ABSTRACT

With recent advances in wireless communications and low-power electronics, accurate position location may now be accomplished by a number of techniques which involve commercial wireless services. Emerging position location systems, when used in conjunction with mobile communications services, will lead to enhanced public safety and revolutionary products and services. The fundamental technical challenges and business motivations behind wireless position location systems are described in this article, and promising techniques for solving the practical position location problem are treated.

Position Location Using Wireless Communications on Highways of the Future

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Safety is the primary motivation for vehicle position location. In the United States, the Federal Communications Commission (FCC) has required landline telephone companies to provide 911 emergency service for many years, and in 1994 began investigating similar services for U.S. cellular and personal communication service providers [1]. Basic 911 service automatically forwards any 911 telephone calls to a public safety agency. Enhanced 911 (E-911) service improves emergency responsiveness by including the caller's automatic number identification (ANI) and street address information so that the nearest public safety agency may respond and return calls to the emergency caller. Today, the 911 operator receives very little, if any, of this information from a wireless caller. In fact, [1] indicates that at least one of every five 911 calls is originated by a cellular telephone user, and 25 percent of these users do not know their location when placing the call. In June 1996, the FCC adopted a new rulemaking order based on [1], which requires wireless service providers to support a mobile telephone callback feature and cell-site location mechanism by mid-1997, with completion required by early 1998. For *wireless* E-911 services, private branch exchanges (PBXs) which connect wireless users to the public switched telephone network (PSTN) will be required to indicate the wireless caller's telephone number, the base station location, and an estimate of the location of the caller. With these new requirements, public safety answering points (PSAPs) will have enhanced position location information on each wireless emergency call, and will have the option of requiring even more detailed position information within five years [2].

While safety is the main motivation for wireless position location, other promising applications include accident reporting, navigational services, automated billing, fraud detection, roadside assistance, and cargo tracking. Position location systems will provide new services and revenue sources for wireless carriers, greater crime-fighting capabilities for law enforcement personnel, and new methods for tracking people and parcels. Position location services will not only provide new consumer options and products for wireless carriers, but also features that could differentiate services and markets (i.e., differentiation between PCS, cellular, specialized mobile radio, and paging). Location systems will also provide wireless carriers and vendors who use position location the ability to charge for services based on location, within a particular city, cell site, or specific location such as an office, home, or car. This will allow wireless service providers to control customer usage by offering cost incentives that match service plans to the wireless infrastructure and networking resources.

In 1991, the U.S. Transportation Research Board and the National Research Council defined research needs and implementation requirements for Intelligent Transportation System (ITS) communication standards [3]. In 1993, the U.S. Transportation Research Board focused on seven unique aspects of ITS communications, including vehicle monitoring, highway automation, and traffic management systems. Specific problems targeted for research included candidate technologies for on-board vehicle location and position location from wireless base stations [4]. Meanwhile, commercial forces in the United States have created nearly 100 percent coverage of analog mobile phone system (AMPS) and paging services, as well as worldwide coverage of the global positioning system (GPS).

In the remainder of this article, we provide an overview of existing position location systems, followed by a survey of fundamental concepts in position location, a summary of advanced algorithms for position location, and a discussion of research and future issues for ITS position location for wireless systems.

OVERVIEW OF EXISTING POSITION LOCATION SYSTEMS

A number of position location systems have evolved over the years that are useful for ITS applications. More recently these systems have become synergistic with wireless communications. Already, large shipping and trucking companies such as Highway Master and United Parcel Service have location capabilities which use existing cellular systems and GPS. Qualcomm's OmniTRACS® system provides satellite-based fleet management, whereas Highway Master uses the terrestrial cellular system. Below we provide an overview of some of the popular commercial position location systems and the communication technologies with which these systems work.

