Chapter 1

Wireless Positioning Systems:
Operation, Application, and Comparison

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Recent years have seen rapidly increasing demand for services and systems that depend upon accurate positioning of people and objects. This has led to the development and evolution of numerous positioning systems. This chapter provides an overview of the main positioning techniques: time-of-arrival (TOA), direction-of-arrival (DOA) and received signal strength indicator (RSSI). It then introduces positioning systems that are either in use or being developed ßfor a variety of applications. Operations of these positioning systems are summarized using flowcharts and figures. In addition, the chapter compares positioning systems on the basis of system characteristics and performance parameters. Many of these positioning techniques and systems are introduced in greater details throughout different parts of this handbook. The chapter concludes by reviewing a number of emerging positioning systems and outlining some future applications.

1. Introduction

Positioning systems determine the location of a person or an object either relative to a known position or within a coordinate system [1]. In the last few decades, various positioning systems have been motivated by demand and developed. Some of the applications of positioning systems include (but are not limited to) law enforcement, security, road safety, tracking personnel, vehicles, and other assets, situation awareness, and mobile ad-hoc networks.

As shown in Figure 1, positioning systems can be classified into two categories:

    1) Global Positioning
    2) Local Positioning

Global Positioning Systems (GPS) allow each mobile to find its own position on the globe. Local Positioning System (LPS) is a relative positioning system and can be classified into Self and Remote Positioning. Self Positioning systems allow each person or object to find its own position with respect to a static point at any given time and location. An example of these systems is the Inertial Navigation Systems (INS).
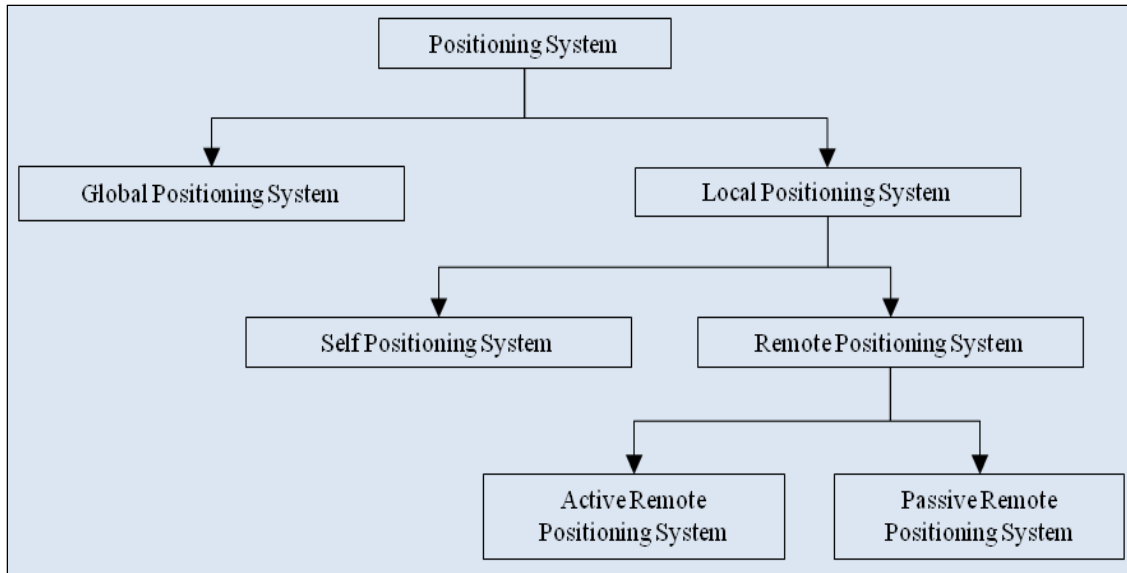
Figure 1: Positioning System Classification.

Remote Positioning System allows each node to find the relative position of other nodes located in its coverage area. Here, nodes can be static or dynamic. Remote Positioning Systems themselves are divided into:

a. Active target remote positioning
b. Passive target remote positioning

In the first cast, the target is active and cooperates in the process of positioning while in the second, the target is passive and non-cooperative. Examples of active target positioning systems are RFID, Wireless Local Positioning Systems (WLPS) [2], and traffic alert and collision avoidance systems (TCAS) [2]. Examples of passive target positioning systems are tracking radars and vision system. Figure 1 summarizes the classification of positioning systems.

This chapter reviews the operation of several key positioning systems and compares their operation, application, and pros and cons. Several key positioning parameters such as accuracy, capability in Line-of-sight (LOS) versus Non-LOS (NLOS) positioning, number of base stations required for positioning, and power consumption are considered as the benchmark for comparison. Moreover, tables summarize information on the operating ranges of the positioning parameters for the positioning systems discussed in this chapter. This information will guide system designers in selecting a positioning system for a particular application based on requirements that may be specified using a combination of parameters discussed in this chapter.

Section 2 discusses the fundamentals of various techniques that form the basis of almost all the positioning systems. Section 3 discusses the operation of several key positioning systems, while Section 4 compares the positioning systems and highlights their pros and cons. Section 5 outlines futuristic applications of several positioning systems.

2. Basic Methods Used in Positioning Systems

Here, the fundamental techniques of positioning systems are explained. Different combinations of these techniques form the basis of various positioning systems.

Time-of-Arrival (TOA) Estimation: As is detailed in Part II of this handbook, TOA estimation allows the measurement of distance thus enabling localization. Here, multiple base nodes collaborate to localize a target node via triangulation [3]. It is assumed that the positions of all base nodes are known. If these nodes are dynamic, a positioning technique such as GPS is used to allow base-nodes to localize their positions (GPS-TOA positioning). In some circumstances, multiple base nodes may cooperate to find their own position before any attempt to localize a target node [4]. TOA estimation methods are discussed in Part II of this handbook.

Assuming known positions of base nodes, and a co-planar scenario, three base-nodes and three measurements of distances (TOA) are required to localize a target node (see Figure 2 (a)). In a non-coplanar case, four base-nodes are required. Using the measurement of distance, the position of a target node is localized within a sphere of radius R_i with the receiver i at the center of the sphere (where, R_i is directly proportional to the time-of-arrival τ_i as shown in Figure 2 (a). The localization of the target node can be carried out either by base nodes using a master station or by the target node itself.

Although TOA seems to be a robust technique, it has a few drawbacks [5]:

a) It requires all nodes (base nodes and target nodes) to precisely synchronize: a small timing error may lead to a large error in the calculation of the distance R_i,
b) The transmitted signal must be labeled with a timestamp in order to allow the base node to determine the time at which the signal was initiated at the target node. This additional timestamp increases the complexity of the transmitted signal and may lead to additional source of error; and,
c) The positions of the base nodes should be known; thus, either static nodes or GPS-equipped dynamic nodes should be used.

Time-difference-of-arrival (TDOA) Estimation: As the name suggests, TDOA estimation requires the measurement of difference in time between the signals arriving at two base nodes. Similar to TOA estimation, this method assumes that the positions of base nodes are known [5]. The TOA difference at the base nodes can be represented by a hyperbola. A hyperbola is the locus of a point in a plane such that the difference of distances from two fixed points (called the foci) is a constant.

Assuming known positions of base nodes and a co-planar scenario, three base nodes and two TDOA measurements are required to localize a target node (see Figure 2 (b)). As shown in the figure, the base station that first receives the signal from the target node is considered as the *reference base station*. The TDOA measurements are made with respect to the reference base station. For non-coplanar case, the position of four base nodes and three TDOA measurements are required.

