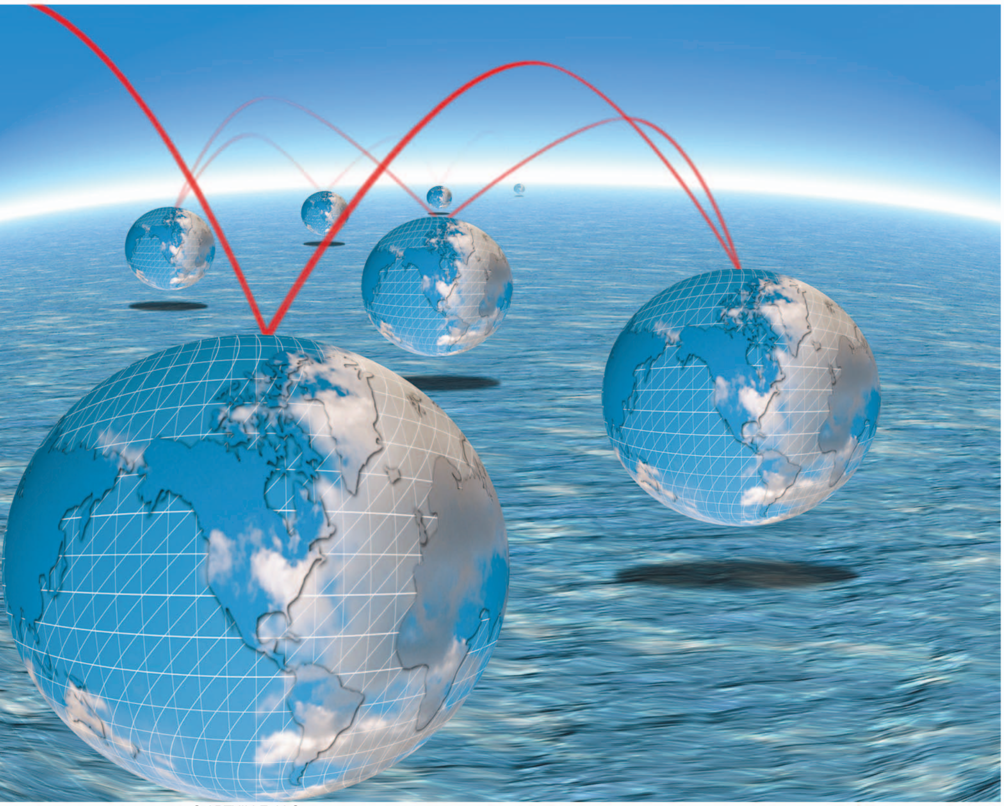
From Single- to Multihop: The Status of Wireless Localization

Vasileios Lakafosis and Manos M. Tentzeris



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Localization is the process of determining the physical positions of nodes with a specific degree of accuracy in indoor or outdoor wireless sensor or ad hoc network fields. The physical location information of a user, device, or mote within an area covered by a wireless network can prove a very useful or even indispensable functionality in many applications. First of all, high correlation between data captured, for instance, environmental, and locality may be required for the data to be meaningful. Device tracking, involving location and bearing, is another type of application that makes use of different localization techniques. Location awareness is also the basic component of a special category of routing protocols, namely, geographic aware ones, where the traffic is relayed to or from a particular area of the

Vasileios Lakafosis (vasileios@gatech.edu) and Manos M. Tentzeris are with Department of Electrical and Computer Engineering, Georgia Institute of Technology, 85 Fifth Street NW, Atlanta, GA, 30308, U.S.A.

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sensing field. Finally, context-aware applications can make smarter decisions in terms of user interface or behavior when knowledge of the physical location of the nodes is available.

This article reviews the most representative and reliable localization techniques, most of which can be easily deployed in existing networks, as well as presents how these have been expanded to provide localization solutions suitable for environments where mostly multihop connectivity can be established with anchor nodes; nodes whose exact location coordinates are known a priori. It should be noted that most of these techniques are based on methods used since ancient and medieval times by Thales from Miletus, Claudius Ptolemaus, Leon Battista Alberti and others [23] and are still used mostly in navigation systems.

