WHY AOA OUTPERFORMS POA IN URBAN INTERFERENCE HUNTING

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CONTENTS

This white paper describes the angle of arrival (AOA) and power of arrival (POA) methods applied to automatic radiolocation of RF interferers from a moving vehicle, comparing their performance with a focus on cellular networks in urban areas.

1 FUNDAMENTALS

In many applications, such as radiolocation of interferers, it is necessary to locate the source of RF emissions based on the measurement of radio wave characteristics. In general, four different radiolocation methods are used:

▶ Angle of arrival (AOA), also known as automatic direction finding or DF
▶ Power of arrival (POA)
▶ Time difference of arrival (TDOA)
▶ Hybrid (combination of two or more of the above methods [1])

POA is sometimes referred to as power difference of arrival (PDOA).

TDOA requires a sensor network surrounding the emitter. Typically, this is not available for interference hunting in practice, so this method is not considered here.

2 WAVE PROPAGATION CONDITIONS

2.1 Propagation environment

The majority of problems associated with RF interference occur in urban areas and in most cases, the direct path between emitter and receiver is obscured by buildings. This situation is referred to as non-line of sight (NLOS) conditions. Moreover, reflected, diffracted and scattered waves from various directions arrive at the receiving antenna; this is known as multipath propagation.

Radiolocation of interferers in cellular networks occurs mostly at frequencies between 600 MHz and 6 GHz, i.e. the wavelength ranges between approximately 50 cm and 5 cm.

This is why virtually all buildings in the path between emitter and receiver block or reflect the radio waves more or less entirely.

In fact, urban areas are a challenge to every radiolocation method. However, the degree of impairment depends strongly on the specific propagation scenario and differs substantially, as we will see later.

2.2 Average path loss

Both theoretical and measurement based propagation models indicate that the average received signal level decreases logarithmically with distance and depends strongly on the propagation environment (described by the path loss exponent, n), referred to as log-distance path loss [2]. On average, the signal level decreases by $10 \times n$ dB with a distance increase of factor 10, where the value of n depends on the specific propagation environment. The table lists typical path loss exponents observed in urban mobile radio environments and free space for comparison [2].

Path loss exponents for different propagation environments	
Propagation environment	**Path loss exponent, n**
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5

Fig. 1 shows the typical log-distance path loss schematically on a linear distance scale for three different path loss exponents. In close proximity to the emitter, the signal power level drops significantly with small changes in distance. With increasing distance from the emitter, significant changes in distance lead to only small changes in signal power level.

Fig. 1: Log-distance path loss for different path loss exponents
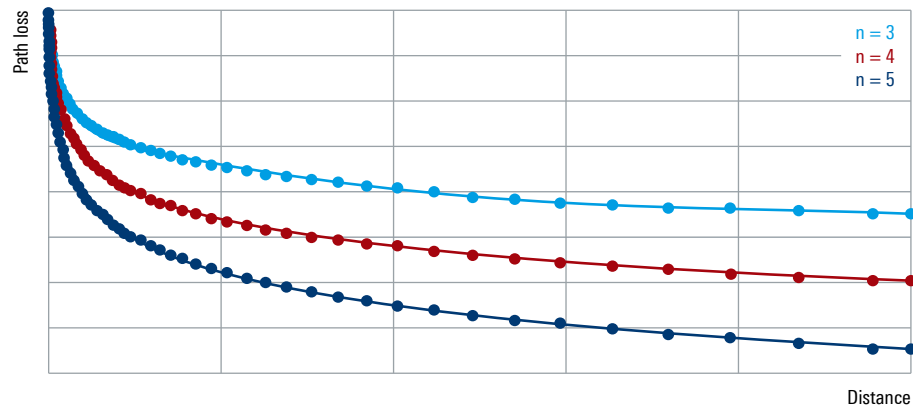

2.3 Fading

The log-distance path loss model does not consider the fact that the surrounding environmental conditions may be vastly different at two different locations having the same distance to the emitter. This leads to significantly different measured signal levels, referred to as fading. In the frequency range discussed here, two types of fading can be observed in particular:
► Fading due to multipath propagation, referred to as fast or multipath-induced fading
► Fading due to shadowing from large obstacles affecting wave propagation, referred to as slow fading or shadowing

Fast fading causes vast changes in signal level varying rapidly with time and distance. It can be compensated by setting a sufficiently high signal level integration time in the monitoring receiver or spectrum analyzer.

