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PROPOSAL FOR THE REVISION OF REPORT ITU-R SM.2211

Comparison of time-difference-of arrival and angle-of-arrival methods of signal geolocation

Background

Report ITU-R SM.2211 contains a fairly detailed comparison of TDOA and AOA monitoring systems in terms of the criteria of system complexity; capability for locating sources of emissions with different types of modulation; protection against reflections, noise and interference; data exchange and processing system requirements; etc. However, the Report gives scant attention to a comparison of such systems on the basis of the criterion of geolocation coverage in networks comprising different numbers of fixed monitoring stations interacting with mobile stations.

It is this omission that prevented the Report from formulating conclusions on the effectiveness of different configurations of local TDOA and AOA monitoring networks comprising different numbers of fixed stations interacting with mobiles; yet this is precisely the criterion, along with cost, that can have a decisive impact on an administration's choice to use one or other system.

Proposal

The proposal set out in the attachment is designed to rectify this omission.

ATTACHMENT

REPORT ITU-R SM.2211

Comparison of time-difference-of-arrival and angle-of-arrival methods of signal geolocation

(~~2011~~201…)

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TABLE 3-1

TDOA strengths

No change

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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 outlining a group of interacting sensors and/or direction finders (DF) ~~of measurement sites~~. Immediately outside ~~the area bordered by measurement sites~~ this perimeter, ~~the TDOA~~ the location precision and effectiveness decrease more rapidly for TDOA than ~~that of~~ for AOA [8], see Annex 1. When the source is far outside th~~e~~is perimeter, TDOA approximates a line of position similar to AOA's line of bearing, but only within areas where the service areas of two sensors overlap [8], see Annex 1. AOA achieves geolocation (i.e. indicates the intersection of two lines of bearing) within zones where the coverage areas of two DF stations overlap. Within the periphery of zones where the coverage areas of at least three sensors and/or DF stations overlap ~~In this situation~~, the uncertainty in location and bearing grows approximately similarly with distance for both methods. For suggestions regarding the effectiveness of TDOA and AOA networks comprising different numbers of sensors/DF stations, see Annex 1.
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 (see also Annex 1).

(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, especially where the DF and sensor parameters are more or less the same in terms of capability to operate with different types of signals and the sizes of coverage areas. Mobile TDOA stations are effective only in the case of hybrid use with AOA.

AOA and TDOA technologies each have their own spheres of effective application for the purposes of geolocation in terrestrial monitoring networks comprising different numbers of sensors/DF stations, and should thus both be further elaborated and developed.

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ANNEX 1

Comparison of TDOA and AOA systems in terms of geolocation coverage

A1 Discussion

Geolocation coverage features for different groups of fixed AOA direction finders (DF stations) and TDOA sensors (hereinafter, we shall also use the term “fixed station” when referring to both a sensor and a DF station) may be analysed by considering AOA and TDOA monitoring networks comprising up to three interacting stations, since these give rise to zones in which the coverage areas of three and two stations overlap as well as areas covered by only one station. From the point of view of geolocation conditions, the case of four or more interacting stations (i.e. with multiple overlapping coverage areas) is not fundamentally different from the case of three stations in areas where their coverage overlaps.

We shall consider geolocation coverage for three fixed sensors, identified in Figure 1 as S1 to S3, and three fixed DF stations, identified in Figure 2 as DF1 to DF3, having the exact same geometry, but operating in TDOA and AOA networks, respectively. The networks are also assumed to be equipped with mobile monitoring stations, identified on Figures 1 and 2 as MS, using equipment with the exact same technology as both the fixed sensors and DF stations (hereinafter we shall use the term “fixed station” when referring to both a sensor and a DF station). Notional individual coverage areas of each fixed station are depicted in Figures 1 and 2 using different coloured contours. Shown in yellow are the overlapping coverage areas of the fixed stations within which the coordinates of the emission source (hereinafter referred to, for conciseness, as the “transmitter”) can be determined using the fixed stations alone, without the need to involve mobile stations. Since TDOA sensors are considered to be more sensitive than AOA DF stations, the corresponding coverage areas of the individual sensors S1 to S3 in Figure 1 are shown as exceeding those for the DF stations DF1 to DF3 in Figure 2.