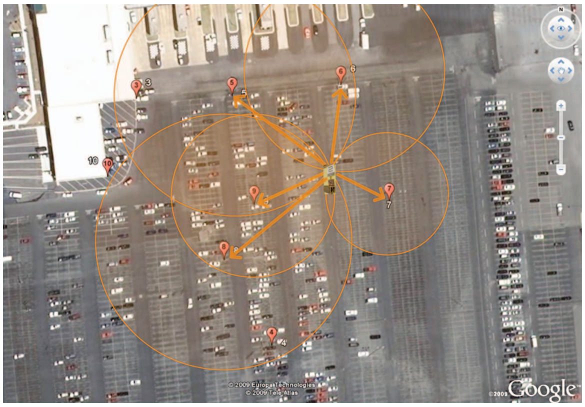

Figure 1. *Satellite photo of a huge parking lot environment where time-stamped identical unique identification packets are transmitted from a semiactive RFID tag in a car and are captured by multiple fixed anchor nodes for multilateration purposes.*

Localization Techniques

Before describing the most prominent localization techniques, it should be noted that these techniques can either be deployed directly in single-hop wireless networks or serve as the basis for techniques used in multihop network environments as described in the next section.

Tri- and Multilateration

Lateration is the approach in which distances from three (trilateration) or more (multilateration) anchor nodes whose positions are well known are used to estimate the node location, either relative to the anchors or to absolute coordinates if the anchor positions are given in absolute coordinates. The minimum number of anchors required for lateration on a plane is three (noncolinear), whereas in a three-dimensional (3-D) space, four are required. The most important methods of lateration are described in the following subsections.

Received Signal Strength Indicator

Many proposed solutions rely on the received signal strength indicator (RSSI) returned by the transceiver after the reception of a packet from another node. Initially, knowledge of the effective isotropically radiated power (EIRP), which takes into account the transmission power, the antenna gain, and the cables losses, is assumed. Plugging this value along with the RSSI into the Friis equation for a specific path-loss coefficient and model, which can be very sophisticated with dependency on the environment, the distance from the emitter can be estimated. The required computation can be done in a localized or a centralized fashion, depending on whether the RSSI value used is of a packet transmitted by an anchor node or by the node whose location is under estimation, respectively.

An example of the centralized case is presented in [1], an application used mostly by car auction dealers for quickly locating a vehicle in huge parking lots and tracking its trajectory over the course of its stay in their premises for cost optimization reasons. Specifically, a paper-based, batteryless, solar-powered tag hung from the front mirror of a car transmits time-stamped, identical, unique identification packets in regular intervals. In Figure 1, such packets are shown to be captured from five different, very low-cost anchor nodes and relayed to a central location along with an RSSI value each.

The two main characteristics that have rendered this method attractive are that neither additional hardware nor additional communication overhead is required. However, there are quite a few parameters that can degrade the accuracy of the RSSI approach. First, incorrect estimations are introduced when the RSSI is extracted from packets that have followed an indirect path due to multipath fading [2], regardless of whether they have been emitted from an anchor node in line-of-sight with the receiver or not. Second, the fast-fading effect, as well as the dynamic nature of the environment, can result in serious oscillations in the RSSI measurements over time. Contrary to the previous problem, this effect can be alleviated using statistical techniques [3] in conjunction with repeated measurements. The authors used the studentized residuals method to identify incorrect distance measurements such as those generated by a reflection; these are likely to have a large studentized residual and, thus, can be considered as outliers in full sets of measurements and removed. Third, since the widely used inexpensive radio transceivers are, in most cases, not calibrated [4], the actual transmission power differs from the configured one [5] and the measured RSSI value does not correspond precisely to the actual received signal strength. Nevertheless, the rather painful and, for some applications, impractical process of calibrating every node in the network can entirely eliminate these problems.

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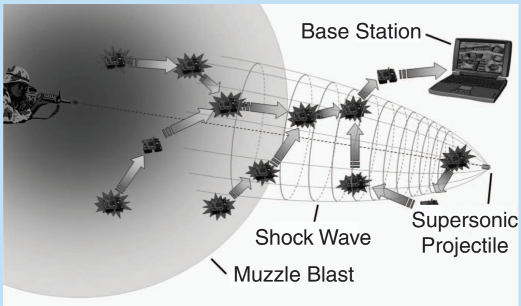

Figure 2. *The sensor network based sniper localization system. (From [6], used with permission.)*

Time of Arrival

The time of arrival (ToA), or time of flight (ToF), corresponds to the propagation time of a radio, sound, infrared, or other signal emitted from a node. Assuming the receiver has precise knowledge of the real emission time, which might require a tight synchronization between the sender and the receiver, the latter can compute the distance between them. Depending on the transmission frequency, the required time accuracy differs. In some cases, this renders particular technologies impractical for wireless sensor networks.