Shadowing from large objects such as buildings and hills causes changes in signal level fluctuations over a wider distance. The log-normal distribution describes the random shadowing effects that occur over a large number of measurement locations that have the same emitter-receiver separation but different levels of clutter on the propagation path. This phenomenon is referred to as log-normal shadowing and it implies that signal level fluctuation from shadowing has Gaussian (normal) distribution and a standard deviation that depends on the propagation environment [2]. Fig. 2 illustrates fast and shadow fading.

Fig. 2: Path loss with fast fading and shadowing
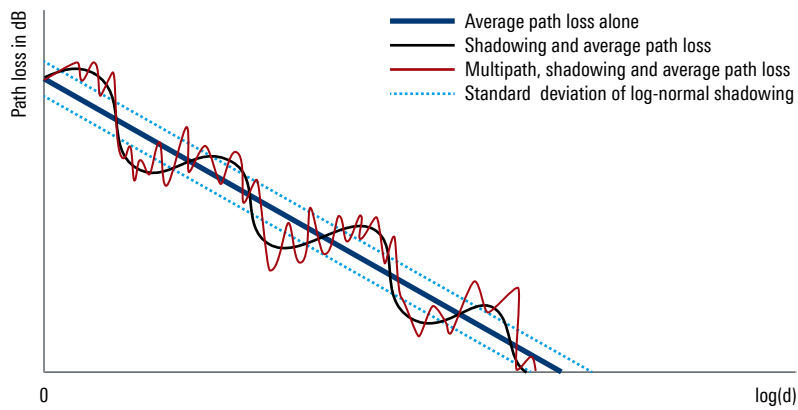
The table below shows the standard deviation σ_s of the log-normal shadowing for different propagation environments.

Standard deviation σ_s for different propagation environments	
Propagation environment	**Standard deviation of log-normal shadowing σ_s**
Urban and suburban, from [6]	approx. 6 dB to 8 dB
Built-up urban, from [2]	approx. 12 dB

2.4 Angular spectrum

Typically, radio direction finders indicate the direction from where the highest amount of RF energy is received. For them, this direction must be biased toward the true direction of the emitter in order to locate it successfully. Non-line of sight and multipath propagation typically found in urban areas raise the question of whether information about the true direction of the emitter is embedded in the wave field at all.

This question is answered by the angular spectrum, which is the angle range from where most of the RF energy is received with respect to the true direction of the emitter averaged across many receiver locations. Both theoretical cluster models (Fig. 8) and measurements in urban areas [3] imply that the angular spectrum is sufficiently narrow to allow radio direction finding, as we will see later.

Fig. 3: Angular spectrum of waves in an urban area
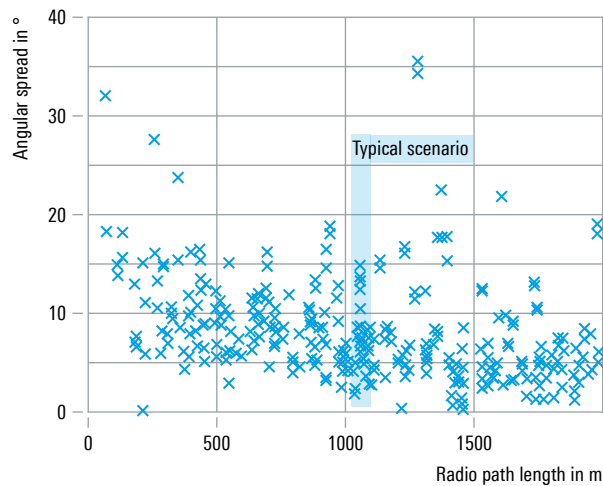
2.5   Propagation scenarios

Line of sight (LOS)

LOS propagation exists when the direct path between emitter and receiver is clear of any obstacles and the amount of RF energy received from any other direction but that of the direct wave is negligible. In practice, a propagation environment is referred to as LOS when the first Fresnel ellipse is free of obstacles.

In urban areas, LOS is rare and happens only if the emitter is very close or located at a position higher than surrounding buildings (e.g. on roof tops), and the receiver is positioned sufficiently free from buildings and other obstacles at the same time.

