspace increases, there is a growing con-

TABLE IV. A comparative analysis of current RF-based UAV localization systems.

Ref.	Method	Drawbacks	Benefits
[56]	Uses mathematical models of location fingerprinting and lateration to assess the suitable techniques for Wi-Fi user localization.	May not perform well in very complex environments with small-scale structures and different materials in the walls, as it does not consider multipath, refraction, and diffraction.	It easily accessible for mobile clients like smartphones, achieve accuracies on the meter level, increase positioning accuracy
[57]	A positioning system for indoor WiFi fingerprint localization called CCPos (CADE-CNN Positioning) that is based on a convolutional neural network (CNN) and a convolutional denoising autoencoder (CDAE).	Does not address the potential limitations or drawbacks of using the K-means algorithm for dataset segmentation or the CDAE-CNN network for location prediction.	Accurate and robust indoor WiFi fingerprint localization, excellent noise immunity and generalization performance.
[58]	BloothAir, a secure multi-hop aerial relay system using Bluetooth autonomous drones with connectivity, for wireless data communication between drones and ground devices.	Does not explore the potential vulnerabilities or security risks associated with the use of Bluetooth Low Energy (BLE) for data communications in the BloothAir system.	Based on autonomous drones with Bluetooth Low Energy (BLE) connections, BloothAir is a secure multiple-hop aerial relay network that ensures secure data transmission and increases system reliability.
[59]	Fingerprinting method was used with Bluetooth beacons for indoor localization.	Does not provide a comprehensive analysis of the energy consumption of the Bluetooth beacons used in the proximity-based positioning system.	Optimizing the best path based on various metrics of interest, accurate indoor localization, achieving less than 2.6m error in 95% of cases.
[60]	Use of AV-mounted Bluetooth receivers to identify and localize a pedalcyclist's Bluetooth device, estimating the distance-to-bicycle from the Received Signal Strength Indicator (RSSI).	Does not address potential ethical considerations or social implications of relying on technology-based solutions for AV and cyclist interactions.	Enhance the performance of contemporary vision-based detection systems, improving cyclist detection performance.
[61]	Zigbee	High latency, low transmission rate, and NLOS path vulnerability	Extremely low energy consumption, low system cost.
[53]	proposes the creation of an Integrated Indoor Positioning System (IPS) by combining the Inertial Measurement Unit (IMU) with Ultra-Wideband (UWB) and the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF).	High latency.	Smoother positional trajectories are provided by increasing the IPS's positioning and navigation accuracy, which also enhances the accuracy of the least squares (LS) algorithm.

cern about interference between UAVs and other communication systems. Ensuring the security of the localization system against intentional interference or jamming is a critical challenge, especially in sensitive applications like defense or critical infrastructure monitoring.

- **Dynamic and Unpredictable Movements:** UAVs are often deployed in scenarios where the movement patterns are dynamic and unpredictable. This could be due to factors like changing wind conditions, sudden obstacles, or unexpected environmental changes. Adapting localization algorithms to handle such dynamic situations is a continual challenge.
- **Multi-UAV Collaboration:** In scenarios involving multiple UAVs working together, coordination and collaboration become crucial. Ensuring that each UAV is aware of the others' positions and movements, and developing algorithms that enable efficient collaboration, remains a complex problem.

- **Resource Constraints:** Many UAVs, especially small or nano-sized ones, have limited computational and power resources. Designing localization algorithms that are efficient and can operate under these resource constraints is an ongoing challenge, particularly for long-duration missions.
- **Ethical and Legal Considerations:** The use of UAVs raises ethical and legal concerns related to privacy, surveillance, and airspace regulations. Addressing these issues and incorporating responsible AI practices into UAV localization systems is essential for widespread acceptance and deployment.
- **Environmental Impact:** The environmental impact of UAVs, including their energy consumption and potential harm to ecosystems, is an emerging concern. Developing eco-friendly localization solutions and minimizing the environmental footprint of UAV operations are areas that need attention.

Continued research and innovation are essential to ad-



TABLE V. Examining the present obstacles to UAV placement using RF localization techniques.

Present Difficulties	Present Remedies	Drawbacks	Benefits
Error NLOS	Using the intrinsic rules for every radio frequency signal to identify changes in signal over various communication paths is known as NLOS identification.	Requires statistical data; insufficient auxiliary nodes reduce efficacy	Resilient to NLOS paths, straightforward to install, and stable performance
	Using the proper model of mathematics to reduce NLOS mistake is known as NLOS mitigation.	Extremely complicated computational structure that becomes unstable when nodes	Not requiring historical data or statistical information, and sufficient precision in most cases
Synchronization of Nodes	Avoiding synchronization by using a communication mechanism	experiencing clock drift or reaction latency, as well as high communication costs	Ease of implementation and minimal complexity in computation
	Using the extra synchronization node or server by using suitable	Limited by the server or synchronization node, expensive communication	Minimal computing complexity, reasonable accuracy, and ease of implementation
	Calculating the relative synchronization clock difference	Heavy processing complexity and the need for a LOS channel between the nodes	No extra parts needed, suitable accuracy using a particular method
Relative Localization and Anchor Self-positioning of UAVs	Utilizing auxiliary nodes to facilitate anchor self-positioning	More machinery is needed, constrained by auxiliary nodes, and requiring prior knowledge	Cheap communication costs and ease of execution
	Utilizing the proper anchor self-positioning approach in an offline procedure	Heavy communication costs and the need for placing nodes of anchoring	No previous knowledge or additional equipment is needed.
	UAV's relative localization	Strong computational complexity and the need for prior knowledge of UAV movement and velocity	Additional nodes are not needed.
Interference or Blockage of Signal	Relaying stations are further auxiliary nodes.	It is difficult to build more auxiliary nodes in an unfamiliar environment.	stable conditions for communication in a hostile setting
	Multiple-hop communication using a particular approach	Performance instability and excessive energy use	No further apparatus is needed.
Usage of Energy	Decrease the complexity of processing and communication.	Decline in localization accuracy	Low localization delay, simple implementation using a specific method, and no additional equipment needed
	An extra server for localization	excessive device cost, excessive delay, signal blockage or interference, and the need for extra equipment	Excellent precision and steady operation; usage of energy should not be taken into account
Inconsiderate Value	Determine the irrational value using a specific procedure, such as the distance calculated by Mahalanobis	Extremely sophisticated computation and identification failure	Stable functioning and no need for prior knowledge
	Using a mathematical framework such as EKF, smooth the output.	Effect on localization performance, erratic performance, need for prior outcome, and extra equipment	Simpleness of implementation

dress these challenges and pave the way for more reliable and versatile UAV localization systems.

Table V offers a thorough explanation of the current approaches being used to address the difficulties in UAV localization using RF-based localization technology.

7 Conclusion

Using a range of radio communication technologies and localization procedures, this research offers an extensive analysis and review of RF-based UAV localization systems. First off, an analysis was conducted on the efficacy of the four localization mechanisms—RSS, AOA, TOA, and TDOA—that are commonly used on RF-based localization systems for UAV positioning. The advantages and disadvantages of the existing radio communication technology methods used by RF-based UAV localization systems (Wi-Fi, Bluetooth, Zigbee, and UWB) were later discussed.

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