A very interesting application in this category is the one shown in [6]; an ad-hoc wireless sensor network-based system for accurate localization of snipers in urban environments. As shown in Figure 2, inexpensive sensors accurately measure the ToA of shockwave and/or muzzle blast events and send these time-stamped events to a central base station. There, sensor fusion techniques, which utilize the spatial and temporal diversity of multiple detections, calculate the shot

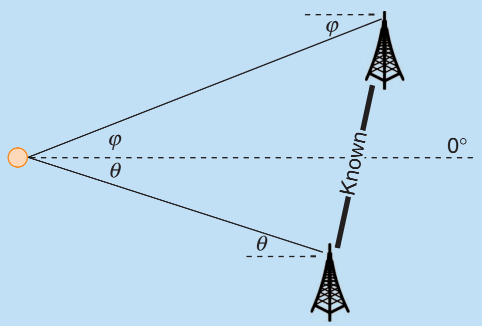

Figure 3. *Location estimation on a plane based on angular information (φ, θ) from two reference points.*

projectile trajectory and/or the shooter location. Mitigation of acoustic multipath effects prevalent in urban areas and the ability to handle multiple simultaneous shots are among the advantageous characteristics of the network. The same research group has moved from this static sensor solution to a highly mobile one [24], mounting the microphone array on soldier helmets and using Bluetooth for communication with the soldier's PDA running the data fusion and the user interface.

Time Difference of Arrival

A very widely used approach that falls in this category involves the simultaneous transmission from the same node of signals of very different frequencies and the measurement on the receiver side of the difference in the arrival time of the two signals. On one hand, the requirement for high-accuracy synchronization, as in ToA method, is eliminated. On the other hand, two different types of transceivers are required in every node in the network. Ward et al. [3] use TDoA for location estimation of devices in indoor environments, which transmit a radio message consisting of a preamble and a unique 16-bit address transmitted in the 418 MHz band along with an ultrasonic pulse at 40 kHz every 200 ms directed toward receivers mounted in an array at the ceiling of the room. The authors report a very good accuracy, with 8 cm error in at least 95% of the position estimates.

Although very similar to the above system, the Cricket [7], a location-support system for in-building, mobile, location-dependent applications, does not rely on any centralized management or control and requires no explicit coordination between anchor nodes. This system allows end devices to compute their physical location locally on their own and provide this information to any user application, thus guaranteeing user privacy.

Angulation

Angular information extracted in reference to multiple anchor nodes, whose positions are well known, can be used to estimate the location of a node. An example of a two-dimensional (2-D) location estimation system is given in Figure 3. Here, since the length of one side of the triangle drawn and two angles are known, the position of the third vertex can be unambiguously found.

Nasipuri and Li [8] propose an angle-of-arrival (AoA) estimation technique according to which at least three fixed anchor nodes continuously transmit a unique RF signal on a narrow directional beam that is rotated at a constant angular speed, known to all nodes. This is depicted in Figure 4. A node equipped with a low-power transceiver translates the time difference of arrivals (TDoAs) of the different beacon signals to angular values and, eventually, evaluates its angular bearings and location with respect to the beacon nodes using trigonometry. According to the simulation results reported, the maximum error is within 2 m in a

75 × 75 m area; the performance does not depend on the absolute dimensions of the network area, but narrow beamwidths of 15° or less are assumed.

An interesting alternative approach is the lighthouse laser-based location system [9]. Here, lighthouse base stations use broad horizontal beams that rotate at a constant speed. A node equipped with a photodetector measures the start and end time of the beam passing by and uses this sweep time along with the known complete rotation time to estimate its position at high precision. Indicatively, using an early 2-D prototype of the system, node locations could be estimated with an average accuracy of about 2% and an average standard deviation of about 0.7% of the node's distance to the base station.