In this scenario, all RF energy comes solely from the direction of the emitter.

Restricted line of sight (RLOS)

RLOS exists when the direct path between emitter and receiver is relatively clear of obstacles, but the receiver is surrounded by scattering objects such as buildings (Fig. 4). This causes significant levels of RF energy to be received from other directions than that of the direct wave.

In this scenario, the distance d between emitter and receiver is less than the critical distance d_c, as described below.

Fig. 4: RLOS cluster model
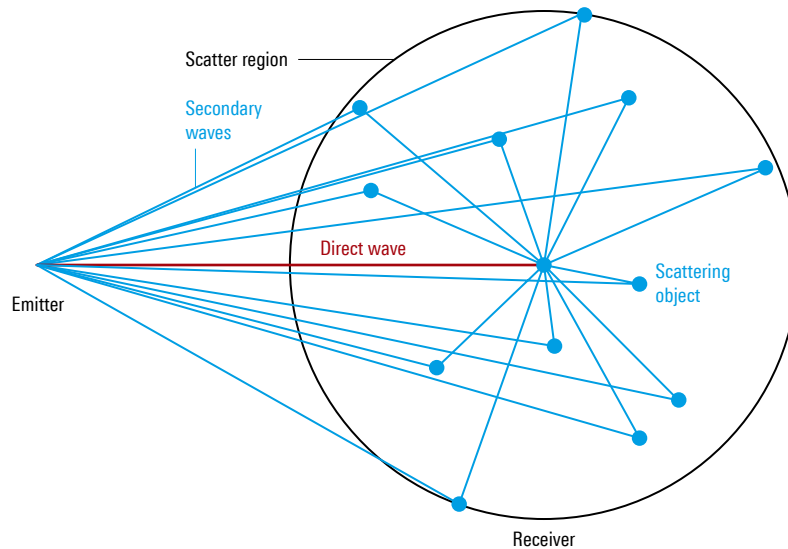
Typically, the RLOS scenario exists when the emitter is located at a position higher than surrounding buildings (Fig. 5) [8]. It is therefore sometimes referred to as over-the-rooftop propagation.

Fig. 5: Position of emitter and scattering objects in the RLOS environment

In the RLOS scenario, the azimuth spread depends substantially on the specific propagation environment and ranges from 0° to 30° (Fig. 6) [8]. This means that most of the RF energy comes from a narrow angular sector.

Fig. 6: Angular spread in the RLOS environment

Non line of sight (NLOS)

In the NLOS scenario, both emitter and receiver are surrounded by scattering objects such as buildings and the direct path is blocked entirely. Substantial levels of RF energy arrive at the receiver from other directions than that of the emitter.
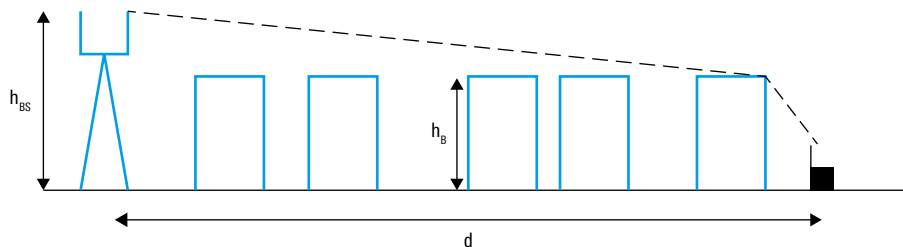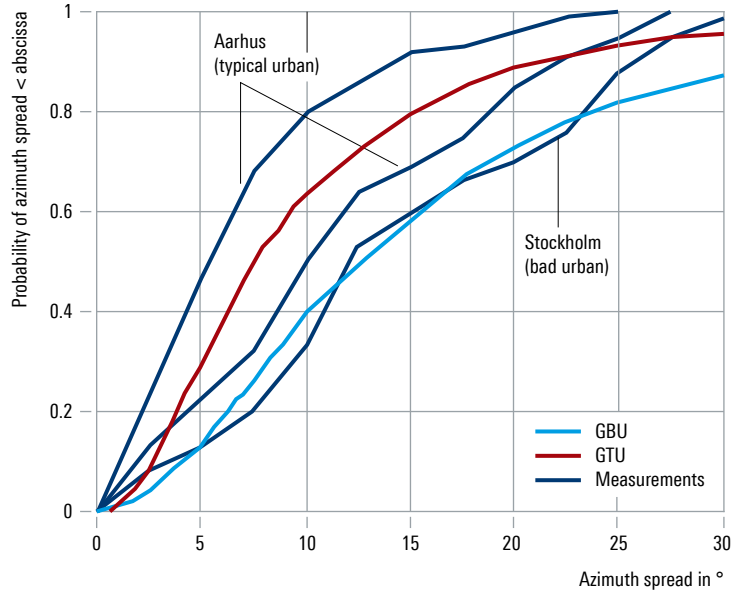
In this scenario, the distance d between emitter and receiver is less than the critical distance d_c, as described below.

