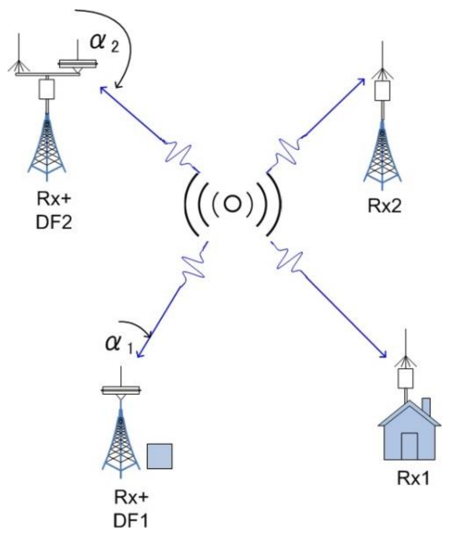
Spectrum Monitoring with Hybrid AOA/TDOA Geolocation

White Paper

This white paper explains the locating methods AOA and TDOA including their differences. It furthermore describes products and solutions for efficient spectrum monitoring with hybrid geolocation



White Paper

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ROHDE&SCHWARZ

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1 Introduction

Radiomonitoring capabilities must keep pace with the ever-growing number of wireless communications signals and services. Public authorities are increasingly tasked with the central challenge of providing authorized users with the clean spectrum that they expect, and doing that requires detecting, locating and eliminating unauthorized emissions. As part of the spectrum management process, radiomonitoring systems help plan the frequency bands and then verify the actual spectrum in order to avoid interference. When equipped with open interfaces, they can be connected to the spectrum management system. This allows operators to produce and evaluate data for properly checking and assigning vacant channels. For these operators, but also for those who frequently face the challenge of hunting for sources of interference, advanced geolocation capabilities are a valuable asset.

Over time, the number of signals crowding the airwaves has increased tremendously. Many digitally modulated standards with larger bandwidths have come into common use, resulting in more complex and denser signal environments. Emissions within densely constructed urban areas are reflected multiple times; that causes multi-path propagations, which can present a challenge for geolocating emitters. Further changes in the wireless world, such as the use of weaker signals and the increase of man-made noise, reduce the usable signal level and require receivers for locating nearby the emitters. This proximity to the signal sources necessitates the use of more receivers within the area to being monitored.

The hybrid geolocation technology that this spectrum monitoring system makes use of two different methods for determining emitter locations: the angle-based location method, which measures the incoming wave front's angle of arrival (AOA), and the time-based principle, which measures the signals' time difference of arrival (TDOA) at different positions. The resulting hybrid geolocation system can apply both the TDOA method and the conventional AOA method in parallel.

The TDOA principle is not new, but it has only recently become economically justifiable. The availability of increased computing power, broadband data links, accurately distributed timing signals through GPS, and advanced technology makes this geolocation method a viable alternative to AOA in many cases. These two complementary methods each have their own set of advantages and disadvantages. Their combination can improve the coverage, increase the geolocation accuracy and reduce the number of required monitoring stations.

Authorities can upgrade also existing systems with TDOA functionality.
Rohde & Schwarz's modular solution for doing that allows continued operation of existing devices, infrastructure and sites, and it ensures that measurements are performed according to ITU recommendations with excellent radio frequency (RF) parameters. The scalability of the Rohde & Schwarz solution permits to compose different systems for different requirements and thus represents a future-ready investment.

2 Geolocation Methods

Geolocating an emitter is often a crucial requirement in spectrum monitoring. Knowing a transmitter's location can be a means of identifying it. This is necessary for routine measurements, or when a transmitter is operating outside its licensed parameters or even illegally. Especially when hunting for interference, the source's location is the most essential information. Usually, emissions not only travel to the intended receiving station or to stations that they interfere with, but – more or less – in all directions. That characteristic makes it possible to intercept signals within the emitter's surroundings and geolocate the source. Today, spectrum monitoring systems increasingly combine two different methods for determining an emission's location:

1. The angle-based method that calculates the emitter's location from the signal's angle of arrival (AOA) at different positions
2. The time-based scheme that calculates the emitter's location from the time difference of arrival (TDOA) for the signal when measured at different positions

Both methods provide advantages and imply limitations. Determining which method is superior to the other depends on the signal type, the environment and other parameters. The sections below will take a closer look at these considerations and provide background information.

2.1 Angle of Arrival (AOA)

The angle of arrival method makes use of simple geometry: When two angles of a triangle and their positions are known, it is possible to determine the triangle's opposite vertex. In practice, the method pinpoints an emitter's location by taking bearings on the signal from remote positions.

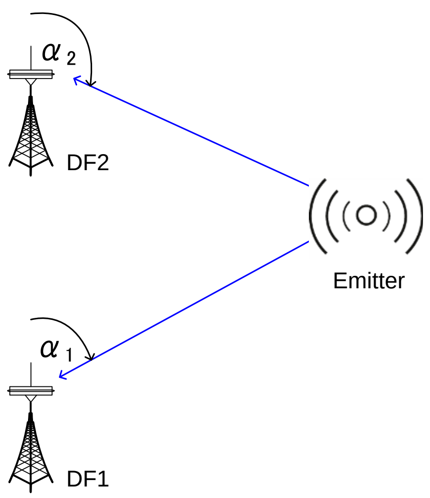

Fig. 1: Cross-bearing with two direction finders (DFs).

The AOA method makes use of direction finders and assumes that their positions are known. Each of them measures the incoming wave front's angle of arrival (AOA) in relation to a reference direction. Usually, this reference direction is geographic North, and it is called the azimuth α. When these bearings are merged, the emitter's location can be found at their intersection.

It is important to keep in mind that direction finders determine the wave front’s bearing. In environments in which wave propagation is free of any influences, direction finders can achieve high accuracy over wide frequency ranges. However, impact on homogeneous wave propagation is common, and that can reduce direction-finding accuracy. Especially in urban areas, buildings and other obstructions often influence homogenous wave propagation, which results in wave fronts that are altered by interference and are sometimes even redirected. These reflections, diffractions and diffusions can dramatically falsify the direction finders' results, because the measured phase differences at the antenna elements deliver ambiguous findings. Inaccurate bearings then result in incorrect geolocation estimates.

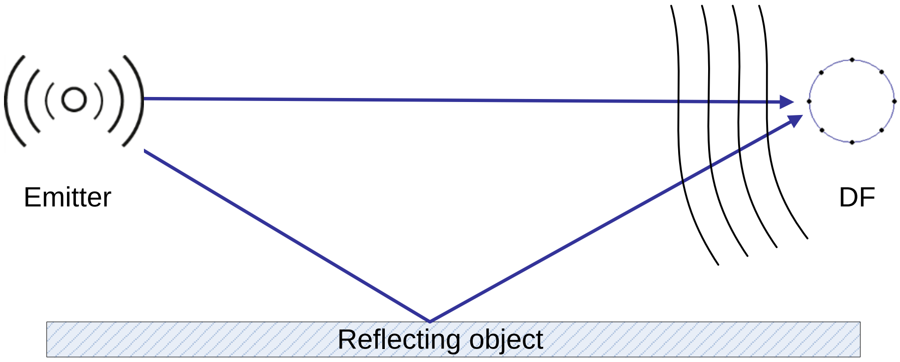

Fig. 2: Objects reflect the waves and cause them to arrive at the DF antenna in distorted form.

In the VHF/UHF range most modern broadband direction finders make use of the correlative interferometer principle. This method determines the bearings by measuring the phase differences between antenna elements and then comparing the reference values with the measured values. In order to reduce the interference of an incoming wave front, it is desirable to ensure certain spacing between the direction finder's antenna elements. Obviously, the greater the spacing between the antenna elements is, the smaller the influence of the distortion becomes. The decisive parameter is the aperture of a DF antenna that is defined by its diameter divided by the received wavelength. Since taking more phase-difference measurements and performing averaging increases accuracy, employing a large number of antenna elements can help diminish interference effects. This means that distorted wave fronts can be handled best by wide aperture direction finding antennas that feature a large number of elements.