Radio Interferometric Geolocation

Maroti, et al. [10] reported a radio-interference-based localization method for wireless sensor networks. The key enabling idea behind this novel implementation is the use of two nodes emitting radio waves simultaneously at different frequencies very close to each other so that the composite signal has a low-frequency envelope that can be measured by an inexpensive transceiver such as the Chipcon CC1000 radio [11]. The phase offset of the low-frequency envelope signal is measured, corresponding to the wavelength of the high-frequency carrier signal, and the measurements of the relative phase offset at the two receivers eliminate many sources of error. The main advantages of the authors' prototype system are 1) the high accuracy and long range, with an average localization error as small as 3 cm and a range of up to 160 m, 2) the support of 3-D relative localization of the nodes by making multiple measurements in an, at least, eight-node network, and 3) no sensors other than the radio are required. This approach is extended to multiple tracked objects and, to estimate the velocity, the locations of the tracked objects in [25].

Field Fingerprinting

A very accurate and, at the same time, simple but potentially cumbersome localization method is field fingerprinting. The key idea behind its high performance is to accurately capture the radio-wave propagation pattern of the particular environment where the localization system is to be installed just once. For instance, with regard to the solar-powered node localization in [1], the method involves gathering the RSSI values from all possible anchors of the test signal emitted from points in a virtual dense mesh, covering the whole parking lot right after the initial deployment. This capturing phase is recommended to be carried out for different vehicle occupation conditions of the lot (empty, full, etc.) so that multipath and other RF effects are accounted for as much as possible, thus resulting in different field

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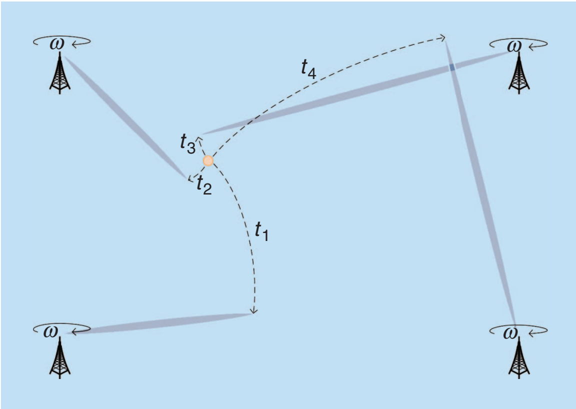

Figure 4. *Location estimation on a plane based on translation of the time difference of arrivals of different beacon signals transmitted by anchor nodes to angular values. (From [8], used with permission.)*

fingerprinting profiles. Another application making use of a similar approach in indoor environments is the RADAR system [12], where the received signal strength values from multiple anchors are compared with premeasured, stored ones.

Localization in Multihop Environments

In multihop wireless networks, often a node whose location is to be determined, does not have direct connectivity to at least three anchor nodes. A representative example is shown in Figure 5, where the aforementioned node colored with a blue circle is within the single-hop neighborhood of only one anchor node and has multihop connectivity to two others.

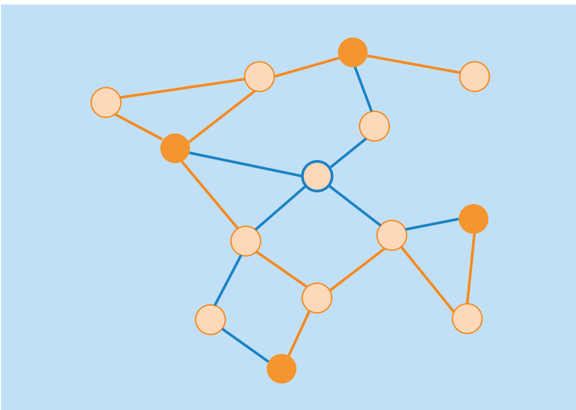

Figure 5. *Single and multihop connectivity of a node (node with blue circle), whose location is unknown, to three anchor nodes (nodes with solid orange color).*

Proximity is the simplest of all the lateration methods.

Proximity

This is the simplest of all the lateration methods, since it exploits the inherent finite topology of the wireless transmissions without the need for any numerical calculation. Bulusu et al. present the application of this connectivity-metric method in outdoor environments, where anchors at fixed reference points having overlapping coverage regions periodically transmit beacon signals [13]. A node infers its location from the intersection of the coverage areas, assuming that the anchors are arranged in a mesh, as in Figure 6. An idealized radio model, under which the transmissions of fixed power from an anchor can be received within a circular area of predetermined radius, is also assumed. The ratio of the number of beacon signals successfully received to the total number of signals transmitted is defined in [13] as a connectivity metric for a specific pair of nodes. The accuracy of localization is dependent on the number of anchors and their relative distance and should not be expected to be high since the actual coverage range is usually not a perfect circle.