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GLOBAL POSITIONING SYSTEM (GPS)

GPS is the most popular radio navigation aide and has overtaken virtually all other forms of radio navigation because of its high accuracy, worldwide availability, and low cost. For ITS applications, a GPS receiver is often coupled with a wireless communications device to relay location information to the PSTN or PSAP.

The principle behind GPS is simple, although the implementation of this time-of-arrival (TOA) system is quite complex [5–7]. GPS uses precise timing within a group of satellites and transmits a spread spectrum signal to earth on L-band (centered at 1575.42 MHz). An accurate clock at the receiver measures the time delay between the signals leaving the satellites and arriving at the receiver. This allows calculation of the exact distance from the observer to each satellite. If three satellites are visible to the receiver, triangulation can be used to find the observer's location. In practice, a lower-accuracy clock is used by the observer, and signals from a fourth satellite are used to correct receiver clock errors. The time traveled by each signal describes a sphere about the satellite. A receiver's position lies at the intersection of three spheres, providing coordinates in latitude, longitude, and altitude.

Currently GPS receivers can be found in quantity for under $200/unit with accuracy of approximately 100 m. More sophisticated units, including those used by the military or using differential GSP, provide accuracy within a few meters. Prices of GPS units are dropping rapidly as production levels and demand increase.

Reducing the cost of GPS receivers is the key to the successful deployment of GPS for ITS applications. NAVSYS Corp. has developed a low-cost GPS sensor called TIDGET™ that takes a 10 ms "snapshot" of the raw GPS sampled data and transmits this information via cellular radio to a remote site where the information and the GPS receiver location are determined [8]. A map database may be incorporated into the processing scheme to allow the position of the GPS receiver to be determined with as few as three satellites in view. The TIDGET receiver can be purchased in large quantities for about $50/unit since only a partial GPS receiver is needed. GPS/TIDGET accuracy is being tested as part of the Colorado Mayday Project with positive early results [9].

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LORAN C

Loran C, developed in the 1950s by the U.S. Department of Defense, operates in the low frequency (90–110 kHz) band and uses a pulsed hyperbolic system for triangulation. It has repeatable accuracy in the 19–90 m range and is accurate to about 100 m with 95 percent confidence and 97 percent availability. Like GPS, its performance depends on local calibration and topography. The system offers localized coverage to the United States and selected countries [10]. GPS has replaced Loran C in most applications.

SIGNPOST NAVIGATION

Signpost Navigation employs a large number of simple radio transmitters to accurately determine position at a mobile. These transmitters are spaced along highways and typically serve as coded beacons, where the code designates the latitude and longitude of the signpost. The transmitter signal strength indicates the relative position of the receiver to the transmitter. This navigation aid works well for limited areas such as a small city. While not originally designed as such, today's AMPS analog cellular radio system may actually serve as a signpost system, since each base station transmits a beacon signal on its forward control channel [11]. As part of the forward control channel structure, an overhead message containing a station identification number (SID) and a digital color code (DCC) is sent every 0.8 s. The SID identifies the market covered by the cellular system, whereas the DCC and forward control channel number may be used by an intelligent receiver to determine location within a cell site. When receivers have a priori knowledge of the location and DCC assignment for each base station, a standard cellular system may be used as a course position locator.

GLOBAL NAVIGATION SATELLITE SYSTEM

The Global Navigation Satellite System (GLONASS), an initiative by the Russian government to provide a similar system to GPS, is in its final stage of development [12]. Although the system uses principles similar to GPS, its operation differs in several aspects. The synchronization period for GLONASS takes only 1/3 as long as GPS, typically under a minute. The integration of GLONASS and GPS receivers offers a synergistic combination to substantially reduce position errors [13].