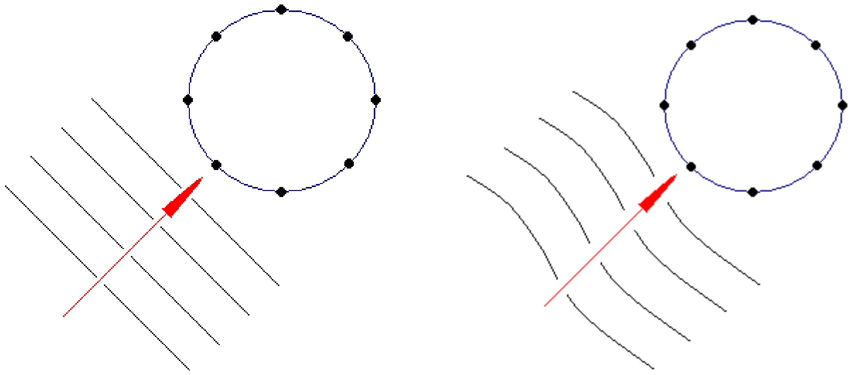

Fig. 3: Homogeneous waves (left) vs. interfered waves (right) arriving at a nine-element DF antenna.

Another challenge in the radiomonitoring world arises when weak and strong emissions are nearby, in particular when it is the weakest signal that is of interest. Excellent radiofrequency (RF) characteristics are required in order to detect, identify and perform direction finding on emitters in such complex signal scenarios. The receivers and direction finders need the highest levels of immunity to strong signals, and that is realized by employing very extensive preselection measures and by minimizing phase noise. When a radio service is subjected to interference, it is often the case that there is another emitter operating on exactly the same frequency. Separating this co-channel emitter visually within the radio spectrum may become difficult. One solution can be to make use of steerable directional antennas and monitor the channel at different positions. Alternatively, operators can apply a direction finder with super resolution capabilities. That option compares the phase differences on all antenna elements with each other and makes use of complex mathematical algorithms for separating several emitters on the same frequency.

It is important to keep in mind that location accuracy depends on the accuracy of the direction finding results. Two exact lines of bearing (LOBs) crossing at an obtuse angle are all that is usually necessary to determine a location. Nevertheless, to increase geolocation accuracy, a third direction finder can be used. Having three units is a great help when it is necessary to determine the location of an emitter that is located directly between two direction finder sites or off in a direction that causes their LOBs to cross at acute angles.

In order to increase the accuracy it is common to apply three direction finders. Then the resulting three LOBs usually do not intersect in a single point, but form a triangle. This provides a better indication about the emitter's geolocation. If available, usually operators decide to apply three or even more direction finders for contributing to the geolocation accuracy.

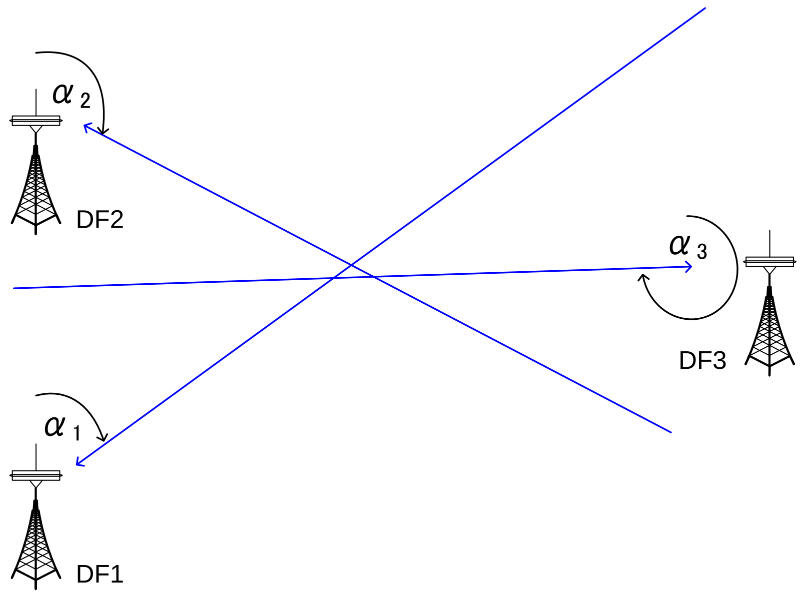

Fig. 4: Geolocation with three direction finders (DFs).

For geolocating an emitter, the DF results from the direction finders are processed at a control center, which can be at a direction finder site or at a remote control center. Several bearing measurements usually provide dispersion around the mean, and, in a first step, bearings that are obviously irregular are eliminated. The system calculates the mean value of the LOBs and their variance. These values from each direction finder are then used to compute the geolocation, which results in a graphical representation of a location ellipse, which is sometimes also called an error ellipse.

The ellipse represents the area of uncertainty with regard to the emitter's location. The dimensions of this ellipse are a measure of the geolocation accuracy. A smaller ellipse means less uncertainty. This level of uncertainty depends mainly on the following factors:

- The DF accuracy of each direction finder: This value is mostly influenced by the environments of the emitter and DF sites and by any obstructions in between them.
- The distances between the DFs and the emitter: Smart site selection and a larger number of direction finding sites can reduce the distances towards probable signal sources.
- The angle of the LOBs between each other: More obtuse angled bearings reduce the error ellipse's size and thus increase geolocation accuracy.

Therefore, it is obvious that employing a larger number of direction finders can increase geolocation accuracy. Operators can then select the stations that provide the best DF results for the signal of interest. Further uncertainties can be caused by reflections and other effects in the wave propagation.

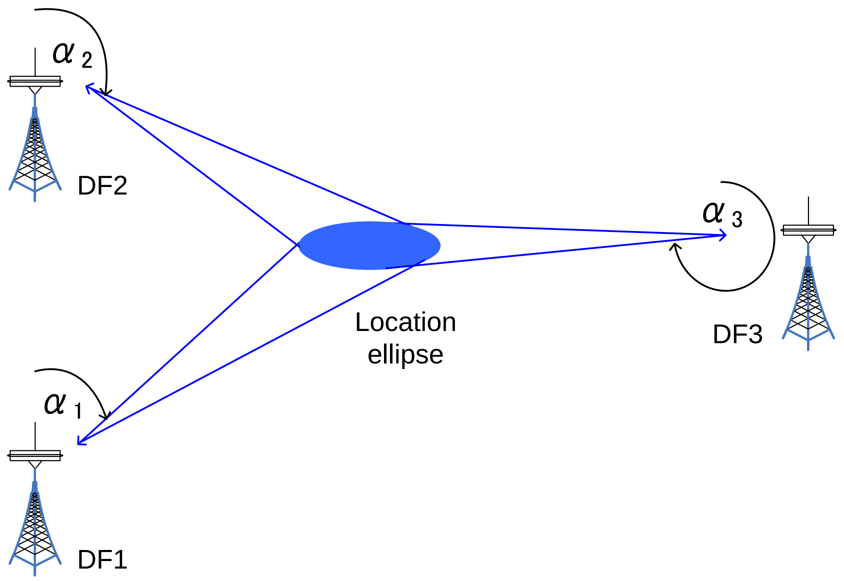

Fig. 5: Geolocation calculations result in an error ellipse.

2.2 Time Difference of Arrival (TDOA)

The time difference of arrival (TDOA) method is a distance-based geolocation scheme, increasingly gaining significance in the field of spectrum monitoring. The principle is not new; it has been used in navigation applications for decades, but TDOA has now become technically and economically viable for use in geolocating emitters. Recently, accurate time synchronization capabilities have become available, computing power has grown and broadband networking infrastructure has been established, all of which has helped to enable use of this localization principle. TDOA's main advantages in urban environments are its modest site requirements. Compared to the direction finding antennas, the TDOA receiving stations do not urgently need obstacle free environment.