Typically, NLOS exists when both emitter and receiver are located on ground level (Fig. 7).

Fig. 7: Position of emitter and scattering objects in NLOS environments
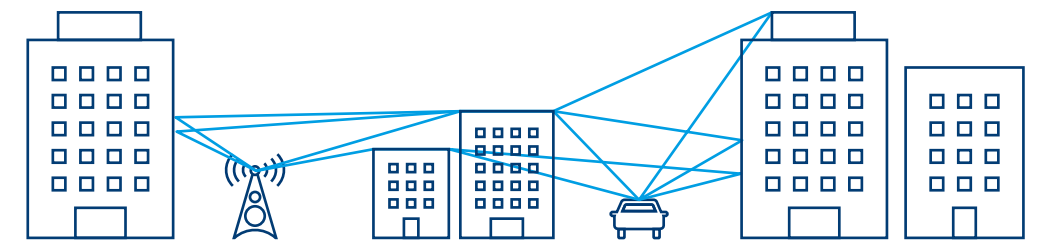
Fig. 8 shows a typical cluster model for this scenario. The scatter region includes all scattering objects that contribute significantly. The distance between emitter and receiver, the diameter of the scatter regions as well as the number of scattering objects depend on the propagation environment.

Main waves, reflected from scattering objects in the vicinity of the emitter, arrive at the receiver within a sector. Secondary waves, reflected from scattering objects in the vicinity of the receiver, essentially arrive from all directions randomly. This indicates that the angle from which most of the RF energy arrives at the receiver is biased on average toward the true direction of the emitter.

Fig. 8: NLOS cluster model
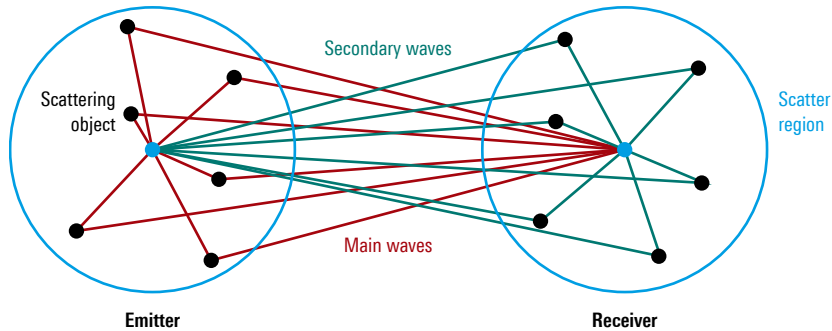
RLOS/NLOS beyond the critical distance
In this scenario, the separation between emitter and receiver is so large that distant-dependent signal level changes from path loss are equal to level fluctuations due to shadowing. Beyond this critical distance, the signal level measured over a specific observation distance changes independently of the distance to the emitter.

Consequently, the critical distance d_c can be defined as the maximum distance beyond which a further increase by the observation distance d_0 causes a decrease in signal level from log-distance path loss, which equals the standard deviation σ_s of the log-normal shadowing (Fig. 9), depending on the propagation environment.

