

Tutorial on Location Determination by RF Means

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Abstract. This paper focuses on radio-frequency (RF) location determination characteristics and implementations. A presentation of RF transmission, propagation and reception characteristics is provided and a summary of some the major developments of RF-based location systems is also discussed. RF determination capabilities are typed and classified and outlined. Finally, examples of RF-based location systems are given.

1 Introduction

Location determination has a long a storied history. From the first navigators guided by the stars and Sun to the electronic systems of today; finding one's place continues to be amongst the most crucial elements in life. The term “location awareness” has sprung into the popular vernacular in recent years in response to the desire for applications and services to provide greater availability and accuracy of location determination at all times. Location awareness helps provide context for feature rich applications and services; making them feel far more personal and interactive. While the relative importance of location awareness may not have increased in the past few decades, the proliferation of location determination technology for assets and persons has increased remarkably. Many of the location determination technologies we take for granted today such as GPS (Global Positioning System), and its international Global Navigation Satellite System, or GNSS, counterparts such as GLONASS, Galileo, Compass/Beidou, etc., were not available 20 years ago. The introduction of global navigation systems has produced a paradigm shift in location awareness that expects high-availability, always-on location determination capabilities. This expectation has, in turn, led to substantial innovation and development in the location algorithms and technology that today provide a myriad of options for various applications.

This paper provides a tutorial on Radio Frequency (RF) of location determination technology. It starts by looking at RF system characteristics versus other options, such as inertial and vision systems. The review of RF location determination systems will begins with RF bands and their properties. It briefly discusses the impact of bandwidth on location determination accuracy. The paper then discusses the different RF location approaches followed by methods employed in RF location determination.

1.1 Frequency Bands and Usable RF Spectrum

When considering the alternatives for location determination systems, one primary question that must be answered is: "Why use RF systems versus other non-RF

approaches?" First, RF represents some of the most flexible kinds of equipment that can be deployed versus the alternates. For example, ultrasound-based systems can have a very fine precision but are strictly limited to Line-Of-Sight (LOS) operation and highly subject to environmental noise [1]. Table 1 shows the performance of different non-RF systems deployed today.

In most cases the most limiting factor is range. Since RF propagation can be used for close-in applications as well as those applied over hundreds of kilometers, it is the most flexible method for use in applications. However, in many cases where RF has superior range it does so at the expense of precision, which is why alternative means of precise location determination will always be sought after. One such example in wide use today is the compliment of inertial sensors and GNSS. This combination can offer very precise location capability without the need for installed infrastructure. This is only limited by the precision of the GNSS system it is paired with as well as the availability of those precise signals to calibrate the inertial sensors. This type of combination continues to be of great interest in development of commercial and consumer systems.

Table 1. Comparison of Different Location Technologies [1]

Technology	Pros	Cons
Inertial	-Precise with expensive sensors -Works in a variety of environments (underwater, indoor, etc.)	-Unusable without frequent corrections from external reference (often GNSS-based)
Vision	-High precision -Works where instrumented	-Limited range, LOS -Extensive instrumentation
Ultrasound	-Very inexpensive emitters and sensors -High precision	-Limited range, LOS -Very sensitive to ambient noise
Infrared	-Inexpensive emitters and sensors -High precision	-Limited range, LOS -Very sensitive to ambient noise
Smart/Active Floors [2]	-Works without instrumenting subject -High precision	-Works only where floor (or furniture) is instrumented -Difficult to distinguish individuals (i.e., track a specific person)
GNSS	-Worldwide coverage -Free to use	-Precision 10m unaided -Limited indoor use

Table 2. Classification of radio frequencies [3]

Band	Frequency	Wavelength
Very Low Frequency (VLF)	< 30 kHz	> 10 km
Low Frequency (LF)	30-300 kHz	1-10 km
Medium Frequency (MF)	300 kHz-3 MHz	100 m-1 km
High Frequency (HF)	3-30 MHz	10-100 m
Very High Frequency	30-300 MHz	1-10 m
Ultra High Frequency	300 MHz - 3 GHz	10 cm - 1 m
Super High Frequency (SHF)	3-30 GHz	1 - 10 cm

Radio propagation is classified as electromagnetic waves between the frequencies of 10 kHz and 300 GHz. Table 2 shows the classification of RF bands into groups. The relationship between frequency, f , and wavelength, λ , is given by $\lambda=c/f$, where c is the speed of light in a vacuum (2.99792×10^8 m/sec). The term "microwave" indicates wavelength between 1 m and 1mm.

One of the most critical aspects of RF location systems is the range in which they can be deployed. Systems that use frequencies at and below HF can transmit over the horizon using a surface wave (follows the surface of the Earth). An issue with using the surface wave is that multipath (more than one version of the same signal arriving at the receiver with different delays or angle-of-arrivals). Multipath affects location systems in three distinct ways: 1) it can produce signal fade due to cancelation of waves at the receiver; 2) it can cause multiple versions of the same signal at the receiver that can alter timing; and finally; 3) for direction-finding systems signals can be received from various directions simultaneously. Other issues in systems employing frequencies at HF and below are antenna size, near-far effects, and interference. Antenna size generally scales with wavelength. The simplest designs of dipole or slot antennas are generally $\lambda/2$ in length with short-dipole or loop antennas are as small as $\lambda/10$ [4]. At this size, simple antennas would be 1 m or longer which may be an issue for some portable location applications. The fields around the antenna can be classified by two different regions, near-field (or the Fresnel zone) and the far-field (or the Fraunhofer zone). In the far-field the energy flow is directed radially (field shape is invariant by distance). As shown in Fig. 1, in the near-field the electric field may be significant and the shape of the field will depend on distance from the antenna.