Another method for estimating node locations in a sensor network based exclusively on connectivity is described in [14]. Doherty et al. model internode communication as a set of geometric constraints on the node positions. The knowledge of the exact position of a few nodes in conjunction with connection-induced proximity constraints restricts the feasible set of unknown node positions. The global solution of this feasibility problem, which can only be computed centrally using existing efficient linear or semidefinite programming techniques, yields estimates for the unknown positions of the nodes in the network. Simulation illustrates that estimate accuracy becomes high when the constraints are kept tight.

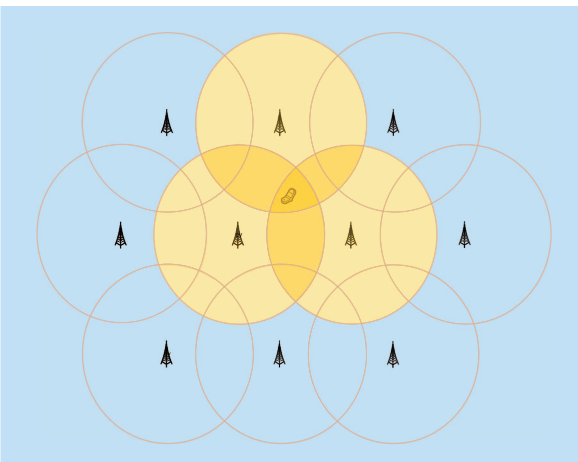

Figure 6. *Proximity-based localization; the node shown in the middle infers its location from the intersection of the coverage areas of anchor nodes.*

Multidimensional Scaling

Multidimensional scaling is a set of data analysis techniques that takes a matrix of elements with distance-like relationships and displays each of them in an x-dimensional space. For x equal to two or three, this can be shown as a 2- or 3-D plot, respectively.

Shang et al. [15] proposed a centralized localization technique, which makes use of multidimensional scaling, relying only on range-free connectivity between nodes. According to the algorithm, the shortest paths between all pairs of nodes are first estimated, and these distances are used to construct a distance matrix for multidimensional scaling. Then, multidimensional scaling is applied on this matrix, and positions of the nodes with approximate relative coordinates are obtained. Finally, this relative map is aligned with a map of known absolute coordinates of the anchors. Simulations demonstrate good results even if only the absolute coordinates of a few anchors are available. Shang et al. present in [16] an improved version of their algorithm, even when the spatial density of the anchor nodes is small, by obtaining not only one but a number of local overlapping maps of individual groups of nodes in the entire field and stitching them together. An example of merging two such local maps based on their common nodes is shown in Figure 7.

A very similar approach to this optimized concept of [15] is proposed by Ji and Zha [17], who demonstrate through simulation that their multidimensional scaling-based distributed sensor positioning method can accurately estimate the sensors' positions in a network with complex terrain and anisotropic topology, where the nodes are not spatially uniformly located.

Distributed Localization

The first approach to be presented in this category is developed by Niculescu and Nath [18], who consider using distance vector-like range estimations exchanged between nodes by multihop communication. In the range-free distance-vector-hop technique, all anchor nodes start independently flooding the network with their location coordinates through multihop packet broadcasts. The hop count field in these messages, which accounts for the number of hops that the latter have traversed from their sources, is updated as they hop from node to node. This value allows each node to maintain a shortest path table to every anchor. Every anchor estimates the average single-hop distance based on the hop count and the known locations of the other anchors and propagates it into the network. A nonanchor node can then use this estimated hop distance, as well as the hop count to other anchors, to perform multilateration. If, instead of hop count values, measured distances between neighboring nodes can also be propagated, then these can be used similarly, resulting in the distance-vector-distance technique. In this case, Euclidean distances from anchor nodes a number of hops away can be estimated, thus increasing the overall accuracy. Angulation information has also been successfully used in the same framework by Niculescu and Nath [19].

In [5], Savvides et al. define atomic, iterative, and collaborative multilateration. As described previously, in the atomic multilateration, a node can estimate its location being within range of at least three beacons. In the iterative multilateration, as soon as connectivity to at least three anchors is established and a node estimates its location, it becomes a beacon for other nodes. This process can be repeated until all nodes with eventually three or more beacons estimate their positions. But even after these two multilateration processes have been completed, a node may still have less than three neighboring beacon nodes, in which case collaborative multilateration should be applied. The ad hoc localization system (AhLOS) proposed in [5] uses iterative multilateration and reveals that this type of multilateration can be problematic in regions where anchor densities are low. Additionally, error propagation becomes an issue in large networks.