Fig. 9: Path loss/fading model with observation distance and critical distance
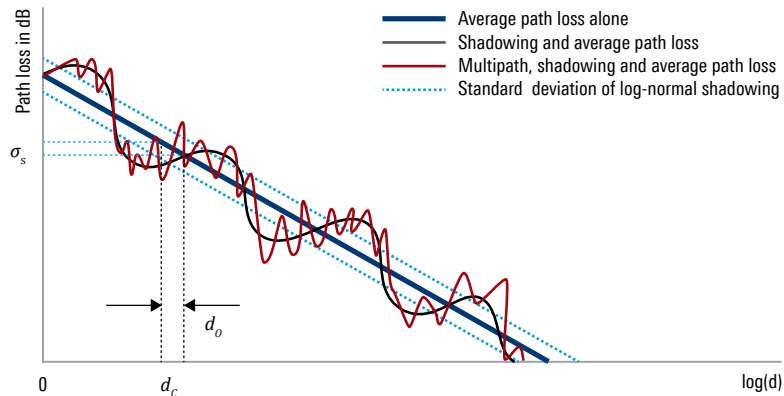
The critical distance is expressed as:

$$d_c = \frac{d_O}{10^{\left(\frac{\sigma_s}{10n}\right)} - 1}$$

where d_O is the observation distance, σ_s in dB is the standard deviation of the log-normal shadowing and n is the path loss exponent. The next table shows the critical distance for different propagation environments.

Practical meaning of the observation distance d_O: While driving in urban areas, the user typically encounters intersections every few hundred meters. In order to change the driving direction at the next intersection, the user needs a reliable indication or voice prompt about the true direction to the emitter. This requires such information to be embedded in the signal level measured over the last few hundred meters of driving (observation distance d_O). Unfortunately, if the distance to the emitter is larger than the critical distance d_c, the changes in the signal level from average path loss measured over the observation distance d_O are equal to or smaller than the level changes from shadow fading. In other words, it is not clear whether the level changes because the distance to the emitter changes or because the level of clutter on the propagation path changes. Hence, the information is ambiguous and unreliable. This improves only if the operator changes the driving direction towards the emitter by chance.

Critical distance for different propagation environments					
Propagation environment	Urban		Densely populated urban		Highly built-up urban	
Path loss exponent	3		4		5	
Standard deviation of the log-normal shadowing	8 dB		10 dB		12 dB	
Observation distance	100 m	200 m	100 m	200 m	100 m	200 m
Critical distance	118 m	236 m	128 m	256 m	136 m	272 m

3 POA BASED RADIOLOCATION

3.1 Fundamentals of POA

POA is based on measurement and comparison of the signal level received at various measurement locations and on estimation of the emitter location solely based on this level information by means of algorithms.

All algorithms used for POA are based on the following preconditions:
▶ The signal level decreases with distance following the selected log-distance path loss model
▶ The propagation environment fits the selected model and does not change during the mission
▶ The emitter has an omnidirectional horizontal radiation pattern and radiates with constant power
▶ Some algorithms also require information about the effective radiated power

In case one or more of the above preconditions are not met, the radiolocation accuracy and mission time can be impacted.

3.2 Operating principle

POA based radiolocation systems continuously measure and average the signal level received at various locations by an antenna with a circular horizontal antenna pattern, temporarily installed on a vehicle roof. This requires driving through the search area and may be supported by indications and/or voice prompts about recommended changes to the direction of driving. After gathering a sufficient amount of level information, the position of the emitter can be estimated.

3.3 Equipment required

POA is the simplest method available for radiolocation from a moving vehicle. It only requires an omnidirectional antenna together with a global navigation satellite system (GNSS, e.g. GPS) connected to the monitoring receiver or spectrum analyzer. Typically, the antenna unit is installed on the vehicle roof temporarily by means of a magnet mount and includes the GNSS receive antenna.

Processing of the gathered level measurements requires sufficient computing power, typically provided by a commercial tablet PC that also serves as a map display.

3.4 Performance

Performance in different propagation scenarios

The table below shows the performance of POA based radiolocation systems in terms of time required for acquiring reliable information about the direction to the emitter and reliable information about the emitter location.