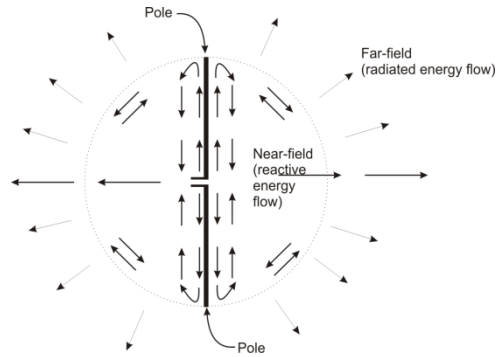


Fig. 1. Near-Field Pattern showing the difference in energy pattern near the element in contrast to the far field which is primarily radial

The near-field radius may be roughly approximated by [4]

$$R = 2L^2/\lambda \quad (\text{m}) \quad (1)$$

where

L = maximum dimension of the antenna, m

λ = wavelength, m

In free-space RF propagation the loss is simply proportional to distance for a given frequency f :

$$\frac{P_r}{P_t} = \frac{1}{(4\pi df / c)^2} \quad (2)$$

where P_r is the received power level, and P_t is the transmitted power level. The difference between received power at two distances d_1 and d_2 is given by:

$$\Delta_p = 10 \log_{10} \left(\frac{P_{r2}}{P_{r1}} \right) = 20 \log_{10} \left(\frac{d_1}{d_2} \right) \text{ (dB)} \quad (3)$$

which represents a 6 dB decrease in power for each doubling of distance and a factor of 20 dB with every ten-times increase in distance (i.e., 20 dB/decade). However, due to interference and interaction between the signal and obstacles between the transmitter and receiver along the propagation path, modeling signal loss based only on distance is almost never possible in real-world scenarios. As discussed previously, models of the signal are dramatically impacted by the chosen frequency, the distance between the transmitter and receiver as well as other characteristics. These lead to fading between the transmitter and receiver which have both long-term and short-term components [9]. Long term fading is characterized by terrain variations between the transmitter and receiver, for example is the area flat or hilly. In contrast, short term fading is due to local effects such as reflection and refraction around objects that are on the scale of buildings or a forest. Fading can also be a temporal function based motion of the receiver, or for a stationary receiver, motion of the surrounding objects creating the fading signals. As computed in [5], path loss due to terrain can be an additional 20 dB/decade due to terrain. From foliage, path loss can be roughly 20dB/decade extra as well. Additional path loss can be attributed to buildings and other structures. As reported in [6], and as shown in Fig. 2, structural path loss at 1-2 GHz and 2-4 GHz can be as high as 50 dB for certain structures. Fig. 3 has the mean

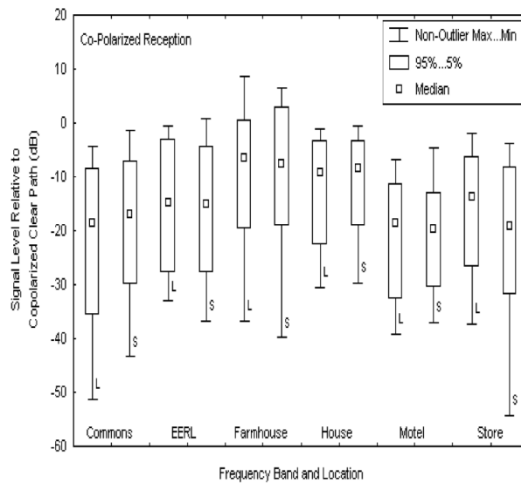


Fig. 2. Attenuation of L-Band and S-Band Signals in a range of indoor settings

attenuation by frequency from 500 MHz to 3 GHz through a farmhouse ranging from 15 dB to 27 dB of loss respectively. It can be seen that frequencies at or above the VHF band, attenuation inside of building can easily exceed 10 dB or more. An advantage to frequencies below VHF is that building attenuation is generally less of an issue. One important note for all frequencies is the so-called near-far problem which is the problem that short distances between a transmitter and receiver can have a huge dynamic range. RF receiver designs usually have a limited dynamic signal bandwidth which is designed for an expected range of received signal powers. This fixes the viable receiver ranges for a given a transmit power and radio-link properties between the transmitter and receiver.

As shown in Table 3, frequencies at MF and below have beneficial signal propagation performance, including good building penetration. However, since efficient antennas at these frequencies are impossible to achieve, high transmit power is required to attain the required signal level at the receiver [4]. For the Loran system which operates in the LF band at 90-110 kHz the transmit power at the stations are 1 MW [1]. While this high power is necessary to operate over long distances (typically 900-1500 km over land, 1500-2000 km over sea [7]) it is also to compensate for antenna losses that could easily exceed 60 dB for a handheld device (<10cm) or 30 dB for a fixed 1 m receiver [4]. While at lower frequencies, efficient antennas are key; at higher frequencies, the local environment becomes the driving factor in location determination. Above 100 MHz, LOS signals become the dominant propagation type but also buildings, vehicles and natural obstructions like trees begin to have greater effect [3]. Multipath becomes a major concern as reflections from these obstacles arrive both in-phase and out of phase at the receiver. Above 3 GHz there is only direct LOS propagation available since obstacles highly attenuate the signal. Multipath is also of substantial concern.

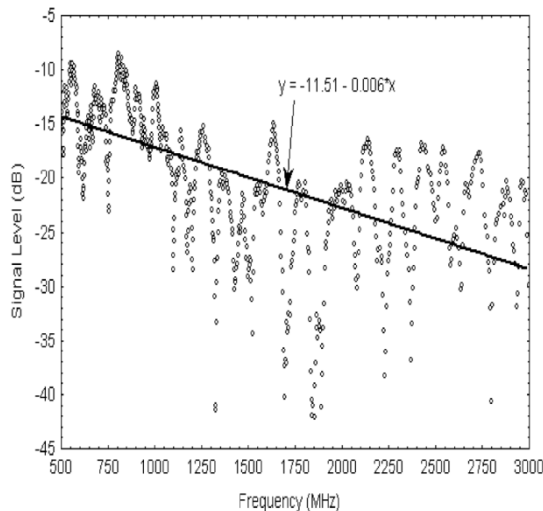


Fig. 3. Dependence on Frequency of attenuation in a farmhouse

Table 3. Characterization of frequency bands

Band	Frequency	Propagation	Antenna Size (half-wave dipole)	Multipath	Structure Penetration
VLF	< 30 kHz	LOS, Surface, Sky	5 km	Ground, Sky	Good
LF	30-300 kHz	LOS, Surface, Sky	0.5-5 km	Ground, Sky	Good
MF	300 kHz-3 MHz	LOS, Surface, Sky	50-500 m	Ground, Sky	Good
HF	3-30 MHz	LOS, Surface	5-50 m	Ground, Artifacts	Poor
VHF	30-300 MHz	LOS	0.5-5 m	Artifacts	Poor
UHF	300 MHz - 3 GHz	LOS	5-50 cm	Artifacts	Very Poor
SHF	3-30 GHz	LOS	0.5-5 cm	Artifacts	Low/None