The collaborative multilateration, extensively presented in [20], addresses the above two issues. This multihop operation enables nodes found a number of hops away from anchor nodes to collaborate with each other and estimate their locations. The operation takes place in four phases. In the first phase, the nodes whose coordinates can be uniquely determined self-organize into collaborative subtrees. During the second phase, each nonanchor node uses simple geometric relationships to estimate its location based on known anchor locations and measured distances obtained with a distance-vector-like algorithm, similar to the one described previously. Iterative least-squares trilateration is applied in the next phase on the initial location estimates to refine them. Finally, all the new location information is used to further refine the location of each node that does not belong to a collaborative subtree.

The parameter that eventually plays the major role in choosing a particular localization technique is the ease of deployment in a new or an existing wireless network infrastructure.

A similar two-phased approach is presented by Savarese et al. [21]. In the start-up phase, the distance vector-like Hop-TERRAIN algorithm is run to overcome the sparse anchor node problem and obtain rough location estimates. In the refinement phase, the accuracy of the initial location estimates

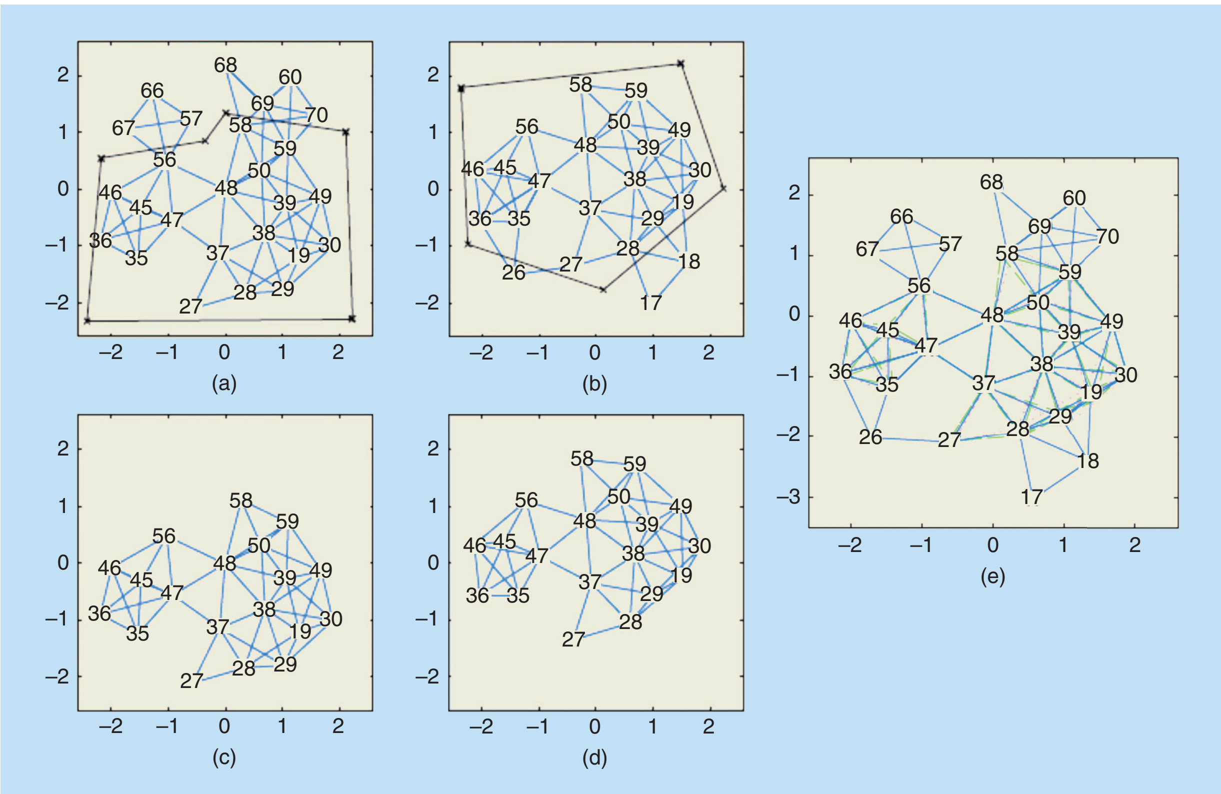

Figure 7. *Improved multidemsional scaling-based localization merging two local overlapping range-free connectivity maps based on their common nodes. (From [16].)*

TABLE 1. Localization techniques.

