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Rounded-edge bow-tie antenna for wideband mobile direction finding system

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Abstract: A novel relatively small wideband antenna is introduced for the mobile application of direction finding (DF) systems covering the frequency range from 150 MHz to 3 GHz. The proposed directional wideband antenna is a rounded-edge directed bow-tie antenna which is electrically small when considering at lower operating frequencies. A good agreement is obtained between the simulation and measurement results of the designed antenna. The performance of the antenna for DF applications is verified both in anechoic chamber measurements and in open field measurements. In addition, in open field DF measurements the proposed antenna is compared with a commercial antenna. During the tests, one of the angle of arrival estimation technique based on phase differences of the signal at the antenna elements, interferometer method, and combination of the phase differences and amplitude values of the captured signal were used. As well as, *k*-means clustering used to reduce undesired error due to environmental effects.

1 Introduction

Direction finding (DF) can be defined as determination the location of unknown radio transmission sources. Mobile DF systems frequently have been used in military to detect locations of the enemy or ally by their radio frequency communications as well as for civilian applications such as wildlife tracking, finding unauthorised transmitter and detecting shadow zones of wireless services [1–4].

Size, weight and shape of the antenna with preserving the performance of the system are becoming more important in designing wideband mobile DF systems. A DF antenna system is an array antenna consists of usually an odd number of multiple antenna elements in a circular form. Generally, omnidirectional antennas such as dipole, monopole and bi-conical antennas [5–8] have been used as a DF antenna element. However, these antennas cannot be used over a wideband frequency range [9, 10].

The direction of the target source with respect to mobile DF system position is defined as the angle of arrival (AoA). AoA estimation algorithms use voltage values induced at the array antennas. The circular arrangement of DF antenna array makes possible to use both amplitude and phase information at the single antenna elements by AoA estimation algorithms. Most DF systems have been using correlative interferometer technique to estimate AoA. This method determines the angle of incidence signal by directly measuring the phase difference of the wave by sampling the incidence signal with elements of a DF antenna array [11–13].

In this research, we propose a relatively small novel wide band antenna as a single antenna element of a DF array which is integrated onto a vehicle-mounted mobile DF system operating over a frequency range between 150–3.000 MHz. The focus of this paper is to introduce the proposed antenna for a DF application rather than a new DF algorithm. The adequateness of the proposed antenna for a mobile DF system is verified both in an anechoic chamber and in open field by using of phase differences of the signal at the antenna elements, interferometer method, and combination of the phase differences and amplitude values of the captured signals. In addition the performance of the proposed antenna is also compared under the same conditions with a commercial antenna which is widely used for DF applications.

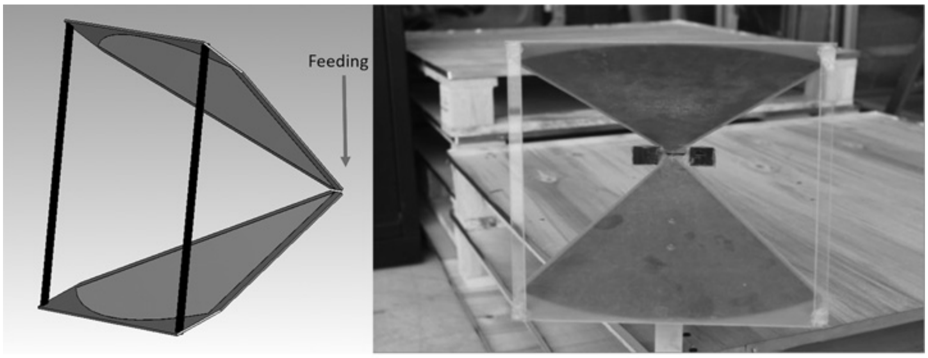
2 Single DF antenna element

To make the antenna array suitable for a vehicle mounted system with wideband frequency coverage, we propose a directed rounded-edge bow-tie (DREBT) antenna [14–16]. The choice for a rounded edge design of the bow-tie radiator is based on our previous study [17] which performs better for DF application. The DREBT antenna has two identical arms that look such as a bow-tie antenna with rounded edge bended with a certain angle for directional propagation. The simulated and realised antenna is depicted in Fig. 1.

Due to simple production process and light weight issues the DREBT antenna is printed on FR4 substrate ($\varepsilon_r = 4.4$, thickness = 1.6 mm). During the modelling several parameter sweeps have been performed such as the length of the arm, flare angle of the arm and the number of antennas in DF antenna array to obtain the optimum design parameters. Distance between antennas from each other's at the DF array must be considered to obtain the flare angle of the antenna. Moreover, mutual coupling of the antennas is one of the other parameter for flare angle [18]. Since higher flare angle decreases the directivity while lower flare angle reduces the band width a trade-off is found at 60° for flare angle. The optimum length of each arm is obtained at 25 cm for a port gap of 1 mm. To obtain a rigid construction the DREBT antenna is supported with plastic rods between the arms on front side and fixed with plastic supports on the feeding side. The antenna is fed at the port to each arm with a balun circuit which contains an impedance ratio of 1:1.

It is well known that the number of the antenna elements in the array must be odd and consist of minimum five antennas for accuracy reasons [19, 20]. To be able to mount on top of a vehicle the whole array radius is restricted to a maximum of 60 cm. The compact size and the performance of the proposed DREBT antenna allowed us to select nine antenna elements to obtain good accuracy of the DF performance taking into account the constraint of 60 cm radius of the circular array.