A great deal of emphasis has been placed in the location determination literature over the past decade using unlicensed-band, short and medium-range communication devices. These devices are generally classified by the terms Bluetooth, ZigBee, 802.11b/g/n (or WiFi), and RFID [1,8]. These devices are generally designed to operate in one or more of the ISM bands (or Industrial, Scientific and Medical as defined by the ITU-R [9]); and must accept any interference from ISM devices (and in turn not interfere with ISM signals). These restrictions make these devices very low power and limited in range. The most popular frequency band in-use today is 2.45 GHz which is used for a broad array of short range communication devices including WiFi, Bluetooth, ZigBee and even some RFID. Also popular is a band at 900 MHz in ITU Region 2 (comprising North and South America, Greenland and eastern pacific islands) and 433 MHz in ITU Region 1 (Europe, Africa, the Middle East west of the Persian Gulf including Iraq, the former Soviet Union and Mongolia). Recently the use of 5.8 GHz has become increasing popular for certain devices. As indicated by Table 3, all of these frequencies perform best under LOS conditions, although some structure penetration (walls and furniture) is assumed, these obstacles can have significant impacts on signal strengths (attenuation) and phase (multipath). Many approaches in the literature either implicitly or explicitly try to take advantage of these propagation characteristics [10]. One problem of the pathloss and multipath issues of these frequencies is that local environmental conditions (placement of furniture, number of people in a room, relative location of receiver/transmitter to a person as well as a host of other variables) can have a strong impact on measurements used in localization. A great deal of effort has been paid recently in the literature on devising algorithms that are more tolerant to these fluctuations [11,12,13]. This will be discussed in greater detail in Section 2.4 of this paper. Another major trend in RF location determination is Ultra-Wide-Band systems or UWB. UWB is defined as a signal with a bandwidth greater than 500 MHz or 20% of the carrier frequency. The benefits of UWB signals for rejection of multipath will be discussed in the next section but the use UWB has its impact. Since UWB signals share the same signal space as licensed and unlicensed bands, they can have an impact on the noise floor for other applications in those bands. In some

countries, UWB cannot be used until these issues are addressed [8] and it received limited approval by the FCC in 2002 [33] for data communications, radar and safety applications across a band from 3.1 GHz to 10.6 GHz. The power limits on the FCC order relegates current UWB applications in these bands to indoor and short-range applications. Commercial systems based on UWB are beginning to be introduced [14] and are definitely worth continued consideration.

1.2 Bandwidth Impact on Received Signals

One approach to describe the signal propagation between a transmitter and receiver is using an impulse response [15]. Modeling the signal from the transmitter to receiver separated by a distance, d , as a impulse response, we have:

$$h_d(t) = \sum_{k=0}^{L_p-1} \beta_k^d \delta(t - \tau_k^d) \quad (4)$$

where L_p is the number of multipath components of the original signal impulse, $\delta(t - \tau_k^d)$, received with k -th propagation delay τ_k^d . Each of the received multipath signal components have a magnitude and phase, $\beta_k^d = |\beta_k^d| e^{j\phi_k^d}$, relative to the original signal based on the additive components at the receiver input. Fig. 4 is a representation of the received signal pattern.

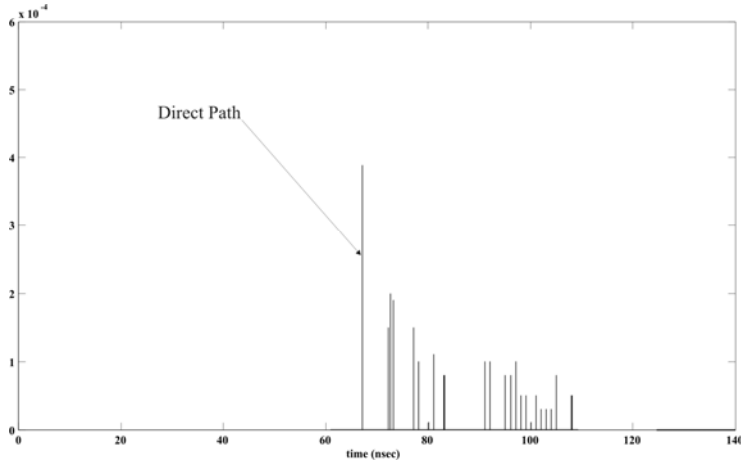


Fig. 4. Multipath profile for an impulse-response channel model

The bandwidth associated with an impulse response is infinite so this channel model has infinite bandwidth. Realizable channels, both because of physical and regulatory limitations, have finite bandwidth (W) and if we represent this signal as $x_w(t)$, the received signal $r_d^w(t)$ is given by the convolution of the limited bandwidth signal and the impulse response [16]:

$$r_d^W(t) = \int_{-\infty}^{+\infty} x_W(\tau) h_d(t - \tau) d\tau \quad (5)$$

Fig. 5 shows a sample channel profile generated by transmitting a raised cosine pulse in a system with 200 MHz of bandwidth. This figure shows how ranging error is observed in the finite bandwidth case versus the unlimited bandwidth case.

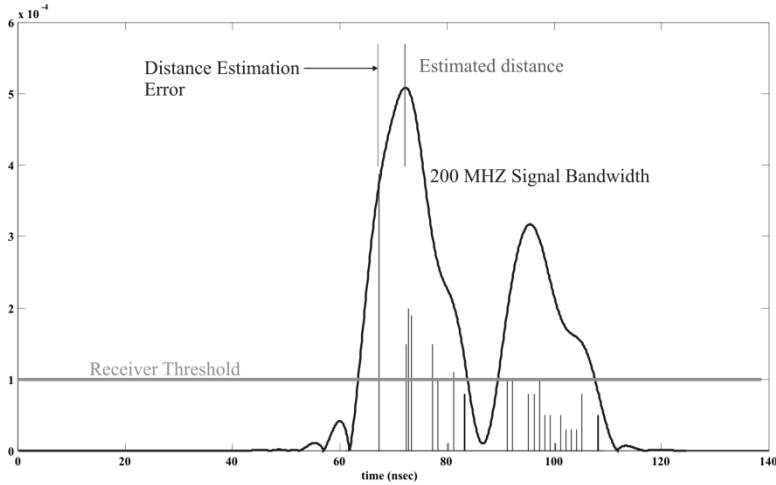


Fig. 5. Distance measurement error due to finite bandwidth signal

2 RF Location Types and Classification

Numerous types of RF location technologies have been implemented over the years. These primarily break down into five major types: 1) Proximity; 2) Direction Finding (DF) or Angle of Arrival (AOA); 3) Doppler; 4) Signal Strength; and 5) Timing or Phase as shown in Fig. 6.