Performance of POA based radiolocation systems		
Propagation scenario	**Performance**	**Rating**
LOS	The received signal level strictly follows the log-distance path loss model, which is why POA based radiolocation is fast and accurate. In contrast to AOA, POA requires taking signal level measurements at several locations in order to give a first estimation about the direction of the emitter.	+
RLOS ($d < d_c$)	In this scenario, the signal level fluctuates from slow fading. This creates local areas with higher field strength, which may be confused with the location of the emitter. This ambiguity can only be resolved by increasing the number of measurement locations and by using a handheld directional antenna.	○
NLOS ($d < d_c$)	In this scenario, the signal level fluctuates vastly and independently of the distance to the emitter due to shadowing from buildings. Since the signal level information is ambiguous, the accuracy of POA based systems is very limited and suggestions given to change the direction of driving are essentially random. This ambiguity can only be resolved by increasing the number of measurement locations and by using a handheld directional antenna.	–
RLOS/NLOS ($d > d_c$)	In this scenario, signal level changes are essentially independent of the distance to the emitter, and fluctuation due to log-normal shadowing may be confused with significant changes in distance. Since the signal level information becomes ambiguous, the accuracy of POA based systems is poor and suggestions given to change the direction of driving are essentially random. The findings in the "RLOS/NLOS beyond the critical distance" section (page 8) suggest that the critical distance is only a few hundred meters in urban areas.	–

Immunity to transmit antenna pattern irregularities

In general, algorithms used for POA work under the assumption that the emitter of interest has a circular horizontal radiation pattern, sometimes referred to as omnidirectional. Typically, this is not the case in practice. Some sources of interference inhibit directional antennas such as bidirectional amplifiers (BDA) or base station antennas. In addition, large buildings in close proximity to the emitter block large sectors and create horizontal power distributions that are strongly dependent on direction.

Immunity to signal modulation and bandwidth

In principle, POA based radiolocation systems manage all signal modulation types, including CW and complex higher-order digital modulation, independent of bandwidth [4].

However, changes in amplitude over minutes resulting from variation in power level radiated by the emitter may affect operation time and radiolocation accuracy.

Immunity to changes in the propagation environment

In general, POA algorithms are based on a path loss model with a specific path loss exponent manually set in the software. As described in the "Average path loss" section (page 3), changes in the receiver surroundings during the drive, such as the size of the buildings and their distance, require the path loss exponent to be adjusted accordingly in order to maintain the same radiolocation accuracy. In practice, the operator changes the respective setting in the software dynamically by observing the area for changes in the propagation environment.

4 AOA BASED RADIOLOCATION

4.1 Fundamentals of AOA

Automatic direction finders estimate the direction to an emitter by measuring and evaluating electromagnetic field parameters. The generated results are called bearings, sometimes referred to as lines of bearing (LOB). Direction finders take spatial and temporal samples from the wavefront and apply digital signal processing according to the selected DF method. Typically, a bearing result takes only a few milliseconds.

Several DF methods are known, such as the Watson-Watt, Doppler and interferometer DF methods. The correlative interferometer DF method is the most popular method used today in the VHF/UHF/SHF range. It is based on measurement of phase angle differences between multiple antenna elements, typically arranged in a circular antenna array.

The basic principle of the correlative interferometer involves comparing the measured phase differences with the phase differences obtained for a DF antenna system of known configuration at a known wave angle.

Only in the case of undisturbed wave propagation is the direction to the emitter identical with the direction of incidence of the radio waves received at the DF antenna. Although this is not the case in urban areas, information about the true direction to the emitter is embedded in the wave field, as described in the "Wave propagation conditions" section (page 3).

Real measurements in urban areas support the findings in the "Wave propagation conditions" section (page 3). Fig. 10 shows a histogram computed from thousands of bearings gathered during a test drive with a mobile direction finder in Munich, Germany. The majority of bearings point roughly toward the emitter.