Potential target location will lie on a circle with radius $R_1 \alpha \tau_1$

Potential target location is one of the two points of intersection of the circles with radius $R_1 \alpha \tau_1$ and $R_2 \alpha \tau_2$

Final target location will be the point that passes through the circle with radius $R_3 \alpha \tau_3$

B_1 τ_1 B_2 B_3

B_1 τ_1 B_2 τ_2 B_3

B_1 Final Target Location τ_1 B_2 τ_2 τ_3 B_3

(a)

Base station that first receives the signal from target location becomes the reference base station

Potential target location will be on a hyperbola that is formed using one TDOA measurement (1-2) with respect to reference base station

Final target location will be the point of intersection of two hyperbolas which are formed using 2 TDOA measurements (1-2) and (1-3) with respect to reference base station

B_3 r_1 B_1 B_2

B_3 (1-2) r_2 r_1 B_2 B_1

Final Target Location B_3 r_3 r_2 r_1 B_2 B_1 (1-3) (1-2)

(b)

B_1 t_1 TOA$_1$

Target Object t_s

B_2 t_2 TOA$_2$

B_1 t_1

Target Object TDOA$_{12}$

B_2 t_2

t_s = Time (as given by the target object clock) at which transmitted signal starts from the target object

t_i = Time (as given by the clock at base node B$_i$) at which transmitted signal is received by the base node B$_i$

(c)

Potential target location will lie on a line whose direction (θ_1) is determined by peak incoming energy signal using antenna array

Final target location will be a point that passed through the intersection of two lines whose directions (θ_1) and (θ_2) are determined by peak incoming energy signals using antenna arrays at 2 base nodes

θ_1 B_1 B_2

Final Target Location θ_2 θ_1 B_1 B_2
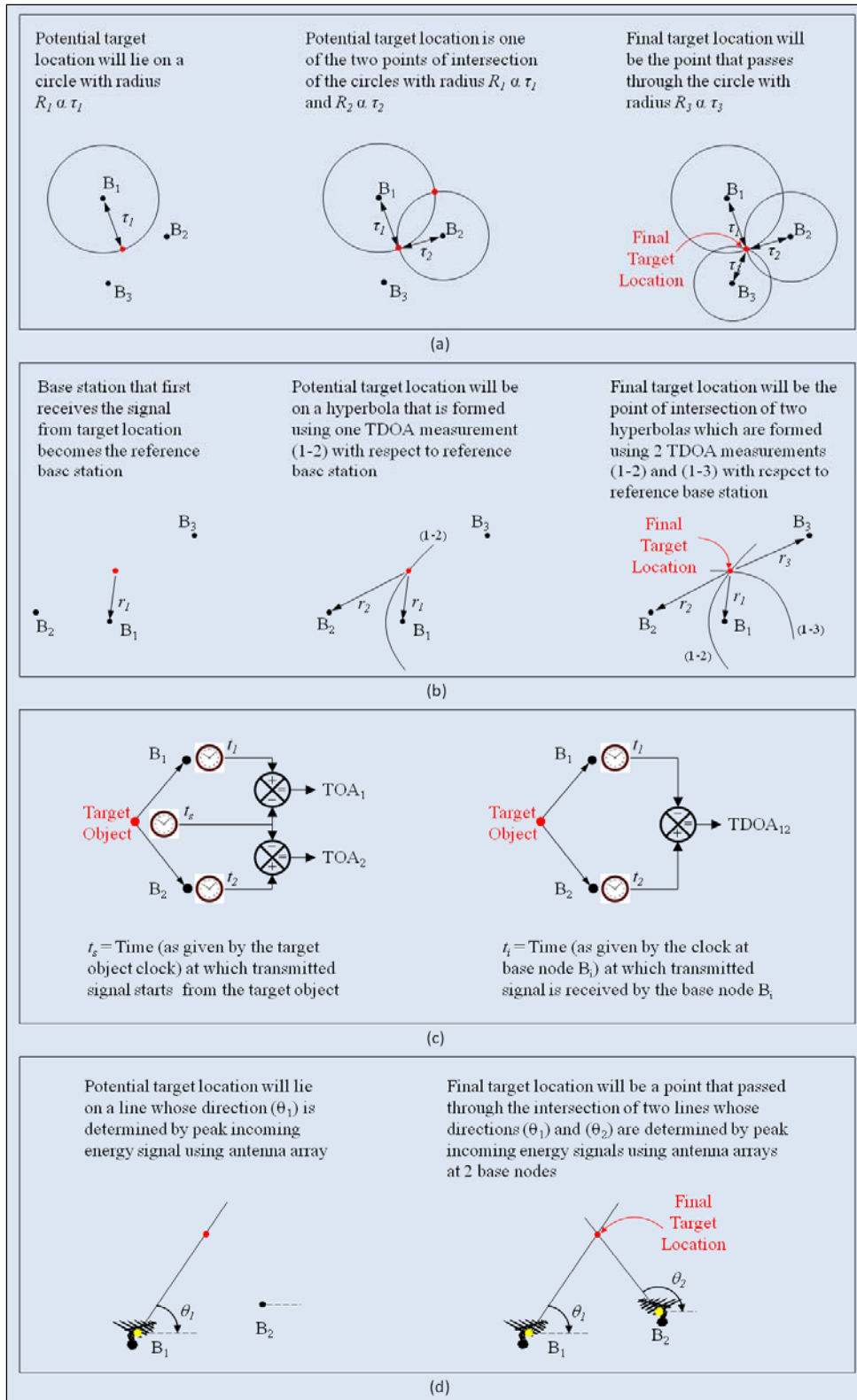
(d)

Figure 2: (a) Operation of TOA and RSSI, (b) Operation of TDOA,
(c) Comparison of TOA and TDOA Calculations, and (d) Operation of DOA

TDOA addresses the first drawback of TOA by removing the requirement of synchronizing target node clock with base node clocks. In TDOA, all based nodes receive the same signal transmitted by the target node. Therefore, as long as base node clocks are synchronized, the error in the arrival time at each base node due to unsynchronized clocks is the same.

As shown in Figure 2(c), TOA is the time duration (or the relative time) between the start time (t_s) of signal at the transmitter (target node) and the end time (t_i) of the transmitted signal at the receiver (base node B_i). However, as shown in Figure 2(c), TDOA is the time difference between the end times (t_i and t_j) of the transmitted signal at two receivers (base nodes B_i and B_j). Thus, in TDOA technique, only base nodes' clocks need to be synchronized to ensure minimum measurement error. In general, the complexity of target node clock synchronization is higher compared to base node clock synchronization. This is mainly due to the use of quartz clocks at target nodes, which are not as precise as atomic clocks that are generally used for timing at base nodes [5]. Target node clock synchronization is further explained later in this chapter.

The base node clock can be synchronized externally using a backbone network or internally using timing standards provided at the nodes. The fact that synchronization of target nodes is not required enables many applications for TDOA-based systems. For example, in battlefield applications, a rescue team may localize the position of a soldier using its beacon signal without the need of synchronization of rescue team clocks with that of the soldier.

With respect to the second drawback of TOA, the transmitted signal from the target node in TDOA need not contain a timestamp, since a single TDOA measurement is the difference in the arrival time at the respective base nodes. This simplifies the structure of transmitted signals and removes potential sources of error. This advantage of TDOA is again exploited by many applications such as emergency call localization on highways [6] and sound source localization by an artificially intelligent humanoid robot [7].

Direction-of-Arrival (DOA) Estimation: In DOA estimation, base nodes determine the angle of arriving signal (see Figure 2 (d)). To allow base stations to estimate DOA, they should be equipped with antenna arrays, and each antenna array should be equipped with RF front-end components. However, this incurs higher cost, complexity and power consumption. DOA estimation techniques are discussed in Part II of this handbook.

Similar to TOA and TDOA estimation, in DOA estimation, the positions of base nodes should be known. However, unlike TOA and TDOA, for the known position of a base node and a co-planar scenario, only two base nodes along with two DOA measurements are required. For a non-coplanar case, three base nodes are required. To determine the DOA, the main lobe of an antenna array is steered in the direction of peak incoming energy of the arriving signal [6].