Proximity-based approaches include contact and near-contact sensors such as in RFID (which stands for RF IDentification). In the case of RFID, these systems establish location based purely by presence. These systems usually operate in the near-field within a few wavelengths. If the tracked transmitter object is close enough for a receiver to get a signal, then the receiver and transmitter are clearly close to one another.

Direction Finding (DF) and Angle-of-Arrival systems provide a means for determining the bearing of a RF transmitter from a receiver. Two or more receivers can be used to triangulate on the 2D horizontal location of the transmitter (altitude could be determined by a third, vertically-oriented receiver).

Location by Doppler uses the phenomenon that when a transmitter and receiver are travelling towards one another the received frequency is higher than transmitted and when they are travelling away from each other the received frequency is lower. By combining multiple measurements of frequency shifts it is possible to ascertain the location and velocity simultaneously.

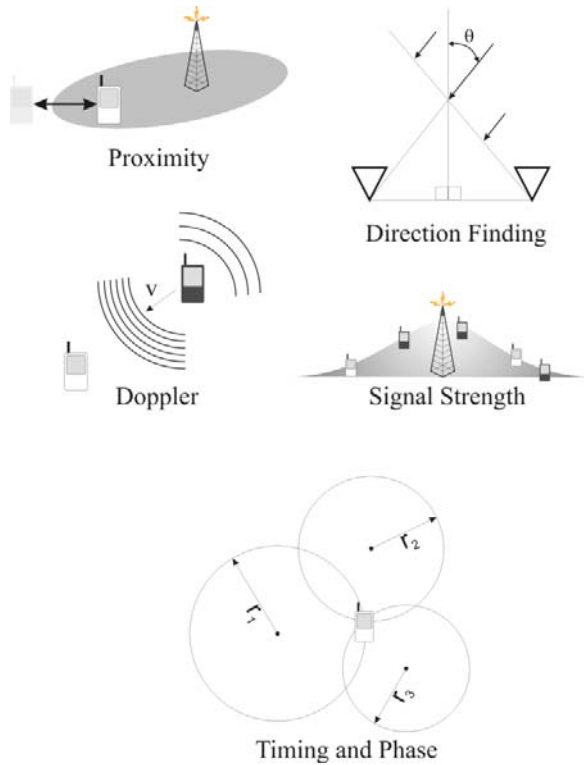


Fig. 6. Types of RF location technologies

Signal strength uses signal power (or other signal-based metrics like Bit Error Rate, or Carrier-to-Noise Ratio) to form an estimate of range or in reference to previously stored location information in a database, otherwise known as "RF fingerprinting." In the ranging case, multiple range estimates can be combined via lateration from multiple reference positions. In the case of RF fingerprinting, previously collected reference values are compared to one or more current measurements to match the current location to the stored data.

Timing and Phase location systems use measurements of the received phase of an RF signal or synchronization with a timing modulation on the signal to estimate the range between a transmitter and receiver. Lateration is used to combine multiple range estimates to form a location estimate. This timing information can be employed directly as in Time of Arrival (TOA) systems, or in Round-Trip-Delay (RTD) measurement, or alternatively in Time-Difference of Arrival (TDOA) systems.

The following five sections will discuss in further detail how these different approaches work and look at them in light of various performance characteristics.

2.1 RF Location by Proximity

One of the simplest approaches to RF location is simply by sensing a RF beacon transmitter that is at a known location. In the simplest case, the location precision of

the receiver is the coverage area of the beacon transmitter. In other words, the range of the signal represents the uncertainty of your location estimate. Depending on the propagation characteristic of the frequency, channel characteristics, directionality of the transmitter/receiver pair, as well as the effective aperture of the transmitting and receiving antenna, the range may be a few meters to hundreds of kilometers.

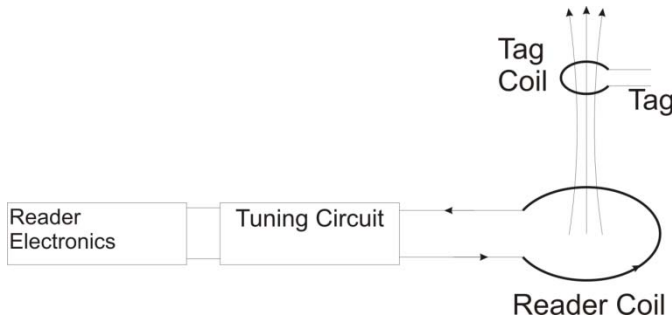


Fig. 7. RFID Operation

The type of device most widely in use today representing proximity-based location is RFID. As depicted in Fig. 7, an RFID system is comprised of at least one "reader" which operates both as a power transmitter and receiver and one or more passive "tags" which are used as transmitters [1]. The system takes advantage of the previously described attributes of near-field RF patterns that allow for electrical and magnetic coupling of the transmitter and receiver. The RFID tags are not usually powered by battery or other power source but derived their power from the reader RF signal. This allows the tag to power a small microchip-based circuit capable of modulating a unique ID code or some other stored information about the tag. Depending on the power transmission of the reader the range to activate the tag can be as little as a centimeter or as large as 30 meters or more [7]. An alternative to passive tags where the reader provides the power for the tag are active RFID tags that have their own power and broadcast information at periodic intervals or when polled by the reader. This approximates a more traditional telemetry system except in this case the tags are designed for minimal complexity, storage and data bandwidth in order to keep their production costs down. RFID operates in different frequency bands. In low-frequency operations it is employed at 30-500kHz and is used mainly for short-range reads (less than 1 meter). Higher frequency system can operate in the range of 850-950 MHz and 2.4-2.5GHz and are designed for longer read ranges.

A novel application that uses a combination of GPS and RFID is the YARD HOUNDTM by PINC Solutions [17] which is in commercial use today for management of tractor trailers at distribution centers. This system places passive RFID tags on tractor trailers either permanently or when they enter the yard of a distribution center. A reader is placed on each of the yard trucks that move the trailers between storage bays and the distribution warehouse as well as the exit and entrance to the yard (for ingress and egress records). The yard trucks also have precise GPS location so that when the reader records contact with a particular tag, it can estimate the location of a trailer to roughly one storage bay thus creating a record of the current

location of each trailer that they pass. These records are transmitted via 802.11b/g/n wireless link from the yard trucks to a monitoring computer running in the distribution warehouse which hosts a web-based interface that allows both managers inside the warehouse sitting at computer terminals well as workers with mobile devices get instant access to the location of the trailers they need to either fill or empty. This dramatically decreases the time and effort of personnel to survey the yard to map the location of trailers at a given epoch.