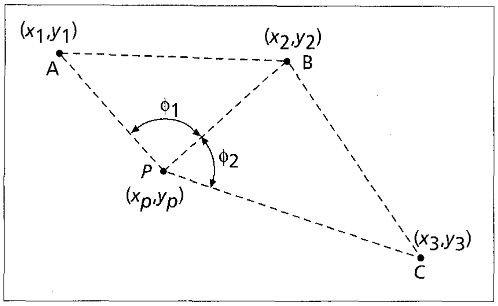
AUTOMATIC VEHICLE MONITORING

Automatic vehicle monitoring (AVM) systems provide position location capabilities for handling large numbers of vehicles. Typical applications include fleet management, vehicle security, and emergency services. AVM systems have been available in the United States for a number of years, starting in 1968 as experimental systems, continuing in 1974 under temporary FCC rules, and in 1995 under permanent rules that recognize the new technologies and new ITS services provided by AVM [14]. In 1995, the FCC changed the name of these systems to "location and monitoring services (LMS)." In the United States, the primary band for LMS is the 902–928 MHz industrial, scientific, and medical (ISM) band, although LMS is supported to a lesser extent in several bands below 512 MHz. LMS systems are licensed systems with up to 300 W peak power for the forward link; however, they share the band with low-power unlicensed devices, such as cordless phones, wireless local area networks, and utility meter-reading systems. The band is also used by federal government radiolocation systems and amateur radio operators, so the prospect of interference between LMS and other users of the spectrum is an issue in the deployment of LMS systems [15].

CELLULAR GEOLOCATION

Cellular geolocation uses principles described in the next section, and relies on the existing infrastructure of cellular base stations. Geolocation offers position estimates of mobiles as they transmit over standard cellular frequencies. This method was demonstrated by Raytheon E-Systems (Falls Church, Virginia) in the Cellular Applied to IVHS Tracking and Location (CAPITAL) project in Northern Virginia [16, 17]. Other vendors such as KSI (Annandale, Virginia) and Associated Communications Corp. (Bala Cynwyd, Pennsylvania) are also working on this approach.

Geolocation offers some advantages to GPS since it concentrates cost at each base station and allows position location to be performed without the need of GPS at the mobile. Thus, standard cellular phones, including handheld portables, may be tracked. Service providers may also use geolocation to accurately determine capacity needs for a particular region, and may adapt the network accordingly. This approach sup-

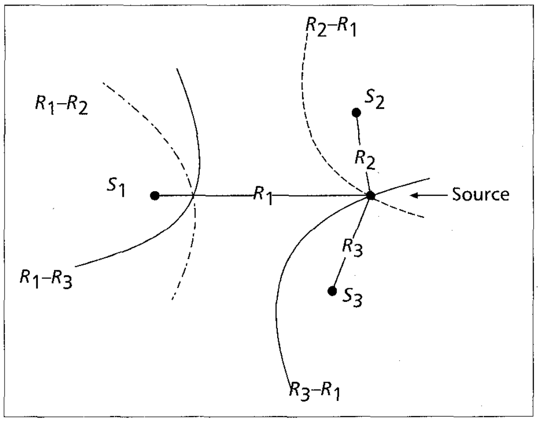


■ Figure 1. *The three-point problem, also known as triangulation. Three fixed beacons (A, B, C) provide signals which allow the mobile to determine its location. The mobile must have an accurate method of measuring angles.*

ports an E-911 implementation that is compatible with any existing mobile phone, and the position location information may be used simultaneously for vehicle traffic management, incident detection, and wireless network management.

In the CAPITAL operational test, geolocation equipment is located at selected cellular towers to collect phone usage statistics and to geolocate phones on designated roadways. In this application, it has been shown that traffic monitoring via cellular has several advantages over conventional ITS traffic monitoring techniques such as buried magnetic sensors or video cameras. These advantages include lower cost as compared to magnetic loop-based approaches, high reliability and low maintenance, and no disruption of road service for installation or repairs.