Fig. 10: Bearing error histogram in shadowed urban propagation environment
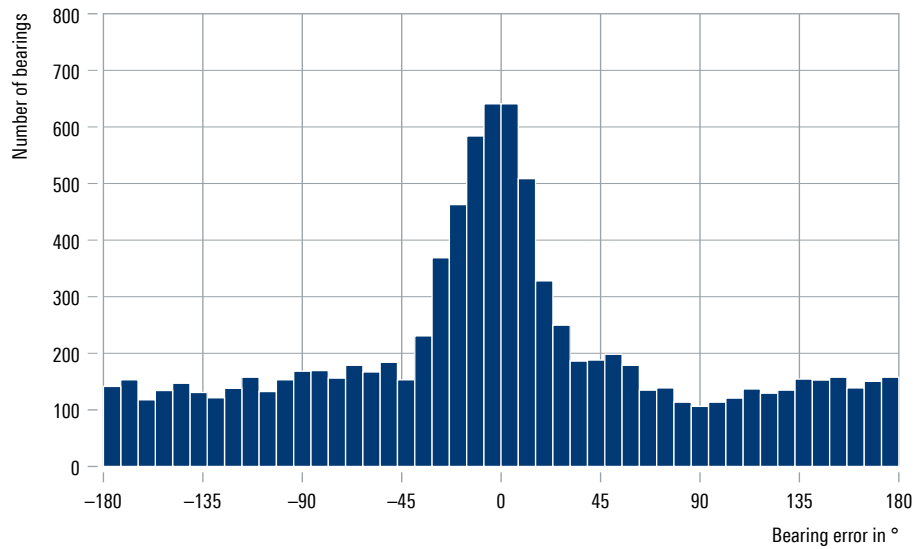

Some DF methods including the correlative interferometer allow calculation of both azimuth and elevation angle of arrival, thus allowing a rough indication of the height of the emitter. In the case of an emitter located inside a building, this information can be used to decide at which floor to start further investigations.

4.2   Operating principle

In general, AOA based systems provide three different methods to locate emitters, as shown in Fig. 11.

Fig. 11: Radiolocation methods based on AOA

Triangulation   **Homing**   **Running fix**
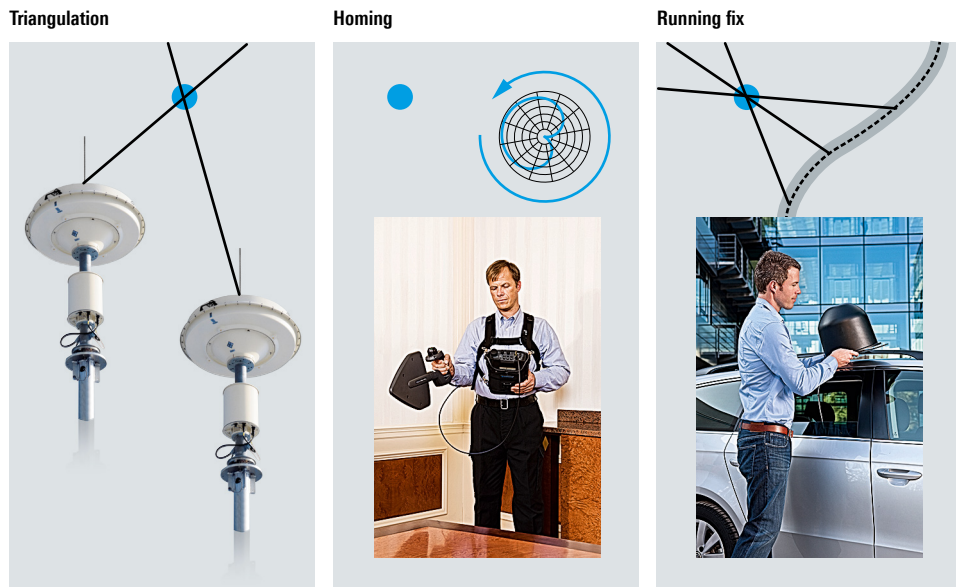
Triangulation requires a network of two or more temporarily or permanently fixed DF stations. Typically, this is not available for interference hunting in practice. For this reason, this method is not considered here further.

Homing is based on manual direction finding, typically by means of a handheld directional antenna. This is the most popular method applied to interference hunting. However, this method is very sensitive to multipath propagation. Since this white paper focuses on automatic radiolocation methods, homing is not considered here further.

The method used for radiolocation of interferers from a moving vehicle is called a running fix. It combines bearings of the same emission from different locations for offline triangulation.

DF results in urban areas are often inaccurate and fluctuate heavily due to multipath propagation. While most of the DF results point roughly to the emitter as described in the "Fundamentals of AOA" section (page 11), it is a challenge for most operators to manually filter out in their mind all the wild bearings.

Recently available running-fix software applies sophisticated algorithms to automatically locate the source of emission, based on thousands of DF results from different locations typically generated during a mission. This software plays a substantial role in achieving geolocation accuracy.