Bluetooth (IEEE 802.15) is another wireless technology for short-range communications. It uses a frequency hopping scheme which makes timing/phase measurements very difficult but it is well suited for proximity-based sensing since its range is dependent on its power class (optionally 1, 10 or 100 meters) [18,19]. Bluetooth operates in the ISM band between 2.400 GHz and 2.485 GHz so it has substantial, but not complete, degradation by structures. Each Bluetooth device is identified by a unique Media Access Control (MAC) address. The advantage of Bluetooth is that it is a pervasive technology in consumer and commercial applications. Many of today's cell phones, computers, printers, and other electronic devices come pre-equipped with Bluetooth.

Similar to Bluetooth, WiFi (802.11b/g/n) and ZigBee (802.15.4) RF signals also operate in the ISM band of 2.400-2.485 GHz and can also be used as proximity sensors as well and could be combined with GNSS in a simple either-or scenario for different applications [20]. Further applications for all three of these RF radio systems will be discussed in the sections dealing with Signal Strength for location determination.

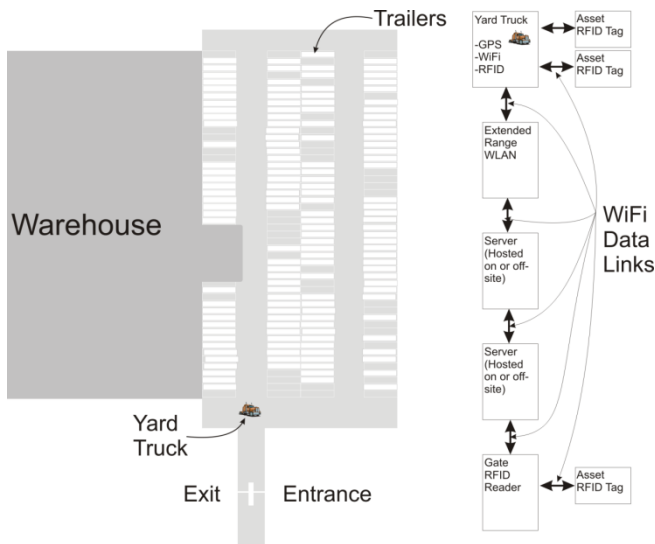


Fig. 8. Elements of the YARD HOUND™ System

In general, proximity-based location can be classified as a ultra-local or local area system where the range generally would not exceed 100 meters. Precision of the location estimate would be inversely proportional to range. Consideration of bandwidth,

signal attenuation in the atmosphere or through structures are generally not important because the devices are often operating in the near-field of the RF bands and so far-field effects are inconsequential. Since the relative distance of the receiver and transmitter is so small, antenna gain is usually not a substantial issue so antennas can be small and power requirement generally low. Of particular note, relative to GNSS systems is that these systems always put a constraint on the maximum number of simultaneous users for a fixed infrastructure. Since they all depend on some external reader or base station which has a limited number of channels these systems will need to increase in size and complexity with an increase in simultaneous users.

2.2 Radio Direction Finding (DF) and Angle of Arrival (AOA)

The basis of radio Direction Finding (DF) and Angle-of-Arrival (AOA) position determination is the use of angular measurements for triangulation as shown in Fig. 9. Triangulation uses the bearings from two or more DF receivers to obtain an estimate of the transmitter's location. Principally these systems operate in the RF far-field of the transmitter and receiver pair with a planar wave incident on the receiver. In practice, multiple signal distortions keep this from being ideal. Work in radio DF dates back over 100 years. The earliest recorded systematic experiments date back to 1899 with the first demonstration of tracking a steamship in 1906 by Marconi using a radial system of horizontal antennas about $\lambda/5$ long. In 1907, work by Pickard and DeForest showed the benefits of loop antenna direction finders which would prove to be the format of choice for many small aperture DF systems (antenna sizes up to about $\lambda/2$). In 1926, the Watson-Watt DF was introduced with used two crossed, quadrature loops that have their output signal directly measured by a cathode-ray oscillograph providing an instantaneous estimate of AOA [21].

In the 1930s leading up to World War II, medium and high frequency radio beacons served guidance and rough navigation functions aircraft. By tracking a single beacon (usually collocated with an airport for aircraft) a relative angular fix can be

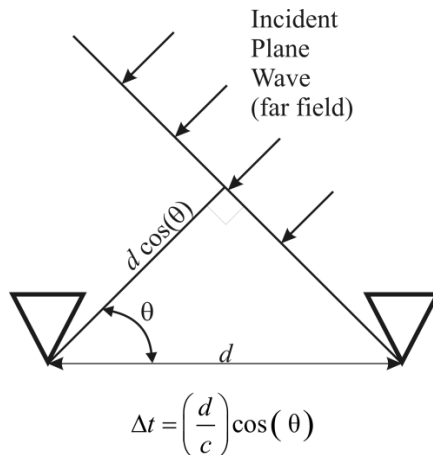


Fig. 9. DF and AOA Principles

made between the axis of the aircraft and the beacon. By tracking two or more beacons, a crude position could be determined through triangulation. “Positive” navigation points were provided at some airports with vertical marker beacons. These vertical beacons were similar to the standard radio beacon except that their signals were directed upward. Tracking this beacon indicates to the pilot that they are directly above it giving them ‘positive’ feedback on their location. As more flights were made on a greater number of routes, the use of airport locations as beacons became undesired. Over time, directional beacons were set up along air travel routes around the world. These routes could take advantage of the lessons learned during World War II. During the war, it was shown that routes directed along prevailing winds (referred to as cyclonic) could cut travel time over the shortest distant method (great circle), thus saving fuel. After World War II, VOR (VHF Omnidirectional Range) stations were developed and put into place. According to [22], outside of the developed world VOR support is provided with the exceptions of the Polar Regions, the South Atlantic Ocean, and much of the Pacific and Indian oceans.