The principle of TDOA is to calculate the location of an emitter from the time difference of the signal's arrival at different receivers. This method makes use of the fact that, for all practical purposes, electromagnetic waves travel through space from the transmitter at a constant speed. When the signal arrives at the first receiver, it is as if the system starts a stopwatch. When a second and a third receiver receives the same signal, the system determines the difference between the times at which the signal arrived at the receivers. In practice, each receiver takes a signal sample of the digital IF and adds a highly accurate time stamp for comparison purposes. However, the signal's actual time of arrival is only used for calculating the time difference values.

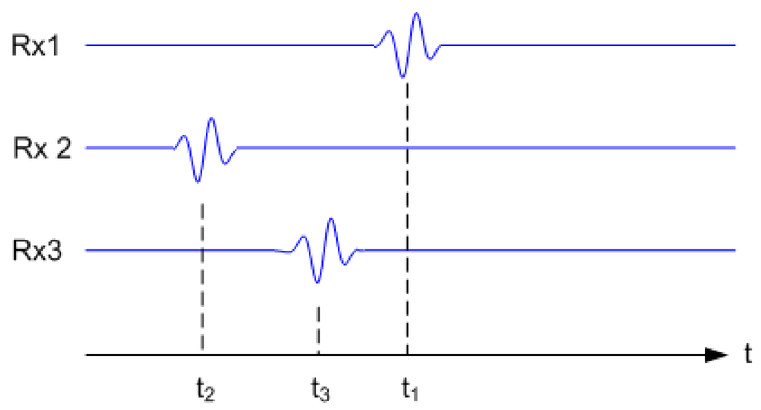

Fig. 6: A signal arrives at different receivers at different times.

When the signal is received by three or more receivers, the system can cross-correlate the digitized signal samples. To achieve an accurate estimation, the time window that is used for each signal sample must be much larger than the maximum time differences. Then the system determines the peak position of the cross-correlation that indicates the three time differences τ:

$\tau_1 = t_1 - t_2$

$\tau_2 = t_3 - t_2$

$\tau_3 = t_1 - t_3$

Calculating the cross-correlation of emissions requires only the differences between the times at which the signal arrived at different positions. The absolute times of the signal's arrivals in the form of time stamps are only used for determining these time differences. Along with the receivers' coordinates, the algorithm then processes these time difference values. In the example above, the signal arrives at receiver 1 later than at receiver 2. The time difference τ_1 is caused by the path length difference that is due to the fact that receiver 2 is closer to the signal source than receiver 1 is. This path length difference is the distance that can be calculated as

$$\Delta d = c * \tau$$

where c is the speed of light. When regarding only receivers 1 and 2, the transmitter can be located at each point that is the same distance Δd_1 closer to receiver 2 than to receiver 1. This means that the calculated distances Δd are directly proportional to the measured time difference τ for each receiver pair's data set.

Obviously, the location accuracy depends on the time accuracy, which must be optimized. Time deviations result in poor distance calculations and consequently lead to incorrect geolocation results. As a rule of thumb, an error of 10 nanoseconds corresponds to about 3 meters. Therefore, proper location results can only be gained by synchronizing the time at each receiver.

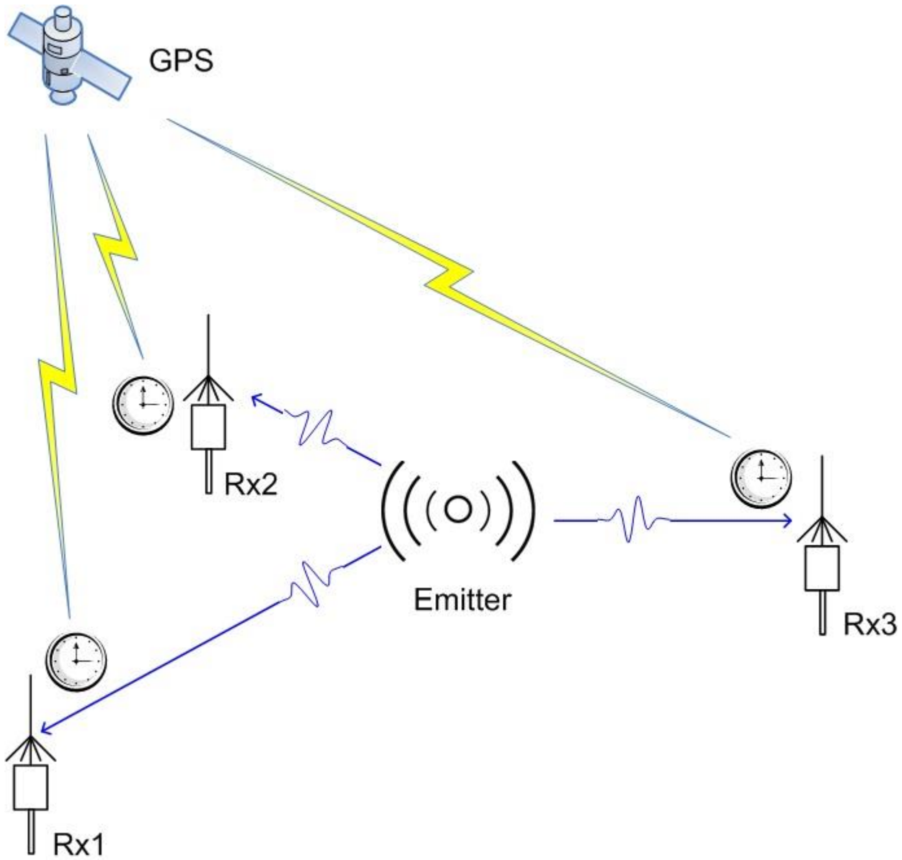

Fig. 7: GPS synchronizes the receiver clocks for correlating a signal that arrives at different receivers at different times.

This is a crucial factor for system accuracy, and it is realized by employing highly accurate GPS-modules at each receiver. Moreover, the receivers must compensate for the time gap from the antenna output through the entire signal processing chain, and thus reduce internal system errors.

For determining the emitter's location a graphical approach can visualize the solution easier. We can begin to conceive of this by imagining a simple situation: If two receivers were to receive the signal at the same time, the time difference would be $\tau = 0$, and consequently the distance would be $\Delta d = 0$. In that case, it would be possible to estimate that the emitter is located exactly in between them or on a plain surface from which each point is the same distance from both receivers.

If there were to be a measurable time difference τ, and consequently a certain distance Δd, the geometrical result would be a hyperboloid in space. In our example, not only the time differences, but also the sequences are measured; the signal arrives first at receiver 2, then at receiver 3 and finally at receiver 1. Therefore, the result of each receiver pair measurement is only one sheet of the two-sheeted hyperboloid. The maximum bending of the surface is located in between the measuring receivers while the surface continues approximating a cone shape but never contains straight lines.

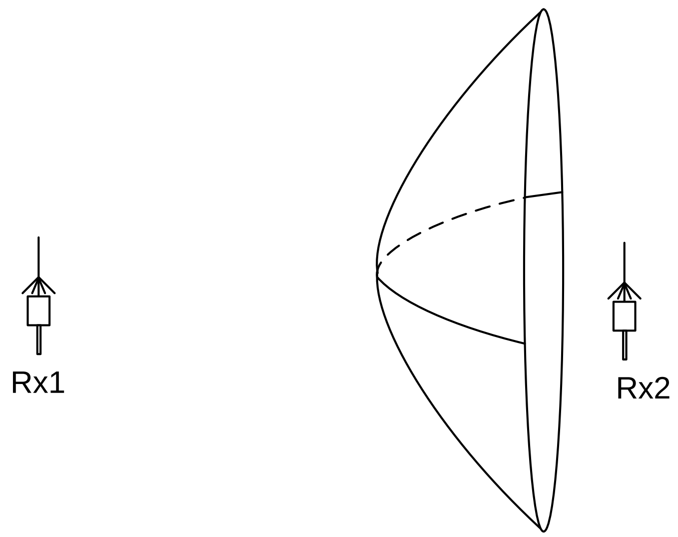

Fig. 8: All points of the hyperboloid are the same distance closer to receiver 2 than to receiver 1.