Received Signal Strength Indication (RSSI): Similar to the TOA, in RSSI, multiple base nodes collaborate to localize a target node via triangulation (see Figure 2 (a)). However, instead of measuring TOA at base nodes, the estimation is carried out using the received signal strength [3]. In this method, the strength of the received signal indicates the distance travelled by the signal. Assuming that the transmission strength and channel (or environment in which the signal is traveling) characteristics are known, for a co-planar case, three base nodes and three RSS measurements are required. Part III of this handbook studies RSS-based methods in detail.

Line-of-Sight (LOS) versus Non-LOS (NLOS): Compared with RSSI, the performance characteristics of TOA, DOA and TDOA techniques are very sensitive to the availability of LOS [36]-[38]. That is, in NLOS situations the computed TOA, DOA and TDOA are subject to considerable error. However, the performance of the RSSI technique is altered only mildly by the lack of LOS: NLOS leads to a shadowing (random) effect in the power-distance relationship, which can be reduced using filtering techniques. Thus many NLOS identification, mitigation and localization techniques have been designed. Part IV of this handbook introduces the details of these techniques.

Positioning, Mobility and Tracking: The difficulty in achieving highly precise location estimates in many indoor and outdoor wireless environments has led a number of investigators to utilize parameter estimation techniques for positioning and tracking mobile targets. These techniques can be very beneficial, for example, in smoothing position tracks in mixed LOS/NLOS situations. Kalman, Bayesian, or Particle filters are widely used as state estimators. These state estimation methods can be applied with a variety of sensor technologies and positioning algorithms to improve positioning and tracking performance in many real-world environments. Part V of this handbook begins with a discussion of positioning as a state estimation problem, and then discusses Kalman filtering and closely related techniques applicable in both indoor and outdoor applications.

Network Localization: Applications and services built upon wireless positioning can be implemented with different forms of infrastructure supporting the positioning function. GPS satellites, cellular base stations, and fixed WLAN access points are familiar infrastructures underlying many well-known applications and services, but for some applications, they cannot be provided, for various economic and technical reasons. For some applications there is no supporting infrastructure at all, and methods must be devised to implement location-based services without infrastructure. In other cases, fixed infrastructure cannot provide a complete solution, and this has led to the development of network-based localization techniques. An important example of an application for wireless positioning systems is a wireless sensor network, comprising a number of geographically distributed autonomous sensors intended to cooperatively monitor some characteristics of their individual environments. Each sensor node is typically equipped with its application-specific sensors, a wireless transceiver, a microcontroller and a power source, usually a battery. Accurate positioning information for each sensor is essential for support of the network's application. Ideally, each sensor would have accurate knowledge of it own position, *e.g.*, from GPS. However, size and cost constraints lead in turn to constraints on power and computational capabilities in the individual sensor nodes. Because of these constraints, a sensor network will typically be deployed with a small number of nodes, called *anchor or reference* nodes, having precise *a priori* location information, while a larger number of remaining nodes, called *unlocalized* nodes, will have no prior knowledge of their locations. An unlocalized node, due to power limitations or signal blockage, may not be able to communicate with anchor nodes. Thus, the unlocalized nodes will estimate their locations by communicating with each other, and schemes must be used to propagate the location information throughout the network. Techniques for accomplishing this are known as *collaborative position location, cooperative localization*, and *network localization*. Part VI of this handbook begins with a chapter on infrastructure-free tracking and then discusses several approaches to network localization.

3. Overview of Positioning Systems

3.1 Global Positioning System (GPS)

The Global Positioning System is based on a man-made constellation of 27 Earth-orbiting satellites (24 in operation and three extras in case one fails). Using these satellites, a person or object can localize their position in terms of latitude, longitude, and altitude [1]. These satellites orbit the Earth at an altitude of 12,000 miles and complete two rotations each 24 hours. The orbits of these satellites are arranged such that at any given time, anywhere on the Earth, at least four satellites are clearly visible. A GPS receiver placed on the Earth can localize its position using any set of four visible satellites.

While GPS can be effectively used for many navigational applications, it has limitations. It is not capable of positioning within buildings and mines due to signal attenuation. Its performance is also degraded in severe scattering environments such as downtown urban areas. GPS is a self-positioning system. To enable this system for remote positioning, which is required for applications such as *ad-hoc* networks, each node should be equipped with a communication system as well to transmit the self-localized data to other nodes. In addition, because GPS transmission features are known, these systems might be jammed by an adversary. This also limits its defense applications. Systems such as Inertial Navigation Systems (INS) can be fused with GPS to enable localization in indoor areas and mines. In addition, Wireless Local Positioning Systems (WLPS) have been developed to enable localization in GPS denied environments. These systems are introduced in this chapter.

Two pieces of information are required to carry out the localization process via GPS:

1) The distance from the GPS receiver to satellites
2) The position of each satellite in terms of its latitude, longitude, and altitude (see Figure 3(a)).

The receiver collects these pieces of information and analyzes and processes high-frequency, low-power radio signals received from the satellites. Mathematical details of localization using GPS are discussed in Part VII of this handbook.

Distance Measurement: Assuming that the clocks of a GPS receiver and a satellite are perfectly synchronized, the distance is measured using TOA estimation. Specifically, the lag between the signal transmitted by the satellite and the one generated at the GPS receiver is used to determine the distance (see Figure 3(a)). Assuming that the satellite begins transmitting a long unique pattern (a pseudo-random code) at midnight and the GPS receiver also starts generating the same pattern at midnight, the lag is determined by comparing the two patterns.

As mentioned earlier, clock synchronization is required down to nanosecond precision for accurate calculations. Therefore, under ideal conditions, both the receiver and satellite should be equipped with high-precision clocks, *e.g.*, atomic clocks. However, since these clocks are expensive, the receiver manufacturers usually use ordinary quartz clocks. Because these clocks cannot be synchronized to nanosecond precision, there is need for an extra step. This step is called *synchronization*. In this step, a fourth satellite is used to determine the error in the receiver clock. Because the satellite transmits a long signal, the spheres generated from three satellite measurements are certainly large enough to intersect each other and produce two possible candidates for the position of the GPS receiver.