VOR broadcasts in a band between 108 and 118 MHz with channels 50 kHz apart (switched to 50kHz from 100kHz in the 1960s to gain additional channels). The ground broadcasts two signals modulated with a 30-Hz tone. The first is a fixed reference tone with an omnidirectional radiation pattern. The second signal is radiated with a cardioid pattern that rotates 30 rotations per second. The receiver uses the relative phase of these two 30-Hz signals to determine bearing to the VOR (which is at a known location). Fig. 10 shows a diagram of a VOR receiver. In addition to the 30-Hz modulation there is an audio channel broadcast modulated at 9660 Hz as well as Morse code identifier of the VOR with a 1020 Hz modulation. The voice signal can be used as a repeating station identifier or as a ground-to-air communications channel [23]. This system design was a U.S. standard by 1946 with later adoption by the International Civil Aviation Organization (ICAO). The performance of this system is only limited by propagation effects and user equipment errors. High-end user equipment can usually achieve 0.1° - 10° of angular resolution. This system only works well when the VOR and receiver are line of sight visible [22].

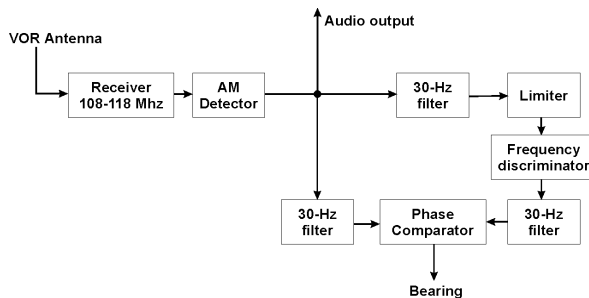


Fig. 10. VOR Receiver Diagram

2.3 Doppler

Another method that can be used to locate a RF device utilizes the well known phenomenon called the Doppler effect. The Doppler effect states that when an object

emits a frequency and moves relative to an observer, the frequency of the observed signal will be shifted up or down. The magnitude and sign of the shift depends on the frequency of the signal and the velocity of the transmitter and observer relative to each other. The Doppler shift is given by:

$$\Delta_f = (f_R - f_T) = -\frac{v}{\lambda} \text{ (Hz)} \quad (6)$$

where

f_R is the received frequency of the signal

f_T is the transmitted frequency of the signal

v is the relative velocity of the transmitter and receiver

λ is the wavelength of the transmitted signal

As illustrated in Fig. 11, the current velocity of a transmitter is mapped onto the LOS to a receiver that produces a measured Doppler shift. As the location and velocity of the transmitter and the Doppler shift is known, the only unknown is the location of the fixed receiver. At a later time another Doppler shift is made from a different transmitter location and these two observations can be used to resolve a 2D location (assuming: perfect frequency references on both the transmitter and receiver, stationary receiver, and no frequency distortion between transmitter and receiver). It should be noted that when dealing with a transmitter and receiver at large distance from one another (as in GNSS) the LOS is not very sensitive to the location of the receiver so precise position is hard to estimate from a single epoch of Doppler data [3]. For short-range Doppler system, where the distance between receivers and transmitters is within an order of magnitude of the desired location precision, Doppler location is far more precise.

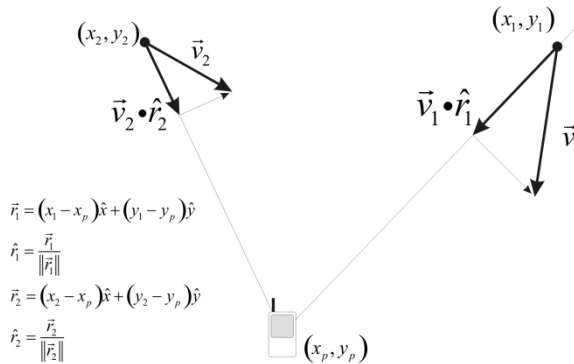


Fig. 11. Doppler velocity location

One interesting approach using Doppler location determination as presented in [24] utilizes a mobile node that transmits a signal at a known frequency and the Doppler shifted signal is measured by fixed "infrastructure" nodes. The speed of the tracked node relative to all infrastructure nodes can be calculated and used to determine both

the velocity and the location of the node. The desired hardware in this approach had low computational power (8 MHz, 8-bit microprocessor) and no specialized Doppler measurement capability. They presented an approach, shown in Fig. 12, that had the tracked node transmit at a frequency f_t and one of the infrastructure nodes generates a signal f_a such that $f_t > f_a$ and when the two signals interfere with one another they produce a signal with an envelope frequency of $f_t - f_a$. This frequency difference can be measured with very fine precision using simple direct sampling. They employed a frequency difference of 300-400 Hz to enable tracking with computationally-constrained hardware. The processor sampled the radio RSSI (Received Signal Strength Indicator) which allows the measurement of the interference envelope at 8.9kHz. They used an observation window of 450 samples or approximately 18 periods of the interference envelope of 300-400 Hz which was a tradeoff between smoothing measurement noise and capturing the dynamic motion of the tracked mobile node. Results of simulation and experiment showed results of 1.3-2.2m and 0.1-0.4m/s in an operational area of 1500m². The limitation of this approach is that each tracked node needs to use a specific frequency (or share it in a synchronized time-sliced method) and thus cannot support an unlimited number of nodes.

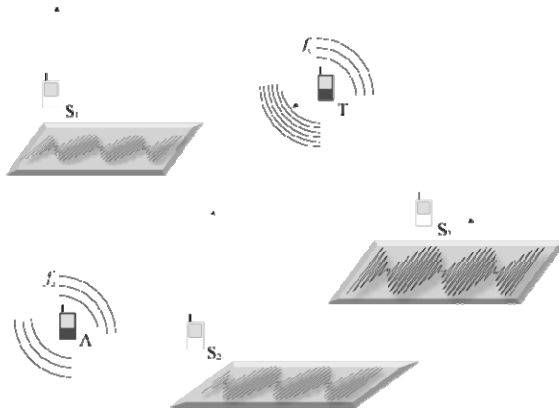


Fig. 12. Interference-based Doppler velocity and location

The advantage of the Doppler systems is that they are relatively simple in overall design. LOS requirements are the same as for any RF-based system, the frequency choice is fairly wide since it is not limited to a particular modulation or bandwidth however, processing of higher frequencies can require specialized hardware unless approaches such as the interference-based model are used.

2.4 Signal Strength

A substantial body of work has been produced examining position determination techniques based on signal strength and other signal-related properties such as signal-to-noise ratio (SNR), bit error rate (BER), Link Quality Indicator (LQI), Response Rate (RR), or carrier-to-noise ratio (C/N₀). The two most prevalent RF sources used

in the studies are WiFi access points (IEEE 802.11) and cellular towers (both GSM and CDMA).