The hyperboloid represents the sum of all points that are the distance Δd closer to receiver 2 than to receiver 1, while receiver 2 is at the focus of the hyperboloid. Out of this three-dimensional hyperboloid, usually only the two-dimensional hyperbola on the earth's surface is of interest. Therefore, the signal's elevation will be disregarded.

To locate an emitter on a plain surface, the geometry would require only two data sets, providing two hyperbolas that intersect at a certain point. However three receivers provide three data sets, resulting in three hyperbolas. These usually intersect close-by, forming a triangle. This triangle indicates the most probable emitter's location.

Usually, a minimum of three receivers participate in this geolocation method, while the system processes always measurements from two receivers. Each receiver pair provides one data set; three receivers provide three and four receivers can even provide six data sets. The more data sets that are available, the better the geolocation result is in practice, which enables the system to process the best measurements. Receivers that cannot receive the signal of interest will not take part in the geolocation process. Therefore, it is mainly the arrangement of the receivers, their density and their sensitivity that limit the number of usable receivers.

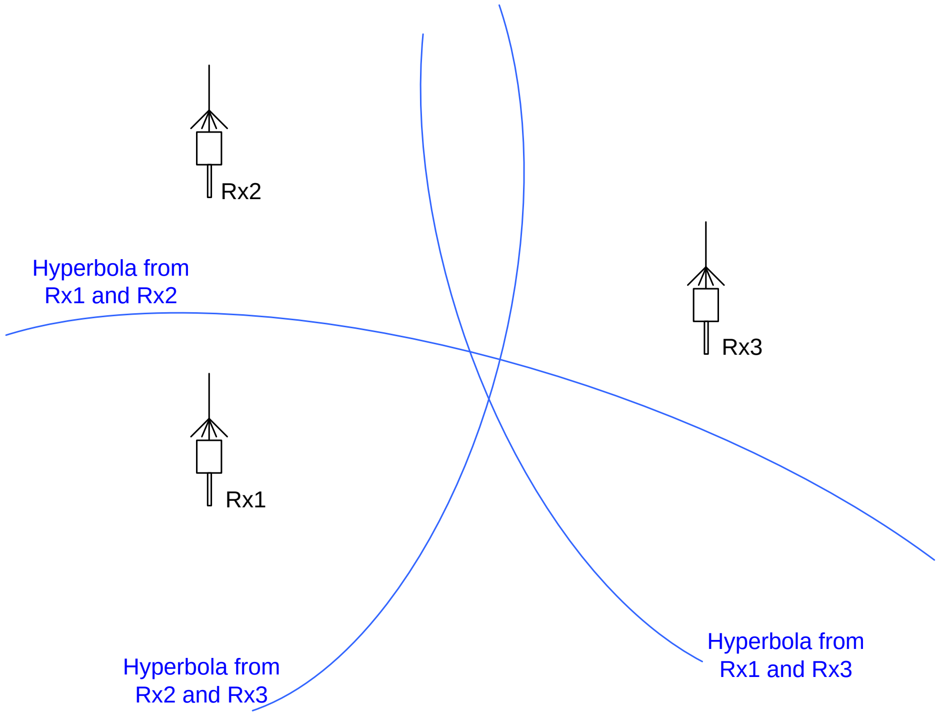

Fig. 9: The intersection of the hyperbolas indicates the emitter's location.

The TDOA method is ideal for locating new and emerging signals, which often feature complex digital modulations, wide bandwidths, and short durations. A large signal bandwidth, a good signal to noise ratio (SNR) and a long measurement period increase location accuracy. These three factors usually ensure proper system performance and can partially compensate for each other. The TDOA method works with low and even negative SNR, provided there is sufficient bandwidth and measurement time. This makes TDOA a good method for spread-spectrum signals like CDMA. With enough SNR and bandwidth, TDOA can even process very short signals, such as TDMA, bursts or pulses.

The most important parameters of geolocation systems are usually their sensitivity and accuracy. It is possible to ensure that the system achieves the required level of sensitivity by employing an appropriate antenna set and a tuner with excellent RF characteristics. The TDOA system's accuracy depends mainly on achieving precise synchronization of the networking receivers. Their accurate time stamp derives from the GPS modules at the receivers and ensures the highest levels of precision for the geolocation results. Please refer to the application brochure “receiver requirements for a TDOA-based radiolocation system”.

2.3 Hybrid Geolocation Technology

Spectrum monitoring systems with hybrid AOA/TDOA geolocation technology fuse the capabilities of both methods for determining an emitter's locus. This chapter summarizes the differences between those two locating methods along with the reasons for combining AOA with TDOA.

There are a variety of aspects to consider when **selecting proper sites** for geolocation systems. Direction finding antennas should be installed on top of a mast with vast obstacle clearance. This requires sites that are much more restrictive than those that operate with the TDOA method only. An exposed location is also desirable for those simpler receivers, but not a must for the TDOA method. In general, choosing TDOA sites allows more options, and the pure receiving stations can usually be deployed faster.

The **geometric arrangement** of the sites determines the system's locating performance. Planners arrange the sites for best coverage of the area to be monitored. Since they take environmental requirements into consideration, the site does not usually follow a strictly symmetric layout. It is important that sites be positioned in a way that is suitable for the AOA and/or TDOA method. It is a geometric fact that intersections are more precise for lines that intersect at obtuse angles. For the TDOA technology, this means that the system can most accurately locate signal sources that the receivers surround, while direction finders can also determine the locations of outlying signal sources.

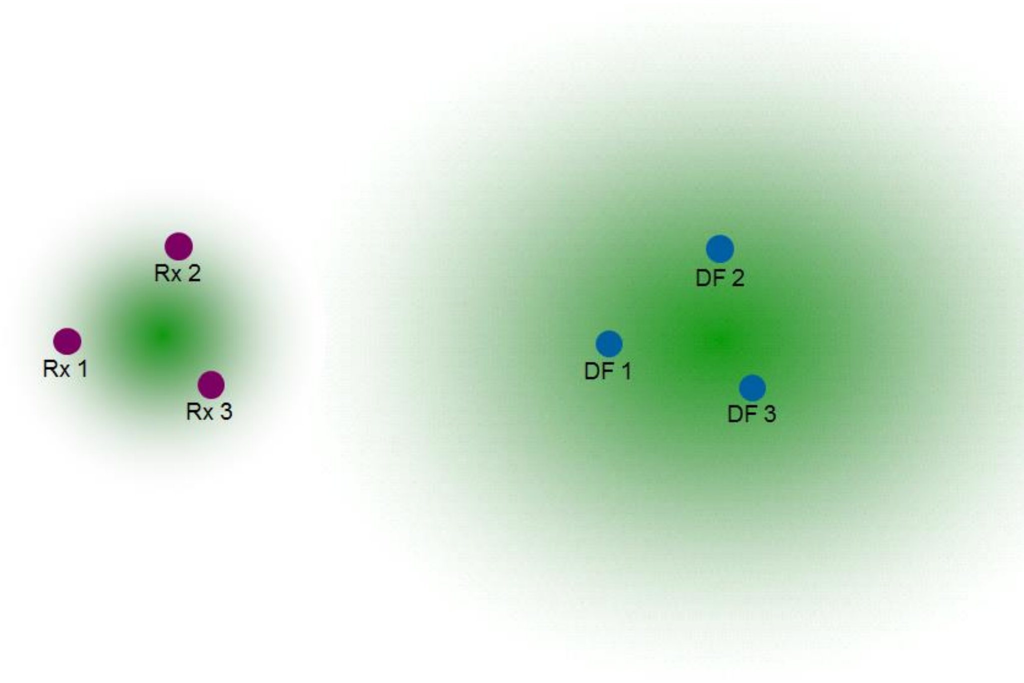

Fig. 10: The areas (green fields) where good geolocating results can be expected: TDOAs left and DF stations right.