When the receiver and satellite clocks are perfectly synchronized, the intersecting point closer to the Earth is considered as the position of the receiver. The sphere that may be generated from a fourth measurement would certainly intersect at this position. However, when receiver and satellite clocks are not synchronized, it is unlikely that the surface of the fourth sphere passes
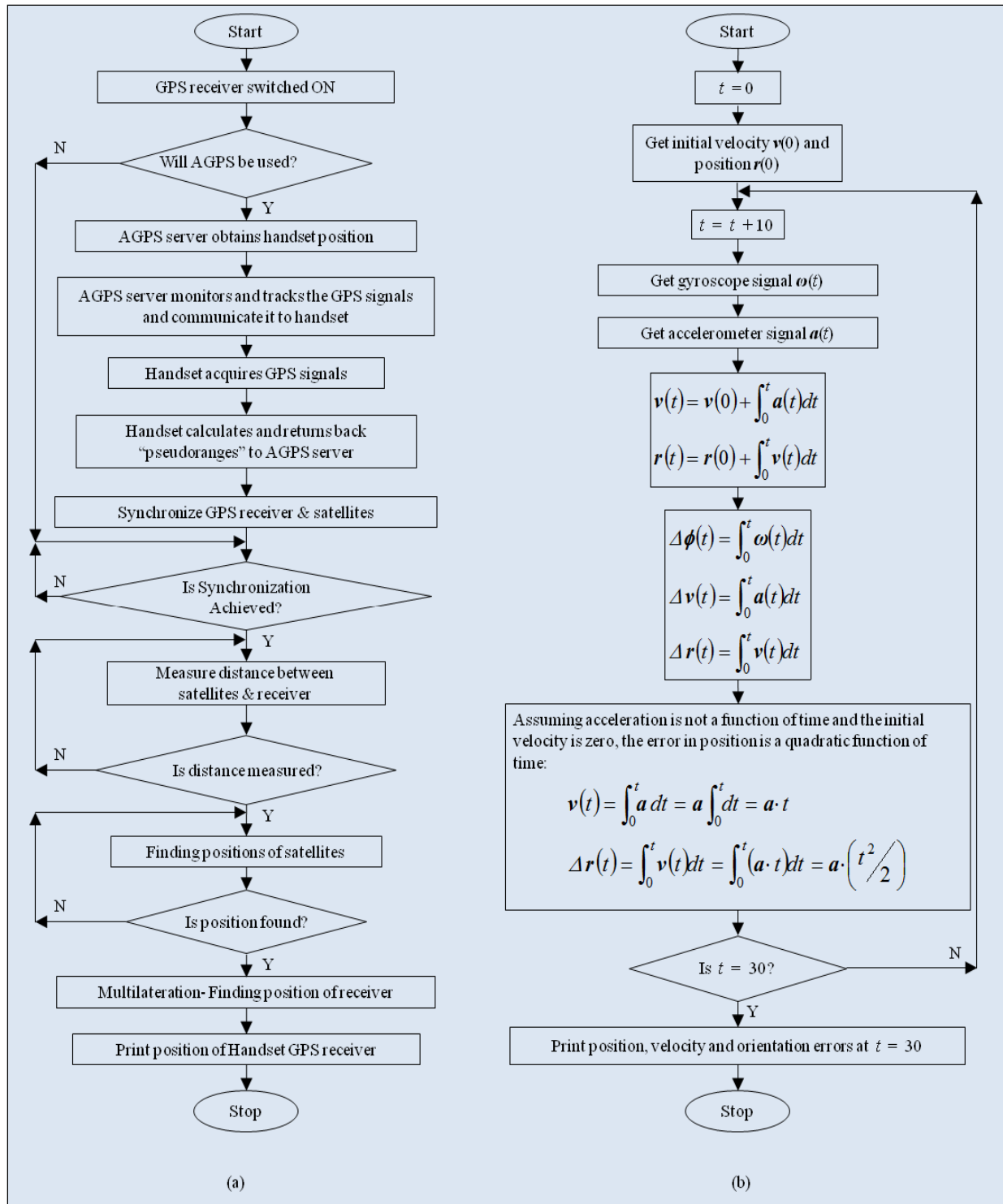

Figure 3: Flow Charts for: (a) the Operation of GPS and AGPS, and (b) Error Propagation in INS.

through either of the two intersecting points. The difference between the distance of the estimated receiver position from the fourth satellite and the pseudo-range of the fourth satellite (the radius of the fourth satellite or the distance to the fourth satellite as measured by the GPS receiver) is used to calculate the error.

In addition to the synchronization of ordinary quartz receiver clocks, the satellite atomic clocks [8] are also corrected periodically. This periodic correction is required to ensure that the *relativistic effects* are removed and the satellite atomic clocks are synchronized to the ground atomic clocks. These relativistic effects are based on two phenomenon explained by the Theory of Relativity: a) the clocks tick faster when they are in weak gravitational field, and b) the clocks tick slower when they moving. Thus, an atomic clock on the satellite ticks faster compared to an atomic clock on the ground due to weaker gravitational field in orbit; and it ticks slower because of relatively higher speed. Although, theoretically the two effects cancel each other, in the case of a GPS satellite clock, the net effect is faster ticks relative to the atomic clock on the ground. Periodic on-board calculations are performed to correct the satellite atomic clock and remove the relativistic effects.

Satellites Positions: This second piece of information is obtainable with little difficulty as the GPS receiver can simply store an almanac that determines the position of every satellite at any given time. The effect of the gravitational pull of the moon and the sun on the satellites' orbits is constantly monitored by the U.S. Department of Defense, which conveys any adjustments to all GPS receivers as part of the transmitted signals. When the information on the distance from satellites and their positions is known, multilateration (a process similar to triangulation in TOA) is used to find the three-dimensional position of a GPS receiver.

3.2 Assisted Global Positioning System (AGPS or Assisted GPS)

GPS operation was summarized in the previous section. Although, GPS is a very robust positioning system, there remains the problem of Time to First Fix (TTFF) or "cold start". That is, GPS receivers are first turned on, they need a long time (in the order of 30 seconds to few minutes) to acquire satellite signals, navigate data, and localize. This time duration varies with the location of the receiver and the surrounding interference. In order to address this problem, Assisted GPS (AGPS) has been developed.

AGPS consists of:

a) A wireless handset with a scaled-down version (with respect to the power requirements, computational capabilities, etc.) of a GPS receiver,
b) An AGPS server with a reference GPS receiver that can simultaneously monitor and track the same satellites as the wireless handset, and
c) A wireless network infrastructure consisting of base stations and a mobile switching center.

The AGPS server obtains handset position from the mobile switching center, and can locate the cell of the handset and even the sector of the handset within a set if directional antennas are used at the cell base stations [1]. Because, the AGPS server monitors and tracks the GPS satellites, it can predict the satellites that are sending the signals to the handset at any given point of time. Thus, the AGPS server can communicate the satellite information to the handset. This enables

the handset to acquire GPS signals quickly when it is first turned on, reducing TTFF from minutes to less than a second. Once the satellite signals are acquired by the handset, it calculates the distances to satellites without clock synchronization. These satellite distances are sent back to the AGPS server for further computation, as can be seen in Figure 3(a). Thus, the AGPS server also shares the computational load of the handset, reducing the handset battery power consumption.

3.3 Inertial Navigation System (INS)

INS uses accelerometers and gyroscopes to track the position, velocity, and the orientation of an object relative to a known starting point, velocity, and orientation. Gyroscopes and accelerometers are motion-sensing devices that measure the rate of rotation (angular velocity) and linear acceleration, respectively [9]. Assuming the initial position, velocity, and orientation are known for the object of interest, the updated position, velocity, and orientation are determined by integrating the information received from motion sensors. Thus, the object can continuously track its position, velocity, and orientation without the need for external information.

Actual spatial position and the movement of an object can be described by six parameters: three translational (linear acceleration in x, y, and z direction) and three rotational components (angular velocity in x, y, and z direction). In order to define the movement of the object, three orthogonal accelerometers and three orthogonal gyroscopes are mounted on the object. An orthogonal accelerometer is an instrument that measures acceleration along a single axis. The three orthogonal accelerometers are arranged so that they measure the linear acceleration in the north-south, east-west, and vertical directions. The orthogonal gyroscopes are also known as "integrating" gyroscopes as their output is proportional to their angle of rotation about fixed axes.

Mathematical integration of the acceleration $a(t)$ yields the velocity $v(t)$, which in turn is integrated to determine the distance travelled from the starting point $r(t)$, as shown in Figure 3(b). Orientation $\phi(t)$ can be found by integrating the angular velocity $\omega(t)$, also shown in Figure 3(b). These calculations are performed periodically to trace the movement of the object with respect to global reference frame. While undertaking the integration for the position of the object, acceleration due to gravity is subtracted from the vertical component of the acceleration.

The angular velocity and acceleration measurements made using motion sensors may have errors. When integrating these quantities, the errors in the measured values are propagated to the subsequently calculated position and orientation values. In addition, error is also introduced because the object numerically integrates the measurements at each time step. This error propagation in INS is called integration drift. The localization error can be adjusted to zero by a merger of the INS with other positioning systems such as GPS.

INS is used primarily by military to track submarines, warships, unmanned air vehicles, unmanned ground vehicles, missiles, airborne surveillance and navigation, search-and-rescue teams, artillery shells, *etc*. In addition, INS can be used for civilian applications such as the

estimation of position and the orientation of a moving robot, law-enforcement, underground tunnels/mines, and underwater vehicles.

INS Classification: There are two types of inertial navigation systems: a) Stable Platform Systems, and b) Strapdown Systems. The difference between the two types is the frame of reference in which the gyroscopes and accelerometers operate. The frame of reference can be the body of the object or the global reference frame.