There are basically two general classes that signal strength solutions break down into: distance estimation (leading to lateration) and pattern recognition (also known as fingerprinting).

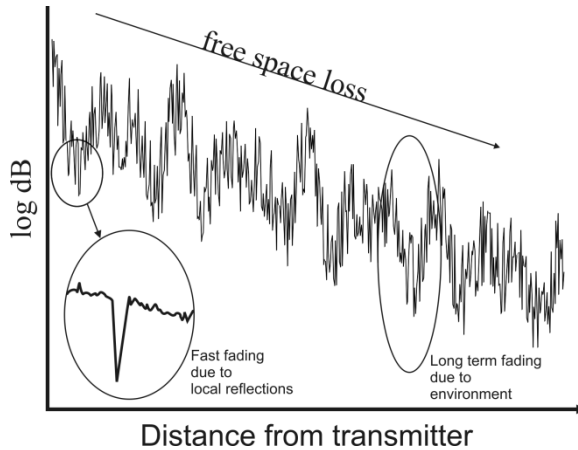


Fig. 13. Propagation Path Loss with multipath

2.4.1 Distance Estimation

As the distance between the transmitter and the receiver increases, the RSS decreases according to as discussed in Section 1.2 and provided in detail from [5,15]. In this way RSS can be equivocated to distance measurements as described in TOA and TDOA in the following section. In cellular and WiFi systems the RSS is used for handoff and traffic processing and is accessible without changing system architecture. Operating on RSS is subject to severe local fading in urban areas and is usually unreliable in many instances [15]. As depicted in Fig. 13, the path loss of the signal strength is dominated by free-space path loss over large distance (generally hundreds of signal wavelengths) but can observe large variations in 10s of dB in shorter lengths (typically less than a few wavelengths) due to short-term fading. Long-term fading (from a few wavelengths to a hundred or so) can see fading due to reflections in the local environment such as buildings and refraction of indirect paths in the atmosphere [5]. As a specific example of a system developed using signal strength is the RADAR system developed by Microsoft Research that used 802.11 Access Points (APs) to estimate the location of a mobile transmitters within an office environment [25]. They implemented this system in two phases, first, they collected signal strength measurement data as a function of location throughout one floor of an office building to build a model (the "training phase"). They then used this model to compute location (the "test phase"). When discussing indoor location systems, it is necessary to model the transmission properties through walls and other obstructions [28]. Also relevant is the relative orientation of the receiving antenna and transmitter can greatly affect the received signal strength [25]. For near-body applications, the torso and to a lesser extent the

head can impact signal strength due to absorption of certain RF frequencies especially prevalent in the microwave frequencies (1-3 GHz). The effects of the body absorption are mostly systematic and result in biases in either test or training data as compared to multipath and other scattering which have less tendency to bias. For this reason the Microsoft team collected not only location data during the training phase but orientation as well. They were able to show location errors around 2 to 3 meters for the office environment, in many cases good enough to isolate the mobile transmitter to a room however the drawback to their approach are the training phase (also requiring re-training if the physical layout should change) and also subject to environmental factors such as the number of people in the office building at a given time [25]. Recent work in ray tracing techniques have shown some promise to lower (or eliminate) the need for training in signal strength approaches providing adequate data is available on the target operational area, but the overall accuracy compared to timing-based approaches is generally lower [26]. Once the range is estimated, the range can be used in the same fashion as the timing-based methods discussed in the next section. Not only signal strength can be used for range estimation, but also Bit Error Rate (BER), Link Quality (LQ) or Response Rate (RR). For example [18] discusses a method where the RR (the percentage of times that a given transmitter was heard in all of the receiver scans at a specific distance from that transmitter) is used to estimate range for isolation of a Bluetooth device to a particular room on an office floor.

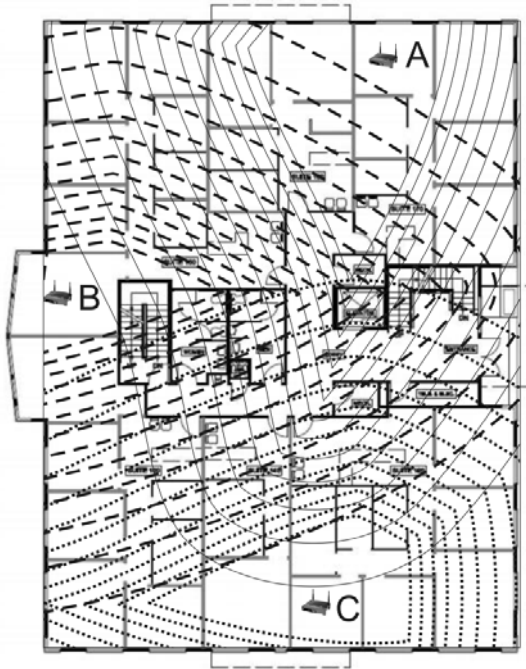


Fig. 14. Location From Signal Strength from multiple basestations

2.4.2 Pattern Recognition

In contrast to approaches that seek to map signal strength into range, pattern recognition techniques have been applied to signal metrics to form location estimates. This type of approach is often referred to as "fingerprinting" and uses previously stored measurements or calculations to map locations for later matching versus measurements. This approach takes advantage of the local-area fading characteristics by using these features from multiple transmitters to uniquely identify a location and, generally speaking, the finer the training grid the better the resultant accuracy [26,31]. Obviously the first crucial step is formation of the radio map (or training) where they can be formed by either empirical or model-based approach as shown in Fig. 14. As described in [10], in the empirical approach the data can be collected as single values at a given location or as a probability distribution. Alternatively, model-based methods can be categorized based on parameters, signal propagation and in terms of representation. In a parameter-based approach parameters can either be provided *a-priori* as in [25] or estimated from a small set of estimation fingerprints as in [28]. The propagation model can either be a direct-path only approach [25] or where multiple paths are used such as in ray tracing [26]. Finally the representation can be single values [29] or in terms of probability distributions [30].

Pattern-matching solutions have been employed on a variety of scales, on the meter-level within a building [27] to city or larger range at lower overall accuracies [31](again, mostly limited to the training set resolution). An important factor about path-loss and pattern-matching in signal strength approaches is that they are not particularly sensitive to the frequency employed. Of course the previous restrictions apply as far as attenuation and LOS issues with different frequencies but if the signal can be measured at the receiver, it can be used in signal strength approach. Another strong suit of this approach is it is not restrictive on the number receivers that can make use of the signal measurements which allows for a large number of users for a given infrastructure.