A proper receiver site requires some infrastructure. Besides electricity, the station needs a **data link** to the control center. Despite the fact that advanced remote monitoring stations can often operate offline, operators must access them from time to time. A data link for controlling the receivers and receiving the measurement data can be installed as a permanent connection or established on demand. Usually, for simple controlling or for reading back results, no special attention must be paid to the required data rate. Large bandwidths are not even required for performing locating tasks with the DF option. Nevertheless, fast data links become necessary when the TDOA mode, which transfers IF samples along with metadata to the central server, is employed. When implementing a monitoring network and its infrastructure, it is important to note that this data rate requirement is asymmetric. Only the upload bandwidth (from the receiver to the control center) demands the higher data rate, despite the fact that compression algorithms have been integrated.

The locating methods also differ in the required **number of receivers**. A single receiver with a direction finding option can determine an emitter's direction. Connected to two AOA receivers, the system can geo-locate a signal source by taking a cross bearing. In contrast to that, locating emitters with the TDOA method requires at least three receivers. In urban areas, numerous TDOA receivers will be installed within and around the area to be monitored, bringing the receivers close to the signals of interest and resulting in a high performance multi-channel spectrum monitoring system.

A variety of factors influence the accuracy of the TDOA and AOA technologies. When applying direction finders, LOB precision is indirectly proportional to the **distance** between the emitter and the direction finder. Further, the locating accuracy not only depends on the distances from the receivers to the signal source, but also on the angles of the intersecting LOBs. Narrow angles cause large error ellipses while rectangular intersections result in more accurate circles. In addition, with the TDOA method, the ellipses should intersect at obtuse angles. In contrast to the AOA method, TDOA geolocation accuracy is independent of the distance between the receivers and the signal source. On the other hand, the accuracy of the TDOA method depends on the **time synchronization** of the receivers.

Urban areas can present a challenge for locating signal sources, because densely constructed areas with high buildings can reflect the electromagnetic waves multiple times. These **multipath signal propagations** superimpose the signals that arrive at the antennas in a distorted manner. This poses a challenge for both, the AOA and the TDOA method. However, direction finders can best handle this by employing a wide-aperture antenna and a large number of antenna elements, enabling the DF processor to calculate the LOBs from more measurements. That, in turn, increases the direction-finding accuracy, and thus the location precision. On the other side, also the TDOA method is challenged by reflections that manipulate the signal samples. This affects the cross-correlation and results in poorer location accuracy too.

Since **noise** reduces the useful signal, it obviously influences location results for both AOA and TDOA. Besides the environmental noise, the receiver's and direction finder's inherent noise also affect location accuracy. When selecting receiver types, it is advisable to ensure a low noise figure and small phase noise. One significant parameter is the ratio of the signal power in relation to the noise level: the greater this signal to noise ratio (SNR) is, the higher the achievable geolocation accuracy becomes. This applies for the TDOA method, where a low SNR results in a less ambiguous cross-correlation. Also direction finders perform better with strong signals and less noise. However both methods can geolocate even weak signals to a certain degree at specific surrounding conditions.

Both AOA and TDOA technologies benefit from a longer **measurement period**. Longer averaging times allow direction finders to compensate for measured spikes. Moreover, TDOA receivers can use a longer acquisition time to correlate distinctive marks for the signal samples.

Besides noise and the measurement period, the signal **bandwidth** is the third non-system-inherent factor that determines the accuracy of TDOA estimates. A large bandwidth provides stronger cross-correlation properties, resulting in more accurate TDOA estimates. On the other hand, less accuracy can be expected when geolocating narrowband signals; while that is indeed the weakest point of this method, the accuracy issues are not as severe as some have proposed. The AOA method, on the other hand, works independently of the signal's bandwidth. However, depending on the situation and the expected accuracy, operators can define a minimum signal bandwidth for making use of the TDOA method.

Another weakness of TDOA is that it does not work with unmodulated signals, and it delivers low performance in connection with some **modulation** types. TDOA works excellent with digitally modulated signals. The number of these signals is increasing, such as WLAN (acc. to IEEE 802.11 standard family with BPSK, QPSK etc.) and DVB-T (with QPSK etc.), as well as traditional FM radio (analog with a 150 kHz bandwidth). The AOA method contrariwise performs well for any signal, regardless of its modulation type.

A direction finder is more complex than a receiver. The DF antenna includes an array of several elements. It needs control and calibration is recommended and, along with the DF processor, it enhances the **complexity** of the AOA method. In contrast to that, the modules for the TDOA method are less complex; installing them is simpler, and they require somehow fewer budget resources.

AOA and TDOA are **complementary geolocation technologies,** and both have advantages and disadvantages. Due to developments in, and the availability of, GPS timing synchronization, computing and networking power, TDOA receivers have become less expensive alternatives in some cases. On the other hand, TDOA's inability to locate unmodulated signals and inaccuracy at narrowband emissions, demand AOA's existence within monitoring networks. As each of the two geolocation methods can neutralize some of the weaknesses of the other technology, a spectrum monitoring system with hybrid geolocation technologies increases the probability of detecting and locating emissions in today's spectrum environments.

In urban environments with their modern (digital wideband) signals, authorities trend to implement TDOA receivers. They additionally enable them to monitor the spectrum at a spot much closer to the emitters. These monitoring receivers should fulfil the recommendations according to the ITU spectrum monitoring handbook and can be upgraded with a direction finding option for hybrid geolocation capabilities. However, also an upgrade of existing direction finding stations with TDOA capabilities can be a way to a hybrid system and thus increase the geolocation accuracy.

3 Products and Solutions

A spectrum monitoring system with hybrid AOA/TDOA geolocation consists of the control center and a monitoring network of several or numerous stations that can cover a large area. The system measures and processes data according to national and ITU recommendations and allows operations on multiple emissions in parallel. Such a scalable system can be configured for all areas in different geographic and spectrum environments.

The network connects several remote monitoring stations to the control center. These stations allow multiple individual measurements and automatic operation. They monitor the spectrum, detect individual signals, perform measurements on them and locate the emitters. Operators in the control center can directly command individual receivers or several at once remotely over the WAN. Nevertheless, no permanent data link to the stations is required, because they can also operate automatically. When a remote station detects an irregular event, it can send an alarm message to the control center.

Each station in the network comprises one or more antennas, a receiver or direction finder and a computer in addition to further accessories. The sections below provide an overview of the Rohde & Schwarz modules and devices for deploying a spectrum monitoring system with hybrid AOA/TDOA geolocation capabilities.

3.1 Antennas

The antennas are the interface to the environment from which the system receives the signals. The system can only process what the antenna intercepts. Therefore, careful planning is advisable when selecting the right antennas. Usually, at least one omnidirectional antenna will be used. Omnidirectional monitoring antennas provide reception characteristics equally well from all directions. The horizontal patterns for omnidirectional antennas are ideally circles. They will be used for different tasks, such as general measurements, interference hunting or TDOA measurements.

Depending on the receiver type – AOA, TDOA or hybrid – further antennas will be added. Besides the frequency range, the installation site is also an important factor for determining what type of antenna should be used. When strong transmitters are nearby, passive antennas are advisable. Antenna control units can switch antennas and control a rotator in order to steer them towards the desired direction and change the antennas' polarizations, if desired. For AOA receivers, direction finding antennas are required. They should be mounted on top of a mast, and they can also take over monitoring tasks, but they are somewhat limited in their measurement performance.

3.2 Receivers and Direction Finders

Monitoring receivers provide an overview of the frequency spectrum, and they can search for signals or demodulate them. Suggested options allow them to perform measurements, take an IF sample for TDOA geolocation purposes or even take bearings on signals.

The R&S®ESMD or the R&S®EB500 monitoring receiver will be the choice for ITU-compliant measurement tasks. Both receivers fulfill the ITU's recommendations for monitoring receivers and are available with or without a front panel for direct operation. If signal parameter measurements are less of interest and basic receiver performance will suffice, the more compact R&S®EM100 can be deployed.