The CAPITAL system geolocates the target mobile by monitoring (at base stations) the reverse voice channel or reverse control channel transmissions from the mobile user. Multiple base stations receive the mobile signal, and the target position is determined by combining angle of arrival (AOA) estimates from each base station and time difference of arrival (TDOA) estimates between multiple base stations. AOA measurements at each base station are made using an adaptive array and a variation of the maximum likelihood techniques described in [18, 19] (discussed later). Signal time of arrival data are measured at each base station and time-stamped with a GPS time reference to determine TDOA position estimates. The impact of multipath is minimized by using highly directional adaptive antennas that offer spatial filtering [17, 20, 24]. However, it is still necessary to do additional processing to sort multipath components from direct components and to identify interfering components. Experimental results showed that position estimates were, for the most part, within 100 m of the true location, and within the accuracy proposed for E-911cellular service [16, 17]. Positions are typically fixed in less than a second, which is faster than a typical GPS configuration. The technology also works for a variety of cellular standards such as AMPS, narrowband AMPS (N-AMPS), and U.S. digital cellular (USDC). Furthermore, cellular and personal communication services (PCS) service providers are likely to use adaptive arrays in the future to increase system capacity. Thus, position location may become a natural by-product of future wireless systems.



■ Figure 2. *2-D hyperbolic position location solution. Two hyperbolas are formed from TDOA measurements at three fixed receivers to provide an intersection point which locates the target source.* S_1, S_2, *and* S_3 *represent the fixed receiver locations, and Eq. (2) is used to determine the two hyperbolas.*

POSITION LOCATION FUNDAMENTALS

The primary function of a position location system is to locate the coordinates of a desired mobile user (called the target) with respect to a set of objects (base stations) with known positions. Position location systems may be unilateral or multilateral. In a unilateral system, a mobile unit forms an estimate of its own position based on signals received from transmitters at known locations. The GPS and the three-point problem from surveying are classic examples of unilateral systems [7, 21–23]. In a multilateral system, an estimate of the mobile location is based on a signal transmitted by the mobile and received at multiple fixed base stations. Most cellular geolocation proposals are multilateral, where the estimate of the mobile's position is formed by the network, rather than by the mobile itself.

Position location via wireless can be accomplished by two general methods: the AOA method and the time of arrival (TOA) method. AOA, also called direction of arrival (DOA), has been used widely in surveying, radar tracking, and vehicle navigation systems [22–24]. The location of the desired target in two dimensions can be found by the intersection of two lines of bearing (LOBs), each formed by a radial from a base station to the mobile target. A single measured angle forms a pair of LOBs and provides the target location. Instead of using the intersection of just two lines, many pairs of LOBs are used in practice, and highly directional antennas are required, making AOA difficult at the mobile. As shown in Fig. 1, AOA methods may use three base stations located at points (A, B, C), and two measured angles to deduce the location of the target at the point of intersection of two circles. This method, known as "resection" or triangulation, may be solved using trigonometry or analytic geometry, or through table lookup [22].

For radio frequency (RF) signals, AOA is usually determined at a base station by electronically steering the main lobe of an adaptive phased array antenna in the direction of the arriving mobile signal. Typically, two closely spaced antenna arrays are used to dither about the exact direction of peak incoming energy to provide a higher-resolution measurement of the AOA. The many adaptive algorithms to accomplish this steering are discussed in the folowing section. AOA is applied to the problem of direction finding (DF), where the target attempts to locate the direction of fixed sensors in order to obtain a position fix, often using high-resolution spatial analysis techniques that have been developed [24–27]. The second primary method for determining position location is with TOA measurements [28]. Since electromagnetic waves propagate at the constant speed of light (c = 3 x 10^8m/s), or approximately 1 ft/ns in a free space medium, the distance from the mobile target to the receiving base station is directly proportional to the propagation time. If the signal propagates in time t_i from the target transmitter to the ith fixed receiver, then the receiver lies at range R_i, where

$$R_i = ct_i. \tag{1}$$

Therefore, if a free space signal arrives at a base station receiver 10 μs after it is transmitted, the target transmitter must lie on a sphere of radius 3000 m from the base station. If TOA measurements are made at a second base station at a second location, the target position can be determined to lie on a circle since the intersection of two spheres is a circle. The three-dimensional position of a transmitter is uniquely determined by the intersection of three spheres using TOA measurements from three base stations [28, 29].