Stable Platform System: In this system, the motion sensors are mounted on a platform that is held constant with respect to the global frame of reference. This is achieved by mounting the platform using gimbals, which allow the platform to rotate freely about all three axes. If the object rotates about any axis, the gyroscopes mounted on the platform send a feedback signal to the motor mounted on the appropriate gimbals. Based on the feedback signal, the appropriate motors rotate the gimbals in opposite direction and cancel the effect of object's rotation on the platform. This keeps the platform aligned to the global reference frame at all times. In order to track the orientation of the object, the angles between adjacent gimbals are measured and appropriate calculations are performed. To calculate the position of the object, the signals from the platform-mounted accelerometers are integrated as described above.

Strapdown System: In a Strapdown system, the motion sensors are mounted rigidly on the object. Therefore, output quantities are measured in the body frame of reference. For orientation calculations, the signals from gyroscopes are directly integrated as described earlier. However, for position calculations, the acceleration signals from the three accelerometers are projected on the global axes. The projected accelerations are calculated by applying a 3×3 rotation matrix to the acceleration signals. The elements of the rotation matrix are generated using the orientation signals. These projected accelerations are then integrated to obtain the position of the object.

3.4 Integrated INS and GPS: GPS signals may not be available at all times and at all places. Thus, INS can be used for reliable navigation by filling the gaps in measurements between two GPS position computations. The INS can also be used in case of GPS outages resulting from jamming, obscuration caused by maneuvering, *etc*. In addition, GPS computations can also help in correcting the error propagation the INS system.

3.5 Radio-Frequency Identification (RFID)

RFID is a wireless system that identifies tags attached to the object of interest. An RFID system consists of a reader and RFID tags. RFID systems are divided into two categories, according to whether they use passive or active tags [10]. Passive tags do not contain a power source and thus are suitable for short-range applications. Passive RFID tags are equipped with an antenna that is excited by output signals at specific frequencies, and these tags are activated by the power of the received signal.

An active RFID system is in fact a full transceiver system including processors, antennas and batteries. Thus, an active tag contains both a radio transponder and a power source for the transponder. An RFID reader constantly sends radio frequency electromagnetic waves, which are received by the RFID tag in its vicinity. The RFID tag modulates the wave adding its

identification information and sends it back to the reader. The reader converts the modulated signal into digital form to determine the tag identity. Active tags are ideally suitable for the identification of high volume products moving through a processing unit.
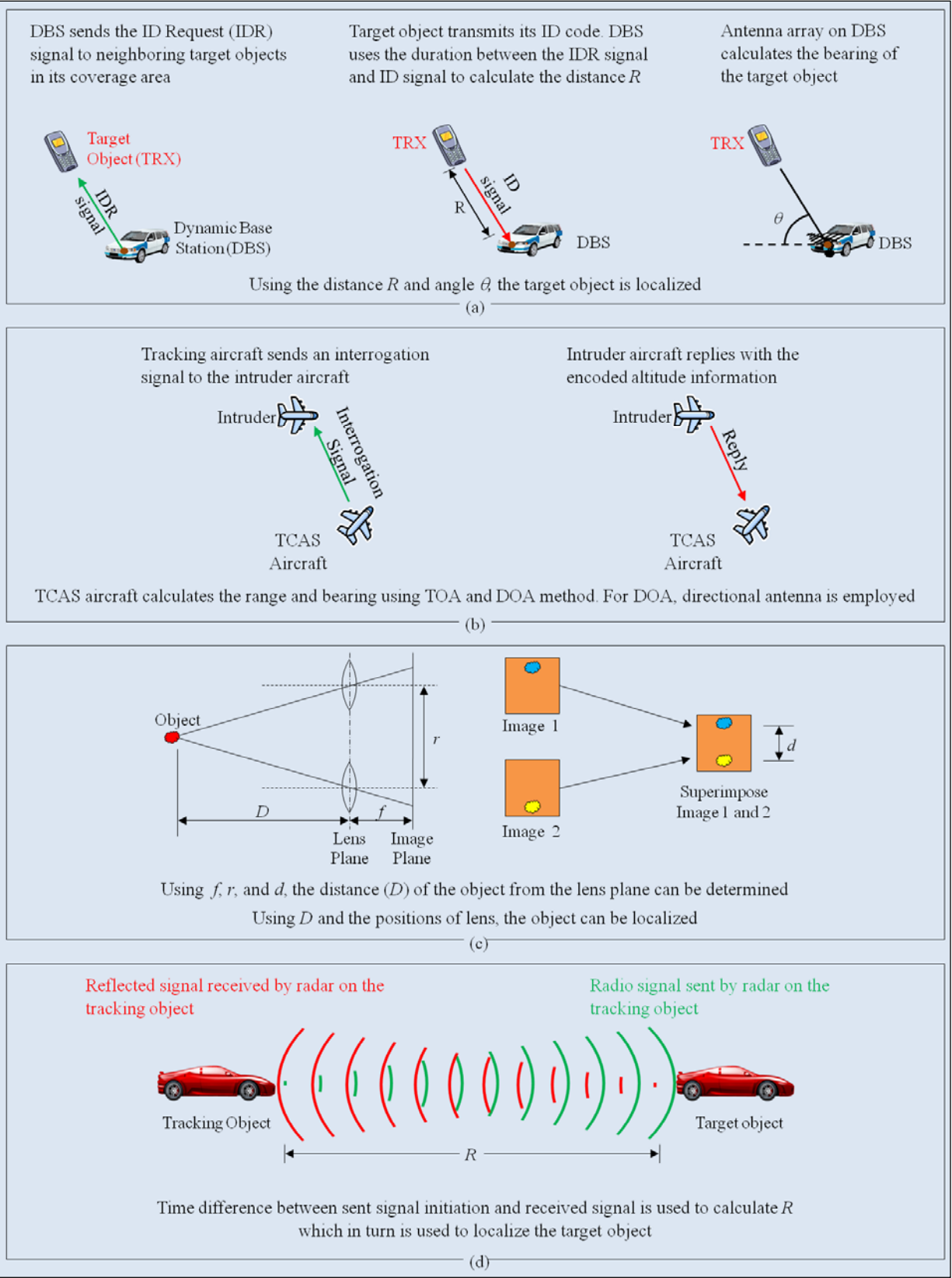
RFID as a Positioning System: RFID can be used to localize the position of a target object. An active RFID tag can be attached to the object, which transmits a signal to the RFID reader. The concept of trilateration, as shown in Figure 2(a), is used along with the RSSI technique to localize the position of the tag. Because the objects to be positioned using RFID are usually in an enclosed environment, there are multipath effects, which decrease the accuracy of the system. In order to increase the accuracy of RFID-based positioning system, the system utilizes additional readers and reference tags. However, these additional readers increase the cost of the system. In order to keep the costs down, Ni et al. [11] proposed an innovative approach that employs the idea of installing extra fixed reference tags. This approach is called the LANDMARC (Location Identification based on Dynamic Active RFID Calibration). In a manner similar to the geographic landmarks we use in our daily lives, the fixed tags serve as reference points in the system.

3.6 Wireless Local Positioning System (WLPS)

WLPS is a hybrid TOA and DOA positioning method. Based on the classification discussed in Figure 1, it can also be considered as an active remote positioning system. The system comprises a monitoring mobile unit (or dynamic base station), and a target mobile unit (or active target) [2], [12]. The active target contains a transponder and is assigned a unique identification (ID) code. As shown in Figure 4(a), the dynamic base station (DBS) sends the ID Request (IDR) signal to all active targets in its vicinity. The active targets respond by each transmitting a packet that includes its ID code back to the DBS. DBS recognizes each target by its unique ID code. For positioning, TOA and DOA of the target are estimated by DBS. As described earlier, DOA is estimated using antenna arrays mounted on the DBS. Using these measured values, the position of active targets can be localized relative to the known position of DBS.