Fig. 11: The advanced radiomonitoring receivers and direction finders from Rohde & Schwarz.

The R&S®ESMD monitoring receiver features include options, a wide frequency range from 9 kHz to 26.5 GHz, outstanding receive characteristics, up to 80 MHz of realtime bandwidth, and a wealth of functions. Due to its sophisticated preselection stages, this receiver combines a high degree of large-signal immunity with high sensitivity, which is important for performing measurements on weak signals in the presence of strong transmitters. The R&S®ESMD monitoring receiver with the DF option is functionally identical to the R&S®DDF255 monitoring direction finder.

The R&S®EB500 monitoring receiver is a compact and powerful unit. The basic version operates in the frequency range from 20 MHz to 3.6 GHz; it can be extended with the HF option down to 9 kHz, and with the SHF option up to 6 GHz. The R&S®EB500 provides a realtime bandwidth of up to 20 MHz, in line with the ITU recommendation ITU-R SM.1794. The R&S® EB500 with the DF option is the R&S®DDF205 monitoring direction finder.

The R&S®EM100 monitoring receiver operates in the wide frequency range from 9 kHz to 7.5 GHz. It is extremely compact and is the perfect monitoring receiver for remote stations and mobile applications where requirements are basic.

Important to mention is that all of the abovementioned monitoring receivers can be upgraded to include TDOA geolocation capabilities and/or DF options.

3.3 The R&S®UMS300 Compact Monitoring and Radiolocation System

The R&S®UMS300 compact monitoring and radiolocation system is a complete spectrum-monitoring station as an outdoor unit. The modular and weatherproof design makes it a universal system for many monitoring and surveillance tasks. It combines ITU-compliant monitoring with TDOA (and optionally AOA) geolocation capabilities. The heart of the R&S®UMS300 is a monitoring receiver covering in the frequency range from 20 MHz to 3.6 GHz (optionally 6 GHz). Its state-of-the-art FFT-based digital signal processing provides high receiving sensitivity and enables detection of extremely weak signals without any loss in processing speed. Controlled by the system's computer, the station can perform measurements automatically or interactively on demand. For operation in dense signal environments, the receiver is equipped with omnidirectional passive wideband antennas and a pre-selection stage (as recommended by ITU) that avoids intermodulation and overloading of the receiving unit.

Fig. 12: The R&S®UMS300 mounted on a roof.

For reliable detection of signals in the frequency spectrum, the receiver provides a fast panorama scan at up to 12 GHz/s across the entire frequency range. Also, the IF panorama span, which is selectable from 1 kHz to 20 MHz, can help operators find and investigate signals in detail. The system allows demodulation of signals with bandwidths from 100 Hz to 5 MHz and recording of both the demodulated audio and the digital IF data.

The R&S®UMS300's modular concept makes it a flexible foundation for various radiomonitoring applications. The standard version performs measurements according to ITU recommendations and supports TDOA location tasks. It can be extended with several options for individual configuration. For hybrid geolocation capabilities, the R&S®UMS300 can be equipped additionally with the direction finding option.

Fig. 13: The R&S®ADD196 and R&S®ADD071 direction finding antennas enhance the system's geolocation performance.

3.4 System Software

All monitoring stations, whether with or without direction finders, as well as the control center are controlled by the integrated R&S®ARGUS spectrum monitoring software. This efficient solution performs all measurements, controls devices, evaluates data and visualizes the measured results. It is a modular, scalable and networked solution for the entire grid network and even for nationwide monitoring systems.

The system provides a multi-level security concept, including flexible user management. Access rights can be assigned individually to user groups. The system controls the operators' access and allocates functions for them on monitoring stations.

Another key feature of R&S®ARGUS is the traceability of measurements. Recordings always include information on the responsible operator, the time and the location. This makes it possible to cite the measurements as evidence.

3.4.1 Measurements

Operators control the receivers via R&S®ARGUS system software over the WAN. In the direct measurement mode (DMM), operators can perform the device measurements. These measurements include:

- Frequency and frequency offset measurements in line with ITU-R SM.377
- Field strength measurements in line with ITU-R SM.378
- Modulation measurements in line with ITU-R SM.328
- Bandwidth measurements in line with ITU-R SM.443

Operators can make use of all device functions and record the measured data. Additionally, they can display the IF panorama and its waterfall display for performing a visual signal investigation. Furthermore, operators can perform a scan in order to visualize the spectrum at a single receiver.

The R&S®ARGUS interactive measurement mode (IMM) supports operators with several functions for efficient operations. These include the following modes:

- Spectrum
- Signal analysis
- Antenna analysis
- Intermodulation analysis
- Coverage measurement
- Violation detection

The guided measurement mode helps operators by providing predefined settings for the measurement device for analog (GMM option) and digital (DM option) signals. R&S®ARGUS guides the operator step by step through dialog windows, which prompt the user to enter the relevant information. Depending on the signal type and the measurement that has been selected, the device settings are automatically set to be a perfect match for the task.

When investigating interference on digital signals, determining the vestigial side band emissions is a particularly important measurement among the supported functions. This is because of the special energy distribution of digital signals: They often have excessively high energy at boundaries to channels of adjacent radio services. R&S®ARGUS provides the spectrum masks needed for measuring the permissible energy distribution within the signal.

Detecting signals that only occasionally arise and cause interference is often a time-consuming process, and it is typically performed unattended. Also, short-term band occupancy measurements that start and stop in the night can be performed without personnel present. In these cases, the operator configures an automatic measurement task in R&S®ARGUS.

The automatic measurement mode enables operators to define measurements according to a schedule. They can combine the measurements with limits, events and alarms. When the measured value violates the defined limit, the system triggers an alarm. This can be a message on a computer in the control center or a text message (SMS) sent to the operator's mobile phone. Furthermore, a new measurement can be started for a detailed examination of a frequency that triggered the alarm. It is possible to record the audio and the emission's bearing or to define other events. Operators can evaluate recorded measurement results while the automatic measurement is still running or after it has been completed.

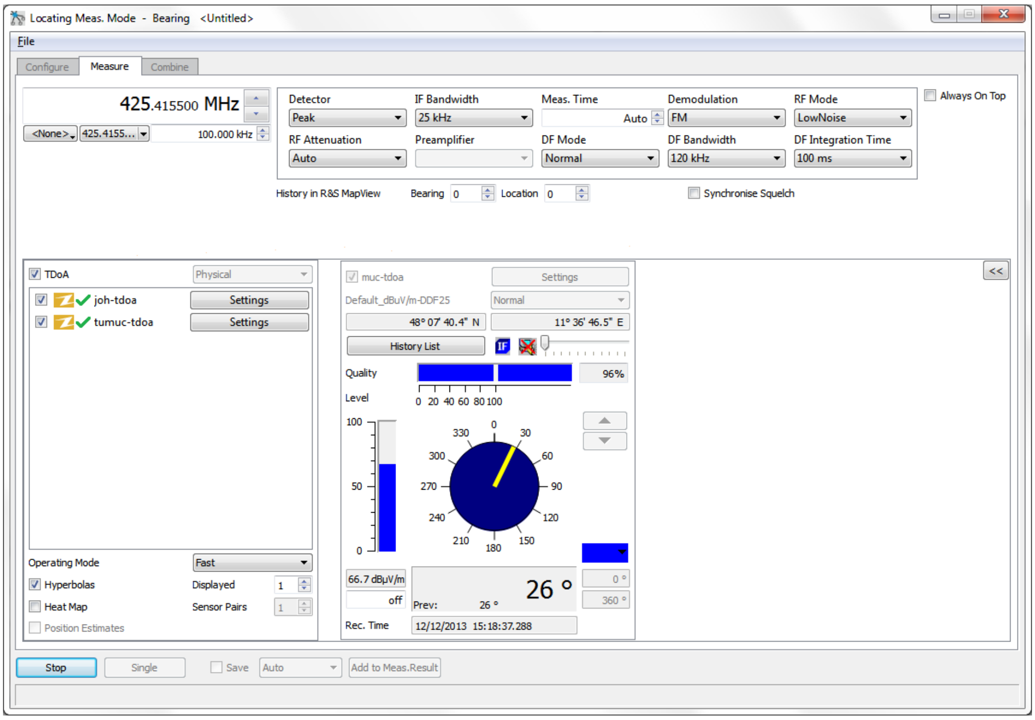

Fig. 14: Efficient hybrid geolocation with R&S®ARGUS location measurement mode.