In general, direct TOA results in two problems. First, TOA requires that all transmitters and receivers in the system have precisely synchronized clocks (e.g., just 1 μs of timing error could result in a 300 m position location error). Second, the transmitting signal must be labeled with a timestamp in order for the receiver to discern the distance the signal has traveled. For this reason, TDOA measurements are a more practical means of position location for commercial systems [30].

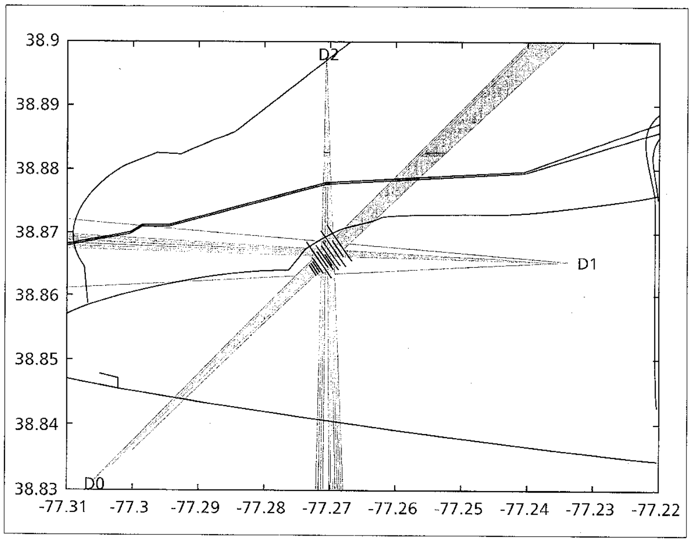


Figure 3. *Geolocation of a cellular signal based on TDOA hyperbolas (gold) and lines of bearing (orange) from three base station sites in Northern Virginia. This figure illustrates repeated attempts on the same signal, with the black "x" indicating the position locations. (Compliments of Joe Kennedy, Raytheon/E-Systems, Falls Church, Virginia).*

The idea behind TDOA is to determine the relative position of the mobile transmitter by examining the difference in time at which the signal arrives at multiple base station receivers, rather than the absolute arrival time. Therefore, each TDOA measurement determines that the transmitter must lie on a hyperboloid with a constant range difference between the two receivers. The equation of this hyperboloid is given by

$$\begin{aligned} R_{i,j} &= \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} \\ &\quad - \sqrt{(X_j - x)^2 + (Y_j - y)^2 + (Z_j - z)^2}, \end{aligned} \tag{2}$$

where the coordinates (X_i, Y_i, Z_i) and (X_j, Y_j, Z_j) represent the fixed receivers i and j, and make up the unknown coordinate of the target transmitter [31]. If the source and all receivers are coplanar, a two-dimensional source location can be estimated from the intersection of two or more independently generated hyperboloids generated from three or more TDOA measurements, as shown in Fig. 2. Three-dimensional source location estimates require at least four independent TDOA measurements.

Unlike TOA measurements, the transmitted signal need not contain a timestamp, and TDOA measurements require only that the fixed location receivers have precisely synchronized clocks. This corresponds to the timing standards already provided at cellular base station sites, making TDOA more realistic than requiring each mobile unit to have an accurate clock. Atomic clocks, such as a Cesium time source, or a GPS receiver clock are typically used for timing at base stations.

