International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R SM.2211

(06/2011)

Comparison of Time-Difference-of-Arrival and Angle-of-Arrival Methods of Signal Geolocation

SM Series

Spectrum management

International Telecommunication Union

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Note*: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

Electronic Publication
Geneva, 2011

REPORT ITU-R SM.2211

Comparison of Time-Difference-of-Arrival and Angle-of-Arrival Methods of Signal Geolocation

(2011)

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1 Introduction

This Report compares the strengths and weaknesses of time-difference-of-arrival (TDOA) versus angle-of-arrival (AOA) methods of signal geolocation. While this Report focuses on TDOA, it should be noted that other geolocation techniques exist[1]. The AOA method determines the angle of arrival of a wave at a measurement point. AOA methods have been commonly used in many direction-finding applications, and have some advantages but also some disadvantages related to antenna requirements, for example. TDOA methods, on the other hand, compute the time difference of arrival of a wave at multiple measurement points, and calculate the source point based on timing and wave comparisons. TDOA methods have not been widely used in spectrum monitoring, but have become increasingly useful due to the availability of inexpensive and compact computing power, more advanced radio receiver technology, ready availability of data links, and accurate distributed timing signal availability. The paper will provide a short overview of TDOA technology and some comparison of the strengths and weaknesses of the TDOA method compared to more traditional AOA methods.

2 Overview of TDOA Technology

The TDOA technique measures the time of arrival of an RF signal at several points in space and compares the time difference between each receiver. The traditional approach to estimating TDOA is to compute the cross-correlation of a signal arriving at two receivers. The TDOA estimate is the delay which maximizes the cross-correlation function. By knowing the location of each receiver, an estimate of the location of the source of the emissions can then be deduced provided all receivers

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[1] Received signal strength (RSS) uses the measured power ratio of a signal at multiple measurement points to compute the source point. RSS is often used for indoor geolocation. Frequency-difference-of-arrival (FDOA) uses the frequency Doppler shift of a moving source (and/or multiple receivers) to calculate the source point. FDOA is often used in conjunction with TDOA for airborne applications.

are time synchronized. The complement to an AOA system's line-of-bearing (LoB) is a hyperbolic line of constant time difference of arrival referred to as an isochron or line-of-position (LoP). A more complete discussion of TDOA methods is contained in the ITU Handbook on Spectrum Monitoring, Edition 2011, Chapter 4.7.3.2.

TDOA methods have been used in radiolocation tasks in some defence applications, and more recently in some specific applications such as location of mobile cellular telephones for emergency responses (fire, ambulance, etc.) The main obstacle in the past to more pervasive civil deployment has been the required nanosecond-level time synchronization. As electromagnetic radiation travels at approximately 30 cm/ns, any significant timing jitter between receivers will translate directly into the dilution of location accuracy. Today, the advent of satellite navigation systems (GPS, Galileo and GLONASS) provides one such accessible and inexpensive means of maintaining time synchronization. As a result, TDOA-based systems are now available today from several vendors in different countries around the world.

3 Strengths and weaknesses of TDOA compared with traditional AOA

To better understand TDOA we present a short comparative survey of its strengths and weaknesses with regard to AOA. It should be noted that TDOA and AOA are complementary techniques for geolocation. A geolocation system that combines both may outperform either alone [1]. Also, having an alternate and confirming method of geolocation can be crucial for spectrum enforcement actions.

To simplify the discussion, we assume that the TDOA system uses cross-correlation based detection, and that measurement receivers relay sampled signals to a central server for TDOA processing. For most spectrum monitoring applications, this method will be preferred for both its location performance and flexibility. To further simplify the discussion, we compare TDOA against a correlative interferometer (CI) AOA system. Correlative interferometry is a widely implemented AOA technique in modern radio monitoring. The correlative interferometer is introduced and discussed in Chapter 4.7.2.2.5 of the ITU Handbook on Spectrum Monitoring, Edition 2011.

(NOTE 1 – "Chapter" references in Tables 3-1 and 3-2 refer to the ITU Handbook on Spectrum Monitoring, Edition 2011. Numbers in parentheses in Tables refer to References listed in § 5.)