4.3   Equipment required

Radiolocation by means of AOA requires a more complex receive antenna as compared with POA. Antenna systems required for automatic direction finding consist of multiple antenna elements, RF switches, amplifiers, couplers and a microcontroller, as well as a GNSS receiver. Design, manufacture and final testing of DF antennas are significantly more complex and time-consuming as compared with omnidirectional antennas.

Typically, the DF antenna is installed temporarily on the roof of a vehicle by means of a magnet mount. In contrast to POA based systems, AOA based systems require the DF antenna to be properly aligned with the vehicle axis.

Processing of hundreds of DF results per minute by automatic running-fix software requires sufficient computing power, typically provided by a commercial tablet PC that also serves as map display.

4.4 Performance

Performance in different propagation scenarios

The table below shows the performance of AOA based radiolocation systems in terms of time required for acquiring reliable information about the direction to the emitter and reliable information about the emitter location.

Performance of AOA based radiolocation systems		
Propagation scenario	**Performance**	**Rating**
LOS	In this scenario, AOA based systems can display the direction to an emitter instantly from a single measurement location, limited only by the operational DF accuracy of the mobile DF system. Mobile automatic direction finders typically feature an operational DF accuracy of 3° RMS in the frequency range considered here, taking into account the vehicle's influence in an otherwise reflection-free environment [5]. The radiolocation accuracy also depends on the relative position between emitter and receiver. However, in this scenario, AOA based systems can accurately locate emitters comparably fast.	++
RLOS ($d < d_c$)	In this scenario, most of the RF energy is received on average from the direction of the emitter. This makes it possible to estimate the emitter location with good speed and accuracy.	+
NLOS ($d < d_c$)	In this scenario, substantial levels of RF energy arrive at the receiver from other directions than that of the emitter. Nevertheless, information about the emitter location is contained in the phase information embedded in the wave field, as implied by the cluster model (Fig. 7). Radiolocation by means of AOA is thus possible, but the percentage of accurate bearings is significantly lower as compared with all other scenarios considered here. Consequently, more time is required to obtain accurate direction and geolocation information.	○
RLOS/NLOS ($d > d_c$)	The accuracy of automatic direction finders is not affected by the distance to the emitter, as long as enough signal energy is received to provide 6 dB signal-to-noise ratio. Radiolocation accuracy of AOA based systems decreases with distance since the bearing error translates into a position error that increases with distance. However, a reliable estimation of the direction to the emitter can still be displayed quickly.	+

Immunity to transmit antenna pattern irregularities

The performance of AOA based radiolocation systems is essentially independent of irregularities in the radiation pattern of the emitter.

Immunity to signal modulation and bandwidth

The ability of AOA based radiolocation systems to manage different signal modulation types depends on the applied DF method. Interferometer DF systems manage all modulation types, including CW and complex higher-order digital modulation, independent of bandwidth [7].

AOA based systems are immune to gradual changes in power level radiated by the emitter.

Immunity to changes in the propagation environment

The AOA radiolocation method does not require path loss models. Therefore, it is not affected by changes in the propagation environment.

5 SUMMARY

The table below shows the differences between the two radiolocation methods compared here with respect to interference hunting in cellular networks within urban areas from a moving vehicle.

Performance comparison for AOA (interferometer based) and POA			
Parameter	Propagation scenario	AOA	POA
Performance in terms of time required for: ▶ Reliable information about the direction to the emitter ▶ Reliable information about the emitter location	LOS RLOS ($d < d_c$) NLOS ($d < d_c$) RLOS/NLOS ($d > d_c$)	++ + ○ +	+ ○ − −
Immunity to transmit antenna pattern irregularities	independent of propagation scenario	+	−
Immunity to signal modulation and bandwidth	independent of propagation scenario	+	+
Immunity to changes in the propagation environment	independent of propagation scenario	+	−
Receive antenna	independent of propagation scenario	multi-element DF antenna	single omnidirectional antenna

AOA outperforms POA in urban interference hunting in all propagation environments considered here. In addition, AOA is more robust against external influences such as irregular transmit antenna patterns and changes in the wave propagation environment.

Rohde & Schwarz offers various products for AOA based radiolocation, for example the R&S®MNT100 RF interference locator, R&S®DDF007 portable direction finder and R&S®PR200 portable monitoring receiver.

6 REFERENCES

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