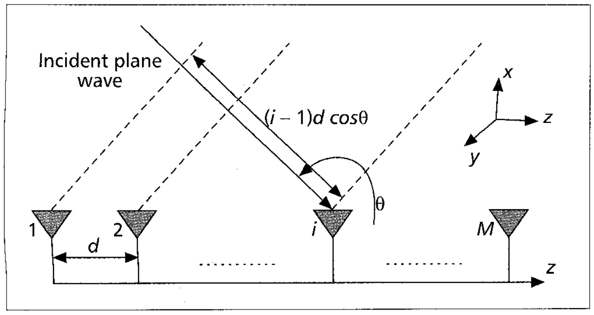
It is possible to combine TDOA and AOA techniques into hybrid systems. For example, the position location system developed by Raytheon E-Systems for the CAPITAL project employs both techniques (Fig. 3) [17]. These two main classes of position location systems may be supplemented with dead-reckoning or inertial navigation techniques. Dead-reckoning can be particularly useful when buildings and terrain obscure line-of-sight propagation between a transmitter and receiver. In this case wheel rotation sensors, which measure distance traveled, or inertial navigation systems using gyroscopes are used to update the location from the last previously known position until a new position fix can be obtained.

The basic position location techniques described above work well if the signals are not corrupted by noise, multipath, or interference. In practical systems, however, position errors occur due to imperfections in the channel [32]. While both AOA and TDOA techniques require a minimum of two or three base stations to determine a unique position location, new cellular or PCS systems are often designed to ensure only one high signal-to-noise ratio (SNR) link between a transmitting mobile and a base station. This is because in a conventional cellular system, base station count (infrastructure cost) and interference between adjacent cells must be minimized when first deploying the system [11]. The ability of multiple base stations to hear the target mobile is paramount to the design of position location systems. This problem is referred to as *hearability*, and it is where the design philosophy of multilateral position location systems diverges from that of wireless communications systems. Hearability is more of an issue in rural cellular systems, where coverage issues dictate the system design rather than capacity demands, which leads to more base stations and redundant coverage in cities [34].

Both AOA and TDOA techniques also rely on a direct line-of-sight path from the transmitting mobile to the base station receivers.

However, both urban and mountainous rural environments induce significant path blockage and multipath time dispersion due to reflections from and diffraction around buildings and terrain. Multipath components may appear as a signal arriving from an entirely different direction, and can lead to catastrophic errors in an AOA system [33]. Although diffraction around a building may have less severe consequences for the relative TOA of a signal in a TDOA system, multipath reflections from distant objects can lead to time distortions of several microseconds [11]. Because of their ability to resolve and reject multipath, wideband spread-spectrum systems and directional antennas will offer advantages for position location in a multipath environment [20].

Real-world channel impairments require special processing techniques to improve the resistance of both AOA and TDOA methods to noise, multipath, and interference. It is often advantageous to use more than the minimum number of TDOA or AOA receivers for a unique solution, in order to



■ **Figure 4.** *Illustration of a plane wave incident on a linear equispaced array. The dotted lines represent the phase fronts of the incident wave.*

average out errors induced by the radio channel. While this affords improved performance by combining additional information, it is usually impossible to obtain a single consistent solution in this *overdetermined* case. As a result, processing algorithms must be capable of combining many noisy and inconsistent measurements. These algorithms are discussed in greater detail in the next section.

ADVANCED ALGORITHMS FOR POSITION LOCATION

AOA ALGORITHMS FOR POSITION LOCATION

This section presents an overview of some of the more popular methods for estimating the AOA of a signal impinging on an array of antenna elements. Because a vast body of literature exists on these direction finding (DF) methods, the discussion here is kept brief, with emphasis placed on those methods most applicable to the cellular/PCS radio environment. More details on the algorithms discussed here may be found in the cited references. In particular, the overviews given in [24, 61] are excellent sources of background information on the problem of AOA estimation.

In general, an angle of arrival estimate is made from a base station using a directional antenna such as a phased array of two or more antenna elements to measure the AOA of the incident signals (Fig. 4). In general, the sensor (e.g., antenna element) spacing used in an AOA measurement is on the order of half the wavelength of the signal carrier frequency. The relatively close spacing of the antenna elements allows the time delay seen by a signal as it propagates across the array to be modeled as a phase shift. This is referred to as the "narrowband model," and is assumed to be appropriate in the development of most AOA estimation algorithms.