It should be pointed out that the coverage areas in both figures are constructed purely notionally, in relation to a certain test transmitter with a specific power and antenna height. If these parameters are modified, this will inevitably alter the contours of the coverage areas to some extent.

For a TDOA network, it is only in areas served by all three sensors, i.e. where their individual coverage areas overlap, that distance determination of transmitter coordinates can be performed using fixed sensors alone. Within this area, the transmitter coordinates are determined on the basis of the area of intersection of the three lines of position, as shown in Figure 1 in relation to transmitter T1, where lines of position 1-2, 3-1 and 3-2 intersect. For an AOA network, geolocation using only fixed DF stations is performed with approximately the same level of effectiveness on the basis of the intersection of the lines of bearing within areas covered by all three DF stations, as shown in Figure 2 in relation to transmitter T1 (bearing lines 1 to 3), as well as in areas covered by only two DF stations, as shown in the same figure in relation to transmitter T2 (bearing lines 4 and 5). Depending on the geometry of the fixed stations in the network, the overlapping coverage areas of two stations may be significantly larger than the overlapping coverage areas of three stations.

FIGURE 1

Geolocation coverage in a TDOA network

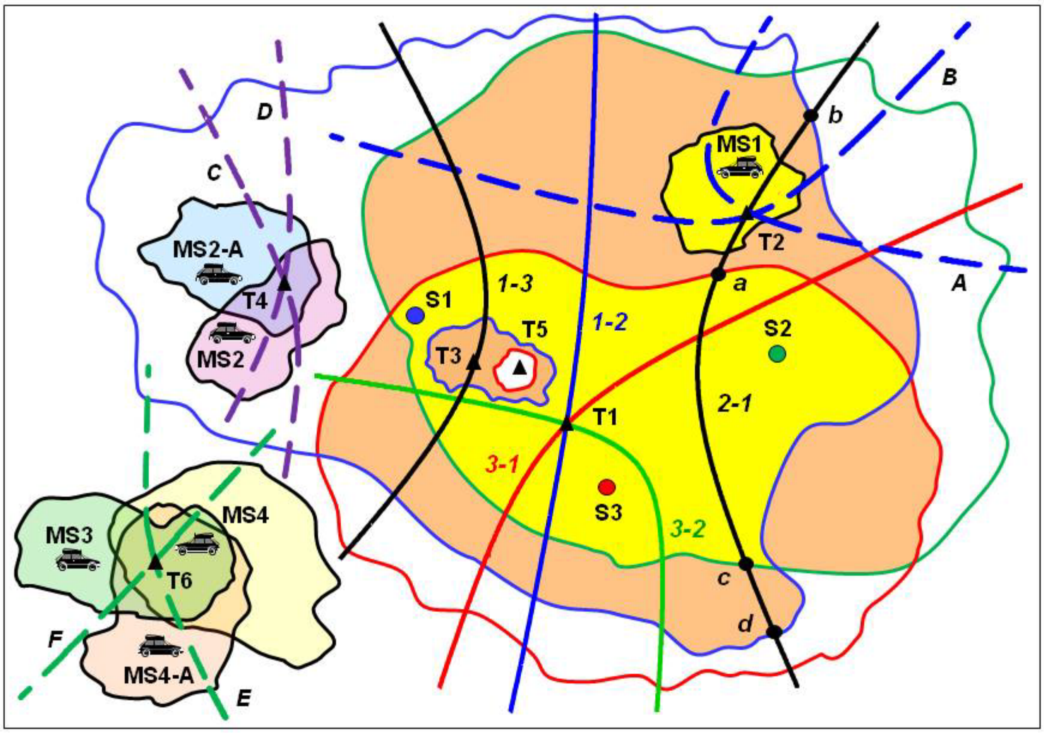
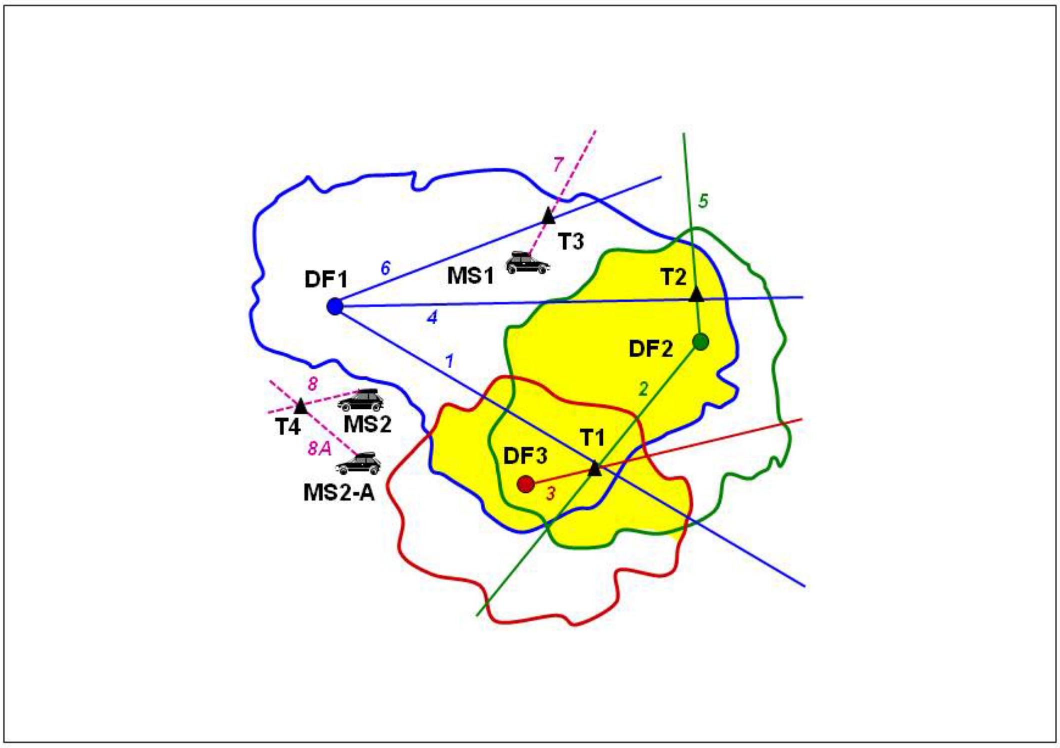