TABLE 3-1

TDOA strengths

Simpler antenna requirements	The antenna is low cost, low complexity, and may be small in size. TDOA receivers may employ a single simple antenna (such as a monopole or dipole). Unlike AOA systems, the antenna does not require high mechanical tolerances and electrical precision, and does not require operational test and measurement for calibration. An added benefit is that the antenna may be made small in size and made inconspicuous. This is important when deploying monitoring systems in historical or architecturally restricted sites or when negotiating siting agreements with 3rd parties.
Simpler siting and calibration requirements	Siting requirements are less restrictive than AOA and require little to no calibration. This allows more flexibility in choosing TDOA sites. As a result, TDOA installations are faster to deploy. In urban installations, additional TDOA receivers may be placed to overcome the shadowing effects of tall structures. In contrast, AOA sites must be chosen to minimize wave front distortion due to re-emanation from local obstacles, ground reflections, and ground conductivity changes. Some AOA antenna arrays must be calibrated after site installation to minimize the resulting frequency and direction dependent errors. Antenna array calibration is one of the most important performance limiting issues in AOA [2]. AOA siting issues are discussed in further detail in Chapters 4.7.2.3.1.2 and 2.6.1.3.

TABLE 3-1 (*continued*)

Wideband, low SNR signals, and short duration signals	TDOA performs well for new and emerging signals with complex modulations, wide bandwidths, and short durations. AOA typically performs well on narrow-band signals, but advanced AOA methods can be applied for locating any signals including wideband, complex, and short duration. TDOA performance is a strong function of signal bandwidth. AOA performance is roughly independent of signal bandwidth provided that the FFT channel spacing is similar to the signal bandwidth. TDOA performance generally improves as signal bandwidth increases. Both TDOA and AOA perform better on higher SNR signals and with longer integration times. The processing gain from correlation allows TDOA techniques to detect and locate low (and even negative) SNR signals. In addition, the correlation processing gain enables additional TDOA receivers to participate in a geolocation although they may have very low or negative SNR. Basic AOA techniques cannot detect and locate negative SNR signals, and may have issues locating low SNR signals. Advanced AOA techniques such as advanced resolution or data aided correlative AOA techniques (reference DF) can process these signals. Although basic AOA does not benefit from processing gain by signal correlation, it benefits to some degree from the system gain which comes from the use of multiple antenna elements and receiver channels. Geolocation of short duration signals requires coordinated receivers, time synchronized to a fraction of the inverse signal bandwidth. This capability is fundamental to TDOA systems. In addition, TDOA can geolocate using very short duration measurements on longer duration signals. If AOA antenna elements are commutated, then the required integration duration will be decreased.
System complexity	The TDOA receiver and antenna are less complex than the typical AOA antenna array and dual or multi-channel receiver. A TDOA receiver requires at least one real time RF channel for gap free processing and highest probability of signal interception(1). This may result in a less complex receiver in simple radio environments. Advanced TDOA processing techniques are necessary when using a simple receiver in complex radio environments. Efficient methods for time synchronization (GPS) and data link interfaces are readily available.
Rejection of uncorrelated noise and interference	The correlation processing used in TDOA can suppress co-channel, time coincident noise and interfering signals that are uncorrelated between sites. This property enables the system to geolocate signals with low signal to interference + noise ratios (low SINR). Time coordinated measurements are made at all receivers. Signals that are not common to two or more receivers are suppressed. With advanced processing, a TDOA system may geolocate using only correlations with the best observation of the emitted signal. A related application of cross correlation techniques for interference analysis is given in Chapter 4.8.5.5. Advanced AOA systems may mitigate the effects of uncorrelated time coincident co-channel interference through the use of correlation with reference signals. Other advanced processing techniques such as MUSIC can be robust to uncorrelated noise and interference. However, such techniques are computationally expensive and not widely used for spectrum monitoring.
Indoor, stadium, and campus geolocation	With advanced processing techniques, TDOA may be used to geolocate high bandwidth signals indoors and outdoors at short range (< 100 m on a side) and in high multipath environments [4]. AOA systems typically do not perform well under these conditions. The challenge of accurate indoor timing synchronization may be overcome with IEEE-1588 compatible Ethernet switches and TDOA receivers. It should be noted that an alternate geolocation technique using received signal strength (RSS), generally outperforms TDOA in high multipath, short range environments, especially for narrowband signals.