The accuracy of the narrowband model is dependent on the signal bandwidth, the antenna element spacing, and the quality of the receiver hardware. The narrowband model is only accurate if the signals received at each antenna element are processed (filtered, downconverted, sampled, etc.) in an identical manner. This means that each channel of the receiver (RF front-end for each antenna element) must have nearly the same frequency response, be highly linear, and use the same oscillators for all mixing and sampling operations. This type of receiver is generally known as a *coherent receiver*. The receiver is a major contributor to the cost of an AOA estimation system, where the cost increases as the number of antenna elements (and hence number of receiver channels) increases. Therefore, it is highly desirable to keep the number of antenna elements in the array to a minimum. The number of antenna elements needed in the array is strongly dependent on the signal environment and the specific AOA estimation algorithms employed. A critical assumption made for most DF techniques is that the number of incident signals is strictly less than the number of antenna elements. As discussed later, this requirement can be relaxed if properties of the incident signal are exploited; if, for example, it contains a known training sequence, or the sequence can be estimated. It should be noted that implementation of adaptive beamforming requires the same type of coherent receiver. Therefore, if smart antennas (i.e., adaptive phased arrays) are deployed at the base station, AOA estimation can be incorporated with modest additional signal processing, and such antenna systems show great promise for emerging high-capacity wireless systems [20]. The array must be carefully calibrated over all measured angles, as well as frequency and temperature. This is an expensive operation, in terms of the cost of both computational storage and periodically performing the array calibration.

The most straightforward AOA estimation approach is phase interferometry. A *phase interferometer* directly measures the phase difference between the signals received on multiple pairs of antenna elements and converts this to an AOA estimate. This approach works quite well for high SNR but will fail for strong co-channel interference and/or multipath.

Another conceptually simple approach is *beamforming*. This method can be viewed as measuring the output power of a beamformer while steering the main-beam of the array over the angular field of interest. This yields a true spatial spectrum, that is, an estimate of power distribution versus AOA. A diagram illustrating the concept of beamforming is shown in Fig. 5. The beamformer weights w_n control the spatial response of the beamformer. Capon's method is closely related but has better angular resolution [35]. However, neither of these methods work well in *coherent multipath*.

Methods that work well in multipath can be derived using the maximum likelihood (ML) framework [19, 24, 36]. Different ML algorithms are obtained by making different assumptions about the incident signals. This leads to the so-called deterministic and stochastic ML methods. In multipath environments the ML methods will estimate the AOA of each path. However, implementation of these methods requires a complex multidimensional search. The dimensionality of the search is equal to the total number of paths taken by all of the received signals. This search is further complicated by the fact that the total number of paths is not known a priori and must be estimated.

Another class of methods that will work well in multipath can be derived by combining spatial smoothing with subspace-based algorithms. Examples of subspace methods include MUSIC [25] and ESPRIT [27, 37]. Normally these methods fail in multipath, but using a spatially smoothed covariance matrix in place of the conventional one allows them to operate properly [38]. Spatial smoothing methods have been combined with property-exploiting adaptive beamforming methods which estimate the spatial signature directly [38]. Estimating AOA from spatial signature vectors has several advantages over estimating AOA directly from the observed data. The principal advantage is that the search is reduced from one where the AOA of all paths must be estimated to one where only the paths contributing to the estimated spatial signature of the desired signal must be estimated. Another advantage is that more multipath components can be processed by a fixed array [33].

A class of ML methods with very useful properties can be derived by assuming that the incident signals are known rather than unknown stochastic processes [39–41]. This allows exploitation of, for example, the training sequences that exist in most digital cellular standards. An interesting application of these methods to the problem of estimating the AOA of code-

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