3.4.2 Geolocation

For geolocating emitters, the system provides extensive functionality. The location measurement mode (LMM) offers AOA and TDOA capabilities, allowing operators to apply the best method for each signal type. Nevertheless, operators can also apply both geolocation methods, AOA and TDOA, in parallel.

The LMM controls up to four direction finders simultaneously. The remote stations operate with the same settings and provide the LOBs for the control center. There, the system displays the direction finder stations, including the location result, on a digital map within the R&S®MapView geographic information software. In order to make sure that all direction finders track the same signal, it is possible to listen to the audio signal of all stations involved. Furthermore, operators may identify the emission with the audio signal and can display the IF spectra from each receiver.

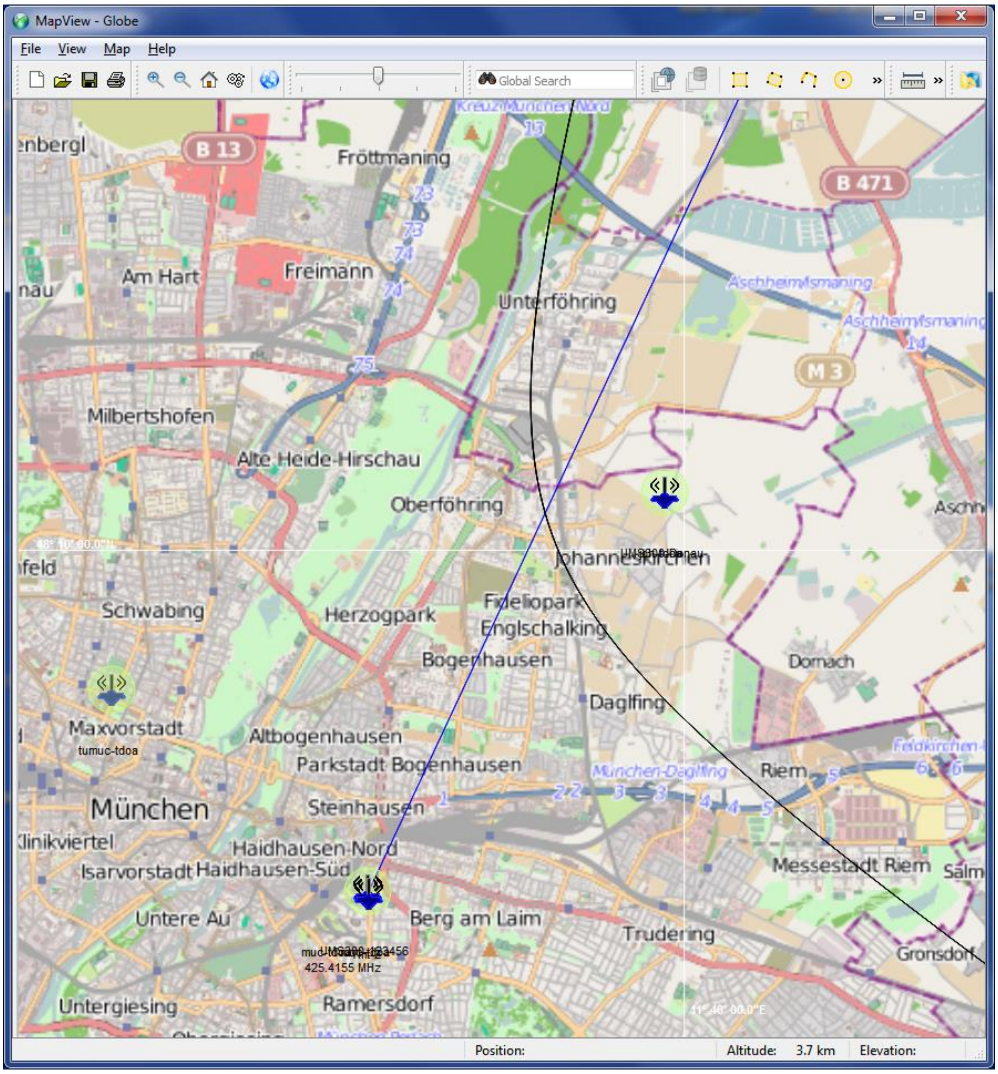

Fig. 15: Two stations provide a hyperbola from a TDOA result, crossing with a LOB.

Within the digital map, operators can select up to ten remote monitoring stations for applying the TDOA method. The system commands the selected receivers, determines the emitter's location and displays the result. It is even possible to utilize both methods – AOA and TDOA – in parallel. Then the system displays all LOBs and hyperbolas.

3.4.3 System Interfaces

As open software, R&S®ARGUS provides several interfaces for different purposes and for integration into various environments. The system uses the TCP/IP protocol and common formats for importing and exporting data. The interfaces for the present configuration include the following capabilities:

The remote control interface (RCI) allows control of the remote monitoring station from headquarters, including all measurement modes.

The web interface (WEB) enables access to the remote monitoring station from any browser-enabled computer within the network.

The Spectrum Management Database Interface (SMDI) imports transmitter data from the spectrum management database in order to verify the licensed parameters. The measurement results can be transferred back to the database.

The order / report module (ORM) is an interface that enables other applications to send orders to R&S®ARGUS and receive results in the form of reports. While planning the spectrum, operators can send measurement orders from their spectrum management system and receive the actual values.

The Data Exchange Interface (DEI) imports frequency lists and exports measurement results and other data in several common formats.

3.4.4 Measurement Evaluation

The R&S®ARGUS EVAL evaluation module calculates statistics according to the ITU's recommendations. The statistical analysis of the measurement results includes the following:

- Frequency band occupancy in line with ITU-R SM.182
- Frequency channel occupancy in line with ITU-R SM.1536
- Measurement value statistics
- Transmission statistics
- Sub-audio tone statistics
- License violation detection

R&S®ARGUS EVAL provides several graphical views for efficient visualization of the evaluated results.

4 System Examples

4.1 TDOA Upgrade of an Existing Spectrum Monitoring System

Upgrading with TDOA technology increases the geolocation performance of an existing spectrum monitoring and direction finding system. Especially in urban areas, where signal reflections are common and emissions are often digital, the TDOA method can significantly contribute to improving the locating accuracy.

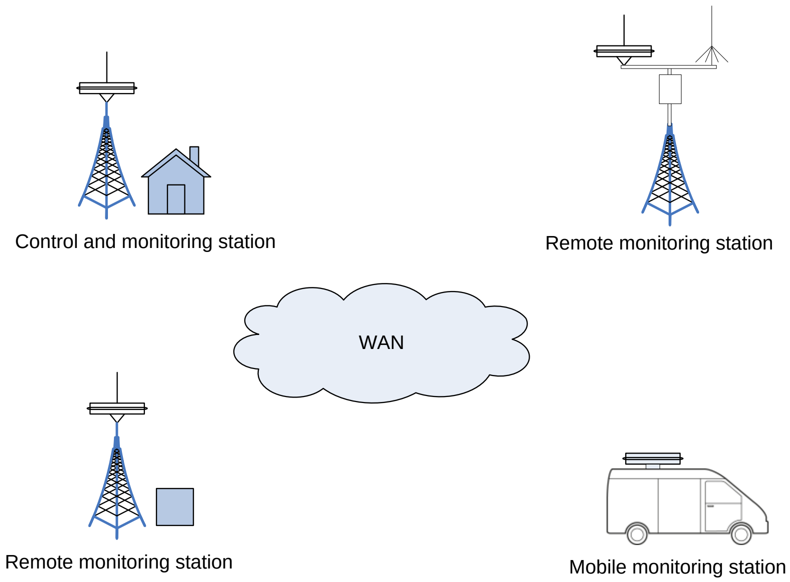

Fig. 16: Example of a small spectrum-monitoring system.