FIGURE 2

Geolocation coverage in an AOA network



If, in a TDOA network, the sought transmitter is situated in one of the areas covered by only two sensors (brown colour in Figure 1), the system can produce only one line of position, as depicted by line 2-1 in relation to transmitter T2. In this case, therefore, the transmitter coordinates can only be determined with the help of a mobile station (MS1 in Figure 1), interacting with the two sensors, on the basis of the place where the line of position 2-1 intersects with two others established by this mobile station (lines of position A and B in Figure 1, depicted by broken lines in order to highlight their variability as the station moves around). Here, the sought transmitter has to be in the coverage area of the mobile station, which is usually small on account of its low antenna height. Thus, in an area covered by only two sensors, a mobile station generally has to fulfil not only the DF homing function in respect of the transmitter, but also the distance determination of its coordinates, which increases the burden and hence reduces the effectiveness of operation of the mobile monitoring station.

In particular, if the mobile station coverage area is inadequate to capture the transmitter signal (T2 in the case under consideration), the operator, having only the line of position 2-1, may conclude that the sought transmitter is most probably situated somewhere towards the outer parts of that line, i.e. within its segments a-b or c-d, rather than in its central segment, which has a greater probability of being covered by all three sensors, if there are no significant irregularities in the local terrain relief there. Here, the operator must take into account that the end points of these segments (a-b or c-d) are not known, insofar as the borders of the coverage areas of individual fixed sensors, including overlapping coverage areas, depend on the power and antenna height of the sought transmitter, which are usually not known until the time when it is effectively detected at its site. Thus, the segments a-b and c-d move towards the centre of the line for low-powered transmitters with low antennas and towards the outer parts of the line in the opposite case, with the distances between the points a-b and c-d also change.