TABLE 3-1 (*end*)

Mitigates coherent co-channel interference (multipath) under certain conditions	Both AOA and TDOA methods are compromised by multipath, also known as coherent co-channel interference. Each method is impacted differently by the position of the sensor in relation to the multipath reflections. With sufficient signal bandwidth, TDOA is less sensitive to wave front distortion from local obstacles (local multipath). TDOA may require advanced signal processing to resolve location ambiguities caused by distant obstacles (distant multipath). Advanced processing can further filter the correlation pairs used in the TDOA geolocation to improve results under high multipath conditions. With advanced TDOA processing, time resolved multipath between sites can be suppressed [5], resulting in good performance in dense urban environments(2).
Geometry considerations	Both TDOA and AOA are most precise when the signal source is centred within a perimeter of measurement sites. Geolocation precision in TDOA is determined by geometric dilution of precision (GDOP), time synchronization quality, and TDOA estimation quality. The location uncertainty is not directly related to the baseline distance between TDOA receivers [6]. This can be advantageous under certain conditions. In contrast, the precision of AOA methods is directly related to the distance between the source and each AOA receiver. AOA position uncertainty is a function of bearing angle uncertainty and distance from the receiver to estimated position. When the source is far outside the perimeter, TDOA approximates a line of position similar to AOA's line of bearing. In this situation, the uncertainty in location and bearing grows similarly with distance for both methods.
Well suited to use in RF sensor networks	For both TDOA and AOA, more receivers lead to better results through proximity gain and improved statistics. TDOA is well suited to multiple receiver deployments due to its lower complexity, size, power, simpler antenna, and simplified siting requirements. A higher density of remote monitoring stations, referred to as RF sensors above, brings the monitoring receiver closer to the signal of interest. The resulting reduction in path loss, sometimes referred to as 'proximity gain', improves detection and geolocation performance [7]. In addition, the processing gain from correlation in TDOA techniques enables additional sensors to participate in a geolocation although they may have very low or negative SNR.
Full offline analysis possible at central server	TDOA systems can store and catalogue time coordinated signal measurements from all receivers, so full offline analysis is possible at a central server. This includes spectral analysis of each receiver's signal, cross correlation measurements, and geolocation. AOA systems may also store and catalogue some signal measurements (such as bearing results and bearing confidence) at a central server. These measurements are time coordinated to the degree of time synchronization achievable in the AOA system. Measurements such as spectral analysis and cross correlations are not typical as they require similar backhaul data rate requirements as TDOA.

(1) Typical correlative interferometry systems employ time-division multiplex (TDM) to reduce the number of receivers required. These systems require two to three receivers switched among the 5, 7, or more antennas. These systems are less complex than fully parallel DF systems but require a longer minimum signal duration for location.

(2) TDOA has been reported to geolocate narrowband (30 kHz) AMPS cell phone signals in dense urban environments to less than a few hundred feet r.m.s (5).

TABLE 3-2

TDOA weaknesses

Narrowband signals	Slowly varying signals, which include unmodulated (CW) carriers and narrowband signals, may be impossible or difficult to locate with TDOA techniques. TDOA performance is a strong function of signal bandwidth and performance degrades as signal bandwidth decreases. Also, multipath is potentially more of an issue for narrow bandwidth signals when the signal's temporal characteristics are wide relative to the delay spread. Under these conditions the pulse-shape distortion caused by the multipath is harder to discriminate, adding error to the time-difference estimation. The minimum signal bandwidth for acceptable performance will vary by application. For example, TDOA has been reported to geolocate narrowband (30 kHz) AMPS cell phone signals in dense urban environments to less than a few hundred feet RMS [5]. Higher SNR conditions and longer observation times can improve TDOA location for some narrowband signals. AOA systems perform well for narrowband and unmodulated signals as well as wideband signals.
Single station homing and standoff not possible	A minimum of two TDOA stations, with at least one of those being mobile, and a data link are required for the homing and standoff methods(1). AOA homing and standoff geolocation methods are possible with just one portable station. This allows for geolocation in environments where networked TDOA receivers are impractical or not cost effective. These methods are described in Chapter 4.7.3.3.
Higher data rate communication links	TDOA systems that transmit sampled waveforms from receivers to a central server require high data rate communications links. The receiver's networking needs are asymmetric with upload bandwidth exceeding download bandwidth. Advanced processing, including signal compression, can reduce the data transmitted. TDOA systems that establish TOA at the receiver will have more modest date rate requirements. TDOA data link requirements are discussed further in Chapter 4.7.3.2.4 "Network Considerations". AOA systems require lower data rates because only some signal characteristics such as bearing angle, frequency, and time, are transmitted to a central site.
Sensitive to sources of signal de-correlation	A TDOA system must carefully mitigate all potential sources of signal de-correlation between receivers. These include relative reference frequency offsets between receivers, relative signal frequency offsets (Doppler shift) due to moving sources or local environment. The maximum coherent integration time will be bounded not just by the signal duration, but also the receiver's reference oscillator stability and the dynamics of the wireless channel. High quality TDOA systems will include tracking loops to maintain frequency and time coherence. Automatic Doppler correction is essential for compensating the de-correlation effects of Doppler shifted sources. Basic AOA systems and some advanced resolution AOA systems (using MUSIC) are not sensitive to signal de-correlation between measurement sites. Advanced AOA systems which correlate with reference signals are sensitive to signal de-correlation.
More accurate time synchronization	TDOA requires high quality time synchronization relative to the inverse bandwidth of the signal of interest. TDOA receiver time synchronization better than 20 ns is achievable with current technology (e.g. GPS). AOA systems have less demanding time synchronization requirements. These can be as loose as a few seconds between receivers. In practice, some signals of interest such as short duration or hopping signals demand higher levels of AOA station synchronization.
Signals containing periodic elements	While unlikely, under some conditions TDOA algorithms may generate incorrect answers for signals that contain periodic elements. Examples of such signals include repeating data sequences or synchronization pulses. This problem and a way to minimize it are further described in Chapter 4.7.3.2.3 "Factors Affecting Accuracy". Since basic AOA systems do not perform signal cross-correlation, they are not susceptible to this issue.