2.5 Time, Phase and Differential Timing (TOA, POA and TDOA)

GNSS systems use timing measurements collected at a receiver, which is referred to as pseudorange or the time of signal flight between the satellite transmitter and receiver corrupted by atmospheric distortion, multipath and uncertainties of the receiver clock. Precision GNSS instruments actually report the carrier phase of the signal (which have similar distortions to pseudorange). These represent Time-of-Arrival (TOA) and Phase-of-Arrival (POA) systems respectively and are not exclusively limited to satellite-based navigation systems. Typically multiple TOA ranges are combined via multi-lateration¹. The range measurement are represented by [36]:

$$r_i(t) = \rho_i(t) + cb_i(t) \quad (7)$$

¹ Multi-lateration is sometimes referred to as trilateration or tri-lateration to indicate that three range measurements at a minimum are required to determine a 2D position without ambiguity. Multi-lateration is chosen to indicate using as many ranges or pseudoranges as required. Many times this is referred to as triangulation which also describes angulation (AOA and DF) in addition to lateration [34].

In GNSS systems this is well-known as a pseudorange of $r_i(t)$ between the receiver and the i -th transmitter. The geometric distance between the transmitter and receiver is given by $\rho_i(t)$, c is the speed of light and $b_i(t)$ is the combined clock offset between the receiver and transmitter from a reference time (such as GPS time), often referred to as the *clock bias*. When examining the three-dimensional (3D) location the receiver the geometric range is:

$$\rho_i(t) = \sqrt{(X_i(t) - X_p)^2 + (Y_i(t) - Y_p)^2 + (Z_i(t) - Z_p)^2} \quad (8)$$

where $X_i(t)$, $Y_i(t)$, and $Z_i(t)$ are the 3D location coordinates of the i -th transmitter and X_p , Y_p , and Z_p is the receiver location at time t . The clock bias is a combination of the receiver clock offset from a reference time as well as the i -th transmitter's clock offset. For GNSS where the satellites are the transmitters, the satellites transmit clock parameters that allow for the correction of the satellite clock (within a small residual error) at the receiver leaving only the receiver clock offset to compute along with the position. For POA systems (Fig. 16), the same formulations as for TOA apply, however, there are usually carrier-cycle ambiguity resolution issues and if these cannot be resolved then phase measurements are used to smooth TOA measurements [25,32]. One of the best advantages of POA systems is the precision of the carrier phase. In GPS for example the codephase cycle length is 299.7 km (293 m per C/A code chip) in range where the carrier cycle length is 19 cm. This enables far more precision in

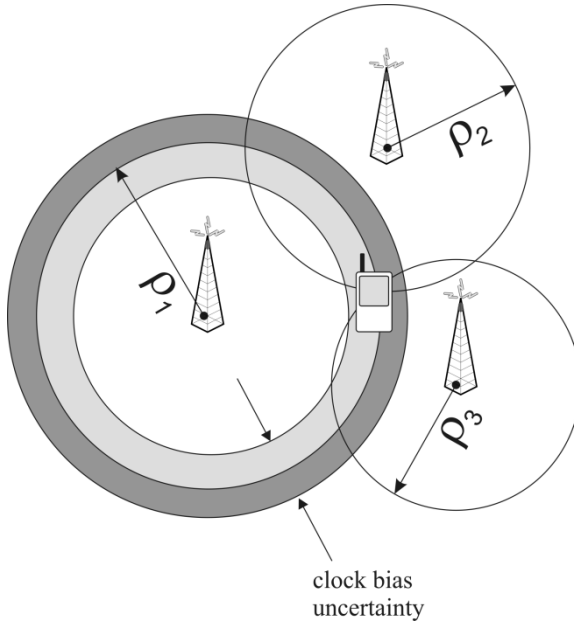


Fig. 15. Location From TOA/POA ranges

ranging measurements at the expense of difficulty in resolving integer ambiguities [3,32]. For example, if there is an uncertainty of 1 m of the initial position estimate there could be as much as 10 integers for a given satellite and 10^n combinations for n satellites which could easily lead to millions of possible combinations.

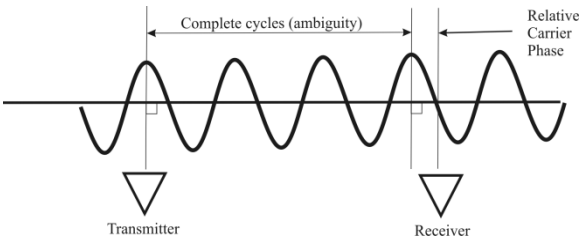


Fig. 16. Carrier Phase Ambiguity

In contrast to TOA, time-difference systems use arrival times from two transmitters at a receiver. Fig. 17 shows that the time differences in the TDOA system represent Line-of-Position hyperbolic curves along which the receiver lies. By using a second difference measurement the two-dimensional position can be determined; as shown in Fig. 17, Point B. In the case of points A and A', a single set of differences may not be able to resolve the ambiguity regarding another difference measurement [23]. A significant advantage of TDOA over TOA is that the receiver clock bias is not an important factor in location determination.

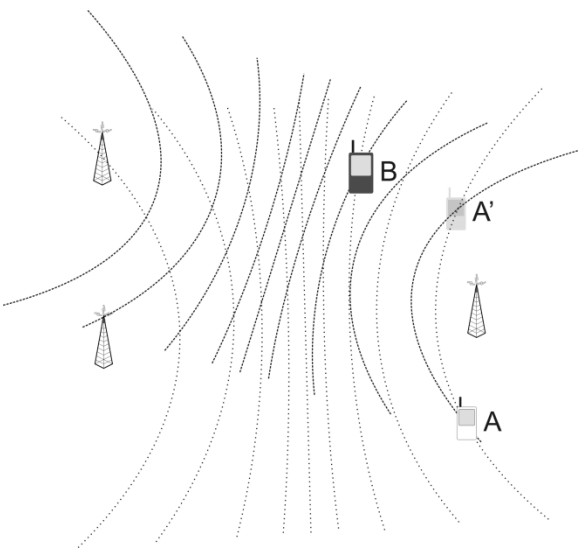


Fig. 17. Location From TDOA hyperbolic traces

3 Conclusion

The level of interest in ubiquitous location determination capability continues to increase for a variety of applications. This paper gave an overview of RF-based approaches that form the basis for all the systems employed today. These systems will continue to be key components in location solutions for years to come.

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