Fixed stations that include the R&S®DDF255 or R&S®DDF205 direction finders or the R&S®UMS300 monitoring and direction finding system need an upgrade in order to be able to perform hybrid geolocation. Particularly monitoring stations without direction finders stand to benefit from a TDOA upgrade. Stations with the R&S®ESMD, the R&S®EB500 or the R&S®EM100 can thus contribute to the system network's geolocation capabilities.

Although it is not common, it is also possible to upgrade mobile monitoring stations with TDOA capabilities. If connected to the control center via a high-speed data link, the mobile stations can also increase the system's geolocation performance.

4.2 New Spectrum Monitoring System with Hybrid Geolocation Technology

There is much to take into consideration when putting together a new spectrum monitoring system, whether for a certain area or for an entire nationwide system. The ITU Spectrum Monitoring Handbook provides a great deal of information on how to establish the operational and organizational structure, depending on the tasks and the available infrastructure.

The following example presents a possible spectrum monitoring system with hybrid geolocation technology. Such a system network can cover a town or a region. In a common configuration, it comprises the following stations:

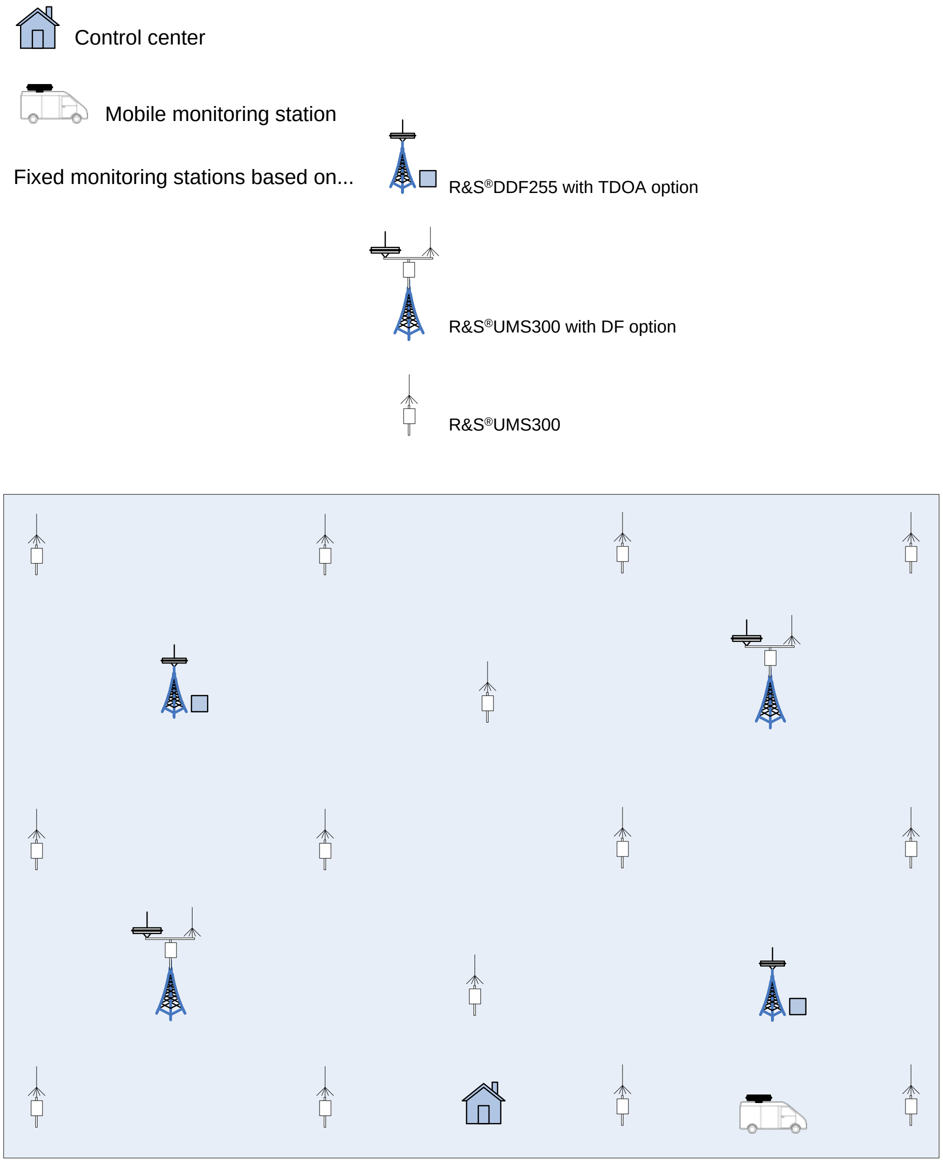

Fig. 17: Schematic example of a hybrid spectrum monitoring system.

TDOA technology provides the best location accuracy when the receivers surround the emitters. Therefore, it is advisable to position the R&S®UMS300 at the boundaries of the area to be monitored. Further receivers are arranged in a manner that allows coverage of the entire area of interest. The receiver stations are positioned at exposed locations. However, ensuring obstacle clearance – which is required for the DF stations – is not necessary for the TDOA method.

The fixed monitoring stations that are equipped with the DF option form a rectangle. Two of them house an operator room; from there, the station can be controlled on demand. The stations can also be controlled remotely, and with the aid of the R&S®DDF255, they offer excellent monitoring and DF capabilities, even in difficult environments with strong emitters nearby. Together with the R&S®UMS300, remotely controlled receivers that are equipped with the DF option, they can even determine the locations of outlying emitters. The tradeoff for the DF's more flexible station arrangement is that the station setup becomes more complex, and there must be a direction finding antenna at the top of a mast to overlook the surrounding area.

The mobile monitoring station is equipped with the compact R&S®DDF205, which allows versatile measurements and direction finding. The vehicle-integrated system can move to any site, and from there, it can take a cross-bearing together with a fixed DF station. It also can detect signals in the vicinity and home in on the signal source. These unique features make the mobile monitoring station indispensable for each monitoring system.

The entire spectrum monitoring network can be interlinked with different data connections, because R&S®ARGUS spectrum monitoring software supports several compression modes as well as automatic offline measurements.

4.3 Summary

Technological requirements and capabilities demand changes in the spectrum monitoring world. Today's technologies make use of advanced signals. These modern signals are increasingly digitally modulated, and their high data rates use larger bandwidths. Together with the availability of simple time synchronization, these trends create an environment that allows application of the TDOA method. Moreover, TDOA's ability to cover the area nearby without high mast makes it attractive in urban areas.

However, TDOA cannot replace conventional geolocation technology. An approach based on direction finders must be applied where TDOA is limited. Since these two methods complement each other, it makes sense to employ a form of spectrum monitoring that takes advantage of hybrid geolocation technology.

New spectrum monitoring systems and sites can be configured with AOA, with TDOA or with hybrid technology. This offers best adaptability to the needs and the environments; it provides highest geolocation accuracy at a minimum number of stations. Also the effort required to upgrade existing stations – with or without direction finders - remains manageable. Furthermore, expanding the system with additional TDOA receivers is uncomplicated and, due to the system's modularity, that step represents an investment in equipment that is ready for the future.

About Rohde & Schwarz

Rohde & Schwarz is an independent group of companies specializing in electronics. It is a leading supplier of solutions in the fields of test and measurement, broadcasting, radiomonitoring and radiolocation, as well as secure communications. Established more than 80 years ago, Rohde & Schwarz has a global presence and a dedicated service network in over 70 countries. Company headquarters are in Munich, Germany.

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