It should be pointed out that the region in which the sought transmitter is situated is usually associated with the site of a receiver suffering interference or (especially in the case of illegal transmitters) is presumed to be known on the basis of other data. Where there is a high density of TDOA fixed sensors (e.g. in large cities), the interference to a receiver located in the lower part of Figure 1 may well be caused by a transmitter located in the upper part of Figure 1, such as transmitter T2. Therefore, in many cases, the mobile station has to move along the whole of the line of position (or a significant portion of it) in order to detect the sought transmitter at its site. This may be quite onerous, which reduces the DF homing effectiveness of a TDOA system in areas with overlapping coverage of only two fixed sensors.

The features considered above also hold in cases where, due to the local terrain relief irregularities or built-up urban zones, an area with overlapping coverage of only two fixed sensors lies inside the broader area covered by all three sensors. As shown in Figure 1 in relation to transmitter T3, here again only one line of position 1-3 is produced and, in order to determine the coordinates of the transmitter on this line, it is necessary to use a mobile station, with the above-mentioned difficulties this entails.

On the contrary, as mentioned above, an AOA system enables the coordinates of a transmitter to be determined in areas covered by only two DF stations almost as effectively as in an area covered by three or more DF stations. As can be seen from a comparison of the lines of position 2-1 and 1-3 in Figure 1 and the line of bearing 4 from a single DF station DF1 in Figure 2, the search area of a mobile station with TDOA is generally twice as large as for a mobile station with AOA. This once again points to the lesser effectiveness of operation of a mobile station in a TDOA system as compared with an AOA system.

In the area of coverage by only one TDOA sensor, determination of the coordinates and DF homing of a transmitter become even more complex and it places an even greater burden on the mobile station. The mobile station, not having any point of reference other than such as the position of the receiver suffering the interference or the presumed region in which the illegal transmitter is situated, has to approach the sought transmitter closely enough for the latter to fall within its coverage area, as shown in Figure 1 in the example of mobile station MS2 in relation to transmitter T4. Even in that case, however, only one line of position C will be produced. In order to determine the coordinates of the sought transmitter on that line, the mobile station, respecting the same conditions, has to move to another point, such as point MS2-A in Figure 1, so as to establish a second line of position D that intersects with the first. Obviously, these operations may be even more onerous than in the case considered above, with a line of position in the area covered by two sensors, and hence even less effective, especially in regions where the road network is poorly developed.

The same effect occurs in the case where, on account of the terrain relief features or built-up urban zones, an area served by only one sensor lies within the broader area covered by all three sensors. As shown in Figure 1 in relation to transmitter T5, situated in an area served only by sensor S3, depicted notionally by a red contour, the network of sensors simply does not "see" that transmitter at all, and its location may only be determined with the help of a mobile station in the same way as described above for transmitter T4.

In an AOA system, location of a transmitter using a mobile station on the basis of a bearing provided by one DF station is a very common operation, carried out relatively effectively, at least under conditions with no reflections present. In accordance with Figure 2, in order to detect the sought transmitter T3, the mobile station MS1 only has to follow along the line of bearing 6, until it acquires the signal from that transmitter. DF homing of the sought transmitter is then carried out on the basis of the bearing of the mobile station itself. If the operator wishes to determine upfront the probable position of the sought transmitter (for instance, so as to select the best approach path), it may take a bearing from any other point, as shown notionally by line of bearing 7 in Figure 2. The intersection of bearing lines 6 and 7 indicates the coordinates of the sought transmitter (in this case T3), which facilitates its subsequent DF homing. Under real conditions with reflections present, reliable geolocation of the sought transmitter may require several bearings from the mobile station from a number of different points.

Any effective geolocation of an interfering or illegal transmitter outside the coverage areas of TDOA sensors is generally unrealistic. Were one nevertheless to try, for such an operation a minimum of two interacting mobile stations would be required, as shown by stations MS3 and MS4 in Figure 1. As a first step, starting from the position of the receiver suffering the interference or the presumed region in which the illegal transmitter is situated, two TDOA mobile stations have to capture the sought transmitter in their overlapping coverage areas for it to be possible to establish the corresponding line of position, but this is highly problematical. That having been said, reception of the signal from the sought transmitter by just one mobile station does show the operators that the sought transmitter is situated somewhere relatively close by, and one of the mobile stations may continue searching in that region until such time as the line of position is established (for example, line of position E between mobile stations MS3 and MS4 in Figure 1). As a second step, one of the mobile stations, respecting the same conditions, must move to another point, such as for example station MS4 to point MS4-A in Figure 1, in order to establish a second line of position F and determine the transmitter's place (T6 in Figure 1) on the basis of the intersection of these lines of position. Only then can one proceed to DF homing.