TABLE 3-2 (*end*)

Geolocation computation speed	Sampled signals are typically transmitted to a geolocation server for computation. This places demands on networking capacity and speed. A slow link can significantly delay geolocation compute time. Typical geolocation rates may be on the order of 1 fix per second for TDOA versus 100 fixes per second for AOA. Use of higher bandwidth data links can improve TDOA geolocation speed. Use of shorter observation times and/or advanced compression techniques can also reduce the data bandwidth requirements. Once measurements have been transmitted to a central server, recomputed TDOA geolocations are significantly faster since they operate on stored local data.
Not well suited to concurrent geolocation of many emitters	Some AOA systems support concurrent geolocation of many frequency separated signals. This is often referred to as wideband DF. This capability is possible with but not amenable to TDOA, primarily because of the much higher data transmission requirements. Data transmission may be reduced for TDOA in the data aided case by performing signal synchronization (establishing TOA) at each receiver.
Single Site Location (SSL) not possible	A minimum of 2 sensors are required to generate a line of position, and a minimum of 3 sensors are needed for geolocation in 2-D, and 4 for geolocation in 3-D. AOA can be used for single site location.
Geometry considerations	Both TDOA and AOA are most precise (best GDOP) when the signal source is centred within a perimeter of measurement sites. Immediately outside the area bordered by measurement sites, the TDOA location precision decreases more rapidly than that of AOA. When the source is far outside the perimeter, TDOA approximates a line of position similar to AOA's line of bearing. In this situation, the uncertainty in location and bearing grows similarly with distance for both methods.
Offline analysis with single site measurements	With AOA, the line of bearing can be analysed offline using measurements from just a single site. Offline analyses of TDOA lines of position are not possible with measurements from a single site.

(1) RSS approaches may be used for homing and standoff with just one portable station.

4 Summary

TDOA is a complementary geolocation technology that is not widely used for radio monitoring. TDOA has become increasingly useful due to the availability of inexpensive and compact computing power, more advanced radio receiver technology, ubiquitous data connectivity, and accurate distributed timing synchronization. It has certain strengths with respect to AOA, particularly in detection and geolocation of modern wideband signals, simpler antenna requirements, ability to process close range multipath propagation in urban environments, and amenability to low cost sensor network deployments. It also has weaknesses with respect to AOA, especially in locating narrowband and unmodulated signals, usually more demanding data backhaul requirements, and it requires at least 2 receivers for line of position information and at least 3 receivers for location in 2-D. Modern signal monitoring is experiencing a trend toward ever increasing signal bandwidths and decreasing power spectral densities. Use of complementary geolocation technologies such as TDOA can improve probability of detection and location of modern signals in many environments. Hybrid AOA/TDOA systems may neutralize some of the weaknesses of each technique alone.

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