Technique	Solution	Accuracy		Scale	Cost	Implemented in Real Scenario?
Multilateration – RSSI	Batteryless, solar powered wireless tag [1]	4 ft	Outdoor		"Inexpensive"	Yes
Multilateration – ToA	Countersniper system [6] (only muzzleblast fusion results)	Avg. error 1.3 m <1 m for 46%, and <2 m for 84%	Outdoor	56 motes in the central area of the McKenna village	"Inexpensive"	Yes
Multilateration – TDoA	Active office [3]	<14 cm for 95%	Indoor	16 ceiling receivers, over a volume of some 75 m^3	–	Yes
	Cricket [7]	4 × 4 feet granularity	Indoor	2 beacons over an area of 36 feet2	$10/component	Yes
Angulation	Nasipuri – directionality [8] (for ideal propagation characteristics)	<2 m	–	75 × 75 m	N/A	Simulation only
	Lighthouse [9]	Overall mean relative offset of the mean locations from ground truth locations is 2.2%	Indoor	5 × 5 m		Yes
Radio interferometric geolocation	Radio interferometric geolocation [10]	<6 cm	Indoor	3 anchor nodes over an area of 18 × 18 m	Low	Yes
Field Fingerprinting	RADAR [12]	<3 m	Indoor	3 base stations over an area of 43.5 × 22.5 m	–	Yes
Multihop Localization – Proximity	Bulusu – GPS–less [13]	Avg. error 1.83 m	Outdoor	4 reference points over an area of 10 × 10 m	Low	Yes
	Convex position estimation [14]	Variable over a wide range depending on simulation scenario	–	200 nodes over an area of 10 × 10 m	N/A	Simulation only
Multihop Localization – Multidimensional scaling	Shang – connectivity [15]	Variable over a wide range depending on simulation scenario	–	>79 nodes in all 3 different scenarios	N/A	Simulation only
	Improved MDS–based localization [16]	Improved compared to ones from [15]	–	>79 nodes in all 3 different scenarios	N/A	Simulation only
	Ji – MDS [17]	0–50% of average radio range	–	400 nodes over an area of 100 × 100 m	N/A	Simulation only
Distributed Multihop Localization	APS [18]	Variable over a wide range depending on simulation scenario	–	100 nodes	N/A	Simulation only
	APS with AoA [19]	Variable over a wide range depending on simulation scenario	–	1,000 nodes	N/A	Simulation only
	Savvides [5]	<2 cm	Indoor	9 Medousa nodes	Low	Yes
	n-hop multilateration [20]	Avg. error 2.77 cm	–	Varying from 10 to 100	N/A	Simulation only
	Savarese [21]	Less than 33% for 5% range measurement error and 5% anchor population		400 nodes over an area of 200 × 200 units	N/A	Simulation only

is increased iteratively using the measured distances between neighboring nodes by means of a least squares algorithm. In contrast to [20], where the refinement process might not converge, the convergence in this work is achieved in almost all cases due to the addition of confidence weights to the position estimates. These confidence weights are close to one for anchors and lower for nodes with less faith in their position estimates.

An extensive quantitative comparison of the approaches in [18], [20], and [21] is presented in [22]. The main conclusion is that no single algorithm performs best; rather, the preference to any of these is application dependent.

Conclusion

The solutions reviewed in this article, which have been proposed to solve the problem of providing reliable localization coordinate estimates in both single- and multihop wireless network environments, are regarded as some of the most prominent ones. Although all these proposed solutions are addressing localization needs in different physical environments with exclusively single-hop or additionally multihop connectivity to reference nodes and have been either hardware implemented or just computer simulated, an attempt to summarize their characteristics in a somewhat comparative fashion is shown in Table 1.

The parameter that eventually plays the major role in choosing a particular localization technique is the ease of deployment in a new or an existing wireless network infrastructure. This involves the existence of a real world implementation of a technique with low hardware complexity, low or no packet transmission overhead, low cost, and as minor limitations as possible. As for the hardware complexity, for instance, solutions based on the RSSI multilateration require only minor software module additions, whereas the lighthouse solution [9] requires the installation of quite complex anchor nodes with rotating mirrors and laser diodes.

Hopefully, this work can serve as an initial small step and reference for researchers in their effort to choose the one localization technique that is most suitable for the requirements and special characteristics of their own application.

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