WLPS can be considered as a node in a wireless ad-hoc network, enabling all nodes (or specific nodes equipped with DBS) to localize all nodes located in their coverage area. The complexity of these systems lies mainly in the DBS, as they use antenna arrays for localization. The cost and complexity of TRX nodes is very low. In many applications, such as battlefield command and control, a small number of DBS (expensive units carried by commanders) and a larger number of active targets (low-cost units carried by soldiers) are required. Thus, the overall cost of these systems across all nodes is minimal.

In the WLPS system, each node can independently find the location of the transceivers located in its coverage area. As discussed in Part II of this handbook, multipath effects reduce TOA and DOA estimation performance. Therefore, the localization performance of each DBS node could be low. Multiple DBS nodes can cooperate to reduce the estimation error of the TRX nodes in their coverage area [13], [14].

DBS sends the ID Request (IDR) signal to neighboring target objects in its coverage area

Target object transmits its ID code. DBS uses the duration between the IDR signal and ID signal to calculate the distance R

Antenna array on DBS calculates the bearing of the target object

Target Object (TRX)

IDR signal

Dynamic Base Station (DBS)

TRX

ID signal

R

DBS

TRX

θ

DBS

Using the distance R and angle θ, the target object is localized

(a)

Tracking aircraft sends an interrogation signal to the intruder aircraft

Intruder aircraft replies with the encoded altitude information

Intruder

Interrogation Signal

TCAS Aircraft

Intruder

Reply

TCAS Aircraft

TCAS aircraft calculates the range and bearing using TOA and DOA method. For DOA, directional antenna is employed

(b)

Object

r

D

f

Lens Plane

Image Plane

Image 1

Image 2

Superimpose Image 1 and 2

d

Using f, r, and d, the distance (D) of the object from the lens plane can be determined

Using D and the positions of lens, the object can be localized

(c)

Reflected signal received by radar on the tracking object

Radio signal sent by radar on the tracking object

Tracking Object

Target object

R

Time difference between sent signal initiation and received signal is used to calculate R which in turn is used to localize the target object

(d)

Figure 4: Operation of: a) WLPS, b) TCAS, c) Vision System, and d) Radar.

13

The WLPS can be used for space, outdoor, and indoor applications [15]. For outdoor and indoor applications, direct sequence code division multiple access (DS-CDMA) integrated with beamforming (supported by antenna arrays) provides a reasonable level of detection performance. WLPS enables many applications such as road safety, security, defense, and robotic collaboration and coordination.

3.7 Traffic Alert and Collision Avoidance System (TCAS)

Traffic alert and Collision Avoidance System (TCAS) is used to detect and track target aircraft in the vicinity of the tracking aircraft [16]. It provides a warning signal to the pilot in the presence of another aircraft that can pose a danger of mid-air collision. This warning signal is provided to the pilot independent of the air traffic control (ATC) [16]. It consists of two components: Interrogator and Transponder. Each aircraft is equipped with both components. The interrogator in one aircraft interrogates transponders in other aircraft and analyzes the replies to determine range, bearing, and relative altitude (if reporting) of the intruder aircraft (see Figure 4(b)). Range is determined by measuring the time elapsed from the interrogation signal to the receipt of the reply. A directional antenna is used to determine direction or bearing of the target aircraft. TCAS gets altitude information directly in the received reply from the transponder on the target aircraft. To determine the altitude, the time-frequency system is employed which uses the synchronized time and frequency (via extremely accurate oscillators on board the aircraft) to transmit the encoded altitude information. Each aircraft is assigned a specific timeslot of few milliseconds during each one-second interval, used to transmit the encoded altitude signal.

3.8 Wireless Local Area Network (WLAN)

As the name suggests, WLAN is used for positioning and identification of objects in limited-range. In this system, Trilateration using the RSSI technique, shown in Figure 2 (a), is used to localize the position of the object. The strength of the signal that a wireless device or target object sends out is measured at multiple receivers to calculate the position [17]. WLAN positioning system consists of base stations and mobile hosts. Each base station and mobile host is equipped with a radio-frequency (RF) LAN technology-based digital Network Interface Card (NIC) [18]. An algorithm is used to mitigate the interference due to noise and multipath. Mobile hosts periodically broadcast packets containing the start time and the transmitted signal strength information. Each base station records the start time, base station identification, and transmitted signal strength. Using this start time, and the signal strength measurement at the base station, the location is determined by combining empirical measurements with signal propagation modeling. Similar to other systems such as GPS and AGPS, the clocks on the mobile hosts and the base stations need to be synchronized.

3.9 Vision Positioning System

In this positioning system, two cameras are used to localize the target object. As shown in Figure 4(c), these cameras [19] capture the picture of the target object. It can also be seen in the figure that the picture of the target object will be created at different locations relative to the center of the image. Superimposing these images, the disparity d in the locations of the object can be determined. Assuming that the distance r between the cameras and the focal length f of

the cameras are known, the distance D of the object from the lens plane of the cameras can be calculated. Given known positions of two lenses and the calculated distance D, the target object can be localized.

3.10 Radar

RADAR stands for RAdio Detection And Ranging. It is used to localize the position of a target in the surrounding areas by transmitting a short burst of energy and processing its reflection from the target [20]. Radar estimates the TOA of the reflected signal and combines it with the DOA of the received signal measured by directional antennas. Let Δt be the time between the transmitted signal and received signal reflected from the target, the TOA is one-half of Δt. Using TOA, the distance of the object from the Radar can be obtained (see Figure 4(d)). Assuming the position of the Radar transmitter is known, the target can be localized using the calculated distance to the object.

4. Comparison of Basic Methods and Positioning Systems

This section compares basic localization methods and positioning systems in Tables 1 and 2. Several positioning parameters are used to compare different methods. Table 1 compares basic positioning methods previously discussed in the chapter in terms of accuracy, a need for the availability of LOS, and the number of base station(s) required for localization. The table shows that on average the accuracy of the DOA estimate is poorer relative to TOA, TDOA and RSSI estimates. This is mainly due to the fact that as the distance between the base station and the target increases a small DOA error leads to higher localization error. The DOA error is very sensitive to the multipath environment and signal-to-noise ratio [20]. Complex algorithms could be used to improve the DOA performance. DOA performance in localization methods such as WLPS can be improved by incorporating its periodic transmission nature [21], [22]. RSSI is different from other methods when the availability of LOS is taken into account, sine it operates in both LOS and NLOS environments. Other localization techniques are very sensitive to the availability of LOS.

Table 1: Comparison of Basic Methods.

	Accuracy (meter) [1]	LOS / NLOS	No of Base station(s)
TOA	M [3]	LOS	≥ 3
TDOA	M [3]	LOS	≥ 3
DOA	L [3]	LOS	≥ 2
RSSI	H to M [3]	Both	≥ 3

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[1] **Scale for accuracy of basic positioning methods** – High (H): 0-50; Medium (M): 50-100; Low (L): >100

Table 2: Comparison of Positioning Systems.

			Accuracy (meter) [1]	LOS / NLOS	Environ. [2]	Power Consump. (W) [3]
Global Positioning System		GPS	H [17]	LOS	O	VL [24]
		AGPS	H to M [25]	LOS	O, I	VL [26]
Local Positioning System		Self Positioning	INS	VH → VL [4] [9]	NLOS	O, I	M to H [5] [27]
	Remote Positioning	Active	RFID	H [11]	Both	I	VL [28]
			WLPS	varies with application	LOS	O, I	varies with application
			TCAS	L → VL [6] [29]	LOS	O	VH [30]
			WLAN	H to M [3]	Both	O, I	L [31]
		Passive	Vision	VH to H [7] [32]	LOS	O, I	M [33]
			Radar	VH [34]	LOS	O, I	H [8] [35]

			Multi- (M) / Single- (S) node Positioning	No of Base Station(s)	Dynamic(D) / Static(S) Base Station	Absolute (A) / Relative (R) Positioning
Global Positioning System		GPS	M	4 [9]	D	A
		AGPS	M	4 [9]	D	A
Local Positioning System		Self Positioning	INS	N/A	N/A	N/A	A
	Remote Positioning	Active	RFID	M	3	S	R
			WLPS	S	1	D	R
			TCAS	S	1	D	R
			WLAN	M	3	S	R
		Passive	Vision	S	1	D	R
			Radar	S	1	D	R

Table 2 compares different positioning systems based on several parameters. The following observations can be made from the table.