One mobile station is enough to detect a transmitter within a territory that does not encompass a network of AOA DF stations. For example, mobile station MS2 in Figure 2, in conditions with no reflections present, immediately establishes the bearing to the sought transmitter (bearing line 8 in

Figure 2) as soon as that transmitter comes into its coverage area. If the operator wishes to determine upfront the probable position of the sought transmitter (for example, so as to select the best approach path), it may take a bearing from any other point, as shown notionally by line of bearing 8A from point MS2-A in Figure 2. The intersection of bearing lines 8 and 8A indicates the position of the sought transmitter T4, which facilitates its subsequent DF homing. Under real conditions, with reflections present, geolocation of the sought transmitter may require several bearings by mobile stations from a number of different points. This procedure is very widely used by many administrations, especially in countries with large territories much of which cannot be monitored using fixed stations for quite understandable economic reasons. This function is virtually impossible to perform with a TDOA system.

A2 Conclusions

In TDOA networks, a sharp drop in geolocation effectiveness occurs at the periphery of a group of sensors, i.e. where the coverage areas of only two sensors overlap and, *a fortiori*, where there is only one sensor coverage area. Insofar as the ratio of the service area covered by a group of sensors to their peripheral zone increases with the number of sensors in the group, the effectiveness of a TDOA network improves as the number of interacting sensors increases. This means that TDOA networks are more effective for serving large cities and industrial centres, where a large number of sensors may be installed at short distances from each other, resulting in multiple overlapping of their individual coverage areas (minimum of three sensors) allowing genuine automation of the monitoring process, including the transmitter geolocation function.

Conversely, relatively small towns and their neighbouring suburbs as well as isolated industrial centres are more effectively served by a small number of DF stations in an AOA system, separated by relatively large distances. The use of only two AOA DF stations is already highly effective for performing geolocation of transmitters in overlapping areas and direction finding in individual coverage areas.

Even a single AOA DF station is relatively effective, since within its coverage area it establishes (as well as measuring emission parameters) bearings to sought transmitters, which significantly facilitates their subsequent DF homing using mobile stations. Single TDOA sensors are not effective here at all.

Mobile stations in a TDOA system can perform successfully only within the aforementioned group of TDOA sensors. At the periphery of the TDOA network, the effectiveness of mobile stations in such a system falls off sharply, whereas in an AOA network it remains relatively high. Therefore, generally speaking, mobile stations equipped only for TDOA cannot be deemed sufficiently effective. Only hybrid TDOA/AOA mobile systems are of interest.

The trend towards use hybrid TDOA/AOA systems for mobile stations leads to another extremely important conclusion: for the monitoring of new radio systems with future broadband modulation types one cannot look exclusively to the use of TDOA technology. AOA monitoring systems need accordingly to be developed, too, in order to be able to compensate for the inadequacies of using TDOA technology for mobile monitoring. Otherwise, a key component for monitoring – mobile – may not be realized. In order to be effective in a hybrid TDOA/AOA network of fixed stations, AOA DF stations must provide coverage areas at least similar to the coverage areas of TDOA sensors.

A network of TDOA sensors, even in the case where there are mobile stations, is more sensitive than an AOA network to the presence of areas served by only two stations and, *a fortiori*, only one station, within the broader coverage area of three or more stations. As the relative surface area of such poorly served areas increases, the effectiveness of a TDOA network and the possibility of automated geolocation therein declines sharply; yet, such automation is acknowledged to be a fundamental compelling motive for changing over to TDOA. This calls for more careful planning of TDOA sensor networks in comparison with networks of AOA DF stations, with the aim of minimizing such poorly served areas.

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