- Most of the systems that operate based on the availability of LOS propagation have higher accuracy. Thus, NLOS introduces error in the calculation, decreasing the accuracy.

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[1] **Scale for accuracy of positioning systems** – Very High (VH): < 1; High (H): 1-5; Medium (M): 5-30; Low (L): 30-50; Very Low (VL): >50

[2] O = Outdoor, I = Indoor

[3] **Scale for power consumption of positioning systems** – Very Low (VL): < 1; Low (L): 1-10; Moderate (M): 10-50; High(H): 50-200; Very High (VH): > 200

[4] The initial accuracy is high (few decimeters) which changes with time due to error propagation

[5] Depends on INS classification (stable platform system consumes high power; strapdown system consumes moderate power)

[6] The initial accuracy is low (few degrees) which decreases with distance

[7] The detection range of vision system is 1 m to 95 m which determines the accuracy

[8] Within the high range, the power consumption depends on the peak power output

[9] In GPS and AGPS, satellites are considered as base stations.

- Many existing positioning systems employ multiple base nodes to localize the target node. This may create a system cost problem for the designer.
- The power consumption for most positioning systems is medium to very low. Thus, using one of the low-power positioning systems does not impose additional constraint on the designer with respect to the required power consumption.
- All positioning systems except RFID-based systems can support mobility.
- Many positioning systems are well suited for both outdoor and indoor environments.

5. Summary and Future Applications

This chapter has provided an overview of positioning techniques and systems that are currently in use for various applications. These positioning systems are usually based on one of the four basic methods: TOA, TDOA, AOA, and RSSI. We described the operation and compared their pros and cons. In addition, a comparison of the basic methods and positioning systems was provided.

The existing positioning systems are used in numerous applications that will likely be expanded in the future, in response to new demands. As shown in Figure 5, the future entails collaboration among various positioning systems especially for applications related to situation awareness. For example, in the case of automatically driven car, the information on the road condition and traffic (situation awareness) may be obtained using various existing position systems such as GPS, Radar, and WLPS. As shown in the figure, the automatically driven car can derive information such as the distance of the surrounding traffic using Radar and WLPS. GPS can help the automatically driven car to recognize roadblocks caused by accident or other factors such as traffic. Thus, in this example, the automatically driven car can be aware of its situation using the positioning technologies.
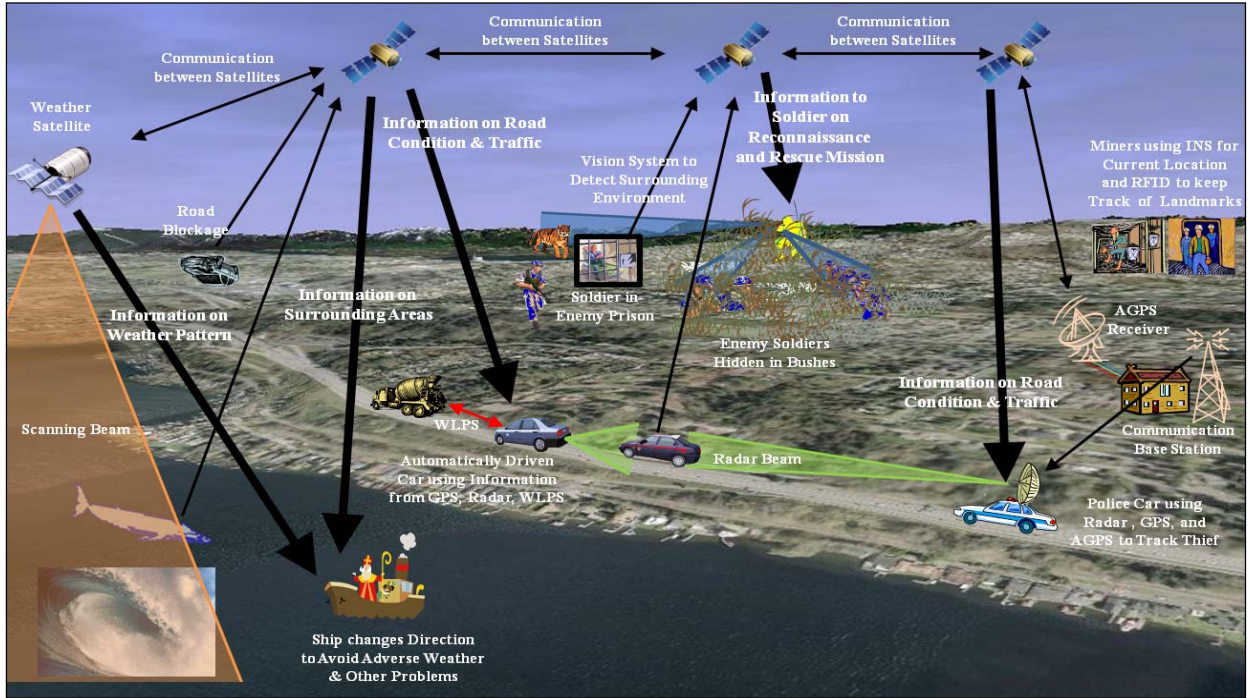

Figure 5: Futuristic Applications of Positioning Systems.

17

In another example that is shown in the figure, a soldier on a reconnaissance or rescue mission can use the information from a vision system, radar, and GPS to be aware of its surroundings or situation. Also shown in the figure is the police car that keeps track of the thief and road conditions using signals from several positioning systems. Miners can also benefit from the positioning systems such as INS and RFID to be aware of their current location and possible escape route in case of emergency. For the miners, it can be envisioned that RFID tags are installed along the mine tunnels as it is explored deeper in the earth crust. The information from these RFID tags can potentially include the depth of the mine, *etc*.

Finally, also shown in the figure is a ship that gathers information from a number of systems and selects its course accordingly. It should be noted that the figure provides only some of the applications where positioning systems collaborate among themselves or other systems (*e. g.,* a weather forecast system) for situation awareness. This handbook reviews the details of many localization techniques that have been briefly introduced in this chapter.

References

[1]   G. M. Djuknic and R. E. Richton, "Geolocation and Assisted GPS," *IEEE Computer*, vol. 34, no. 2, pp. 123-125, 2001.

[2]   H. Tong and S. A. Zekavat, "A novel wireless local positioning system via a merger of DS-CDMA and beamforming: probability-of-detection performance analysis under array perturbations," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 3, pp. 1307–1320, 2007.

[3]   M. Vossiek, L. Wiebking, P. Gulden, J. Wieghardt, C. Hoffmann, and P. Heide, "Wireless local positioning," *IEEE Microwave Magazine*, vol. 4, no. 4, pp. 77-86, Dec. 2003.

[4]   S. Capkun, M. Hamdi and J.P. Hubaux, "GPS-free positioning in mobile ad-hoc networks", *Proc. 34th Annual Hawaii International Conference on System Science*, Maui, Hawaii, Jan. 3-6, 2001.

[5]   T. S. Rappaport, J. H. Reed, and B. D. Woerner, "Position location using wireless communications on highways of the future," *IEEE Communication Magazine*, pp. 33-41, Oct. 1996.

[6]   M. Laoufi, M. Heddebaut, M. Cuvelier, J. Rioult, and J.M. Rouvaen, **"**Positioning emergency calls along roads and motorways using a GSM dedicated cellular radio network," *Proc. IEEE Vehicular Technology Conference*, vol. 5, pp. 2039-2046, Sep. 24-28, 2000.

[7]   U.-H. Kim, J. Kim, D. Kim, H. Kim, and B.-J. You, "Speaker Localization on a Humanoid Robot's Head using the TDOA-based Feature Matrix," *Proc. IEEE 17th International Symposium on Robot and Human Interactive Communication*, Munich, Germany, pp. 610-615, Aug. 1-3, 2008.

[8]   I. A. Getting, "The Global Position System," *IEEE Spectrum*, vol. 30, no. 12, pp. 36-47, Dec. 1993.

[9]   M. Omerbashich, "Integrated INS/GPS navigation from a popular perspective," *Journal of Air Transportation*, vol. 7, no.1, pp. 103-118, 2002.

[10]   J. Werb and C. Lanzl, "Designing a positioning system for finding things and people indoors," *IEEE Spectrum*, vol. 35, no. 9, pp. 71–78, Sep. 1998.

[11] L. M. Ni, Y. Liu, Y. C. Lau, and A. P. Patil, "LANDMARC: Indoor location sensing using active RFID," *Wireless Networks*, vol. 10, pp. 701-710, 2004.

[12] H. Tong and S. A. Zekavat, "A Novel Wireless Local Positioning System via Asynchronous DS-CDMA and Beam-forming: Implementation and Perturbation Analysis," *IEEE Transactions on Vehicular Technology,* vol. 56, no. 3, pp. 1307 − 1320, May 2007**.**

[13] W. Wang, and S. A. Zekavat, "Comparison of Semi-Distributed Multi-Node TOA-DOA Fusion Localization and GPS-Aided TOA (DOA) Fusion Localization for MANETs," *EURASIP Journal on Advances in Signal Processing,* vol. 2008, Article ID 439523, 16 pages, 2008. doi:10.1155/2008/439523, 2008.

[14] W. Wang, and S. A. Zekavat, "A Novel Semi-distributed Localization via Multi-node TOA-DOA Fusion,"*IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, pp. 3426 − 3435, Sept. 2009.

[15] S. G. Ting, O. Abdelkhalik, and S. A. Zekavat, "Differential Geometric Estimation for Spacecraft Formations Orbits via a Novel Wireless Positioning," proceedings *IEEE Aerospace Conference,* 2010.

[16] T. Williamson and N. A. Spencer, "Development and operation of the traffic alert and collision avoidance system (TCAS)," *IEEE Control System Magazine*, vol. 77, no. 11, pp. 1735–1744, Nov. 1989.

[17] J. Hightower and G. Borriello, "Location systems for ubiquitous computing," *Computer*, vol. 34, no. 8, pp. 57-66, 2001.

[18] P. Bahl and V. N. Padmanabhan, "Radar: An In-Building RF-Based User-Location and Tracking System," *Proc. IEEE INFOCOM 2000*, Tel Aviv, Israel, vol. 2, pp. 775–84, Mar. 2000.

[19] K. Saneyoshi, "Drive assist system using stereo image recognition," *Proc. IEEE Intell. Veh. Symp.*, pp. 230–235, 1996.

[20] S. A. Zekavat, A. Kolbus, X. Yang, Z. Wang, J. Pourrostam, and M. Pourkhaatoon, "A Novel Implementation of DOA Estimation for Node Localization on Software Defined Radios: Achieving High Performance with Low Complexity," proceedings *IEEE ICSPC 2007*, Dubai, UAE, 26 − 27 Nov. 2007.

[21] J. Pourrostam, S. A. Zekavat, and H. Tong "Novel Direction-of-Arrival Estimation Techniques for Periodic Sense Local Positioning Systems in Wireless Environment," proceedings *IEEE Radar'07*, 17 − 20 April, 2007, Boston.

[22] H. Tong, J. Pourrostam, and S. A. Zekavat, "Optimum Beam-forming for a Novel Wireless Local Positioning System: A Stationarity Analysis and Solution," *EURASIP Journal on Advances in Signal Processing,* vol. 2007, Article ID 98243, 12 pages, 2007.

[23] M. Sekine, T. Senoo, I. Morita, and H. Endo, "Design method for an automotive laser radar system and future prospects for laser radar," *Proc. IEEE Intell. Veh. Symp.*, pp. 120–125, 1992.

[24] D. K. Shaeffer, A.R. Shahani, S. S. Mohan, H. Samavati, H. R. Rategh, M. del Mar Hershenson, M. Xue, C. P. Yue, D. J. Eddleman, and T. H. Lee, "A 115-mW, 0.5-μm CMOS GPS receiver with wide dynamic-range active filters," *IEEE J. Solid-State Circuits*, vol. 33, no. 12, pp. 2219–2231, Dec. 1998.

[25] V. Zeimpekis, G. Giaglis, and G. Lekakos, "A Taxonomy for Indoor and Outdoor Positioning Techniques for Mobile Location Services," *Journal of ACM SIGecom Exchanges*, vol. 3 no. 4, pp. 19-27, 2003.

[26] F. van Diggelen, "Indoor GPS theory & implementation," *IEEE Position Location and Navigation Symposium*, pp. 240–247, 2002.

[27] C. Piesch, T. Gulde, C. Sartorius, F. Friedl-Vallon, M. Seefeldner, M. Wölfel, C.E. Blom and H. Fischer, "Design of a MIPAS Instrument for High Altitude Aircraft," *Proc. Second International Airborne Remote Sensing Conference and Exhibition*, San Francisco, June 24-27, 1996.

[28] N. Cho, S.-J. Song, S. Kim, S. Kim, and H.-J. Yoo, "A 5.1-µW UHF RFID Tag Chip integrated with Sensors for Wireless Environmental Monitoring," *IEEE European Solid-State Circuits Conference*, pp. 279-282, Sep. 2005.

[29] S. Ractliffe, "Air traffic control and mid-air collisions," *J. Electron. Commun. Eng.*, vol. 2, no. 5, pp. 202–208, Oct. 1990.

[30] H.-C. Lee, "Implementation of collision avoidance system using TCAS II to UAVs," *IEEE Aerospace and Electronic Systems Magazine*, vol. 21, no. 7, pp. 8-13, July 2006.

[31] J. Ebert, B. Burns, and A. Wolsiz, "A trace-based approach for determining the energy consumption of a WLAN network interface," *European Wireless Conference*, Florence, Italy, pp. 230-236, Feb. 2002.

[32] S. Nedevschi, R. Schmidt, T. Graf, R. Danescu, D. Frentiu, T. Marita, F. Oniga, and C. Pocol, "High Accuracy Stereo Vision System for Far Distance Obstacle Detection," *IEEE Intelligent Vehicles Symposium*, Parma, Italy, pp. 292-297, June 14-17, 2004.

[33] N. Sawasaki, M. Nakao, Y. Yamamoto, and K. Okabayashi, "Embedded Vision System for Mobile Robot Navigation", *Proc. IEEE International Conference on Robotics and Automation*, pp. 2693-2698, May 15-19, 2006.

[34] R. Hermann, M. Marc-Michel, K. Michael, and L. Urs, "Research activities in automotive radar," *Proc. MSMW Symp.*, vol. 1, pp. 48–51, June 4-9, 2001.

[35] M. Edrich, "Ultra-lightweight synthetic aperture radar based on a 35 GHz FMCW sensor concept and online raw data transmission," *Proc. IEE Radar Sonar Navig.*, vol. 153, no. 2, pp. 129–134, Apr. 2006.

[36] N. Alsindi, Li Xinrong, and K. Pahlavan, "Analysis of Time of Arrival Estimation Using Wideband Measurements of Indoor Radio Propagations," *IEEE Transactions on Instrumentation and Measurement*, vol. 56, no. 5, pp. 1537-1545, 2007.

[37] W. Xu, and S. A. Zekavat, "Spatially Correlated Multi-user Channels: LOS vs. NLOS" proceedings *IEEE DSP/SPE workshop 2009*, Florida, Jan. 4-7, 2009.

[38] Z. Wang, W. Xu, and S. A. Zekavat, "A novel LOS and NLOS localization technique," proceedings *IEEE DSP/SPE workshop 2009*, Florida, Jan. 4-7, 2009.