The realised antenna measurements were performed with Anritsu MS2037C portable network and spectrum analyser. The comparison between the measurement and simulation S_{11} results obtained with both CST Microwave Studio and Ansoft HFSS commercial simulation tools are shown in Fig. 2. A good agreement is obtained for both simulations and measurement up to 2.3 GHz while a small discrepancy occurs between the simulated and measured results in



a *b*

Fig. 1 *DREBT antenna*

a Simulated antenna
b Realised antenna

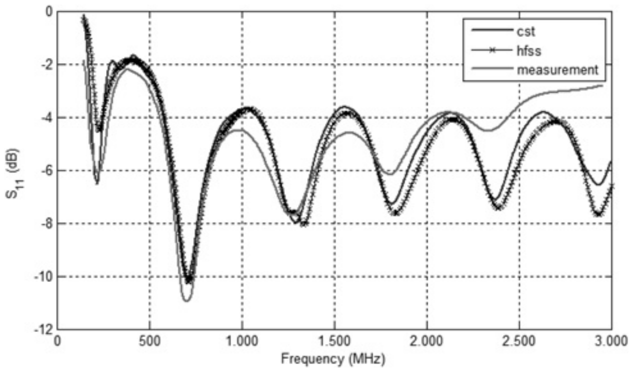


Fig. 2 *S_{11} values of the DREBT antenna*

2.3–3 GHz region probably due to the plastic supports at the feeding side of the fabricated antennas. It can be argued that the obtained S_{11} values are slightly worse than typical commercial DF antennas, however, these antennas generally consist of two or more different type of antennas to cover the whole frequency range of interest (e.g. Poynting DF-A0029). Since we use the antennas only in receiving mode we have to express that these return loss values at the frequency band of 150–3.000 MHz with a compact single antenna is satisfactory for a DF system. Despite the fact that a poor impedance matching reduces the captured signals amplitude the noise floor of the receiver is good enough to detect DF application range of interest. The received power level is still acceptable at low frequencies since the path loss between target source and DF system is substantially less at low frequencies than high frequencies. To improve the impedance matching over the frequency range a matching circuit can be designed by means of capacitors, inductors or PIN diodes (e.g. multi stub tuning) whereas better amplitude values will be shadowed by problems which can arise for the phase of the received signals.

Directivity of the antenna is compared with electromagnetic simulation programs CST Microwave Studio and Ansoft HFSS and depicted at different frequencies in Fig. 3. It is notable to mention that the DREBT antenna directivity increases at higher frequencies. We depict the directivity to show that the amplitude of the received signal can be used in algorithm to obtain a better DF accuracy. The radiation efficiency at 500 MHz is about 97% while with the increase in frequency is reduces to 69% at 3 GHz. Actually such a decrease in realised gain do not have remarkable effect on the practical DF applications.

3 System model

A DF system depicted with its essential components in Fig. 4 consists of an antenna array, a receiving system, a DF processor and a display [21, 22]. Antenna array serves to collect energy from the arriving signal to be used for the determination of AoA. A receiving system can be one to (n) channels synchronous receiver. Because of the expanses of increased number of channels, we used two channels receiver that have analog-to-digital converters. DF processor is a controller that can be a computer which runs AoA algorithm. Display is a screen that simply shows calculated AoA.

As mentioned early, in many applications the array is generally in circular form with omni-directional antennas [23]. Since the single antenna element that we have developed is a directional antenna there is a need for an omni-directional reference antenna to serve for the detection of interested signal. If the frequency of the target signal source is known, reference antenna is not needed. However, in realty interested frequencies is also unknown and, it has to be found by searching the spectrum of doubted frequencies interval. It's important that the reference antenna should be an omni-directional antenna to catch the same signal strength for all possible positions of the target signal source. We did use a bi-conical antenna operating at the interested frequency band as a reference antenna [24–26]. The antenna array configuration of the mobile DF system is depicted in Fig. 5. The number of DF array antenna is chosen 9 due to the physical limitations.

4 AoA estimation techniques

One of the widely used technique is the correlative interferometer which uses phase differences between captured incident signals from neighbouring antennas to compute AoA. The real condition of the travelling signal from transmitter to antennas is shown in Fig. 6*a*. If the transmitter is sufficiently far away, we can assume that d1 and d2 are parallel to each other as shown in Fig. 6*b*.

Phase difference, $\Delta\Phi$, is mapped from AoA for antenna separation a and incident wavelength λ by

$$\Delta\Phi = (2\pi a/\lambda)\sin\theta \qquad (1)$$

The AoA, θ, can be calculated from (1) as:

$$\theta = \sin^{-1}(\Delta\Phi\lambda/2\pi a) \qquad (2)$$

The distance between receiving antennas a, in DF antenna array must be chosen carefully. For an unambiguous AoA estimation, a should be smaller than the half wavelength of the highest frequency of the incident wave if not multiple AoA's can produce the same phase difference in multiples of 2π. On the other hand, smaller antenna distances a decreases the phase resolution for the lower frequencies and increase AoA errors [27–29].

The AoA is computed using correlative interferometer algorithm in computation process as shown in Fig. 7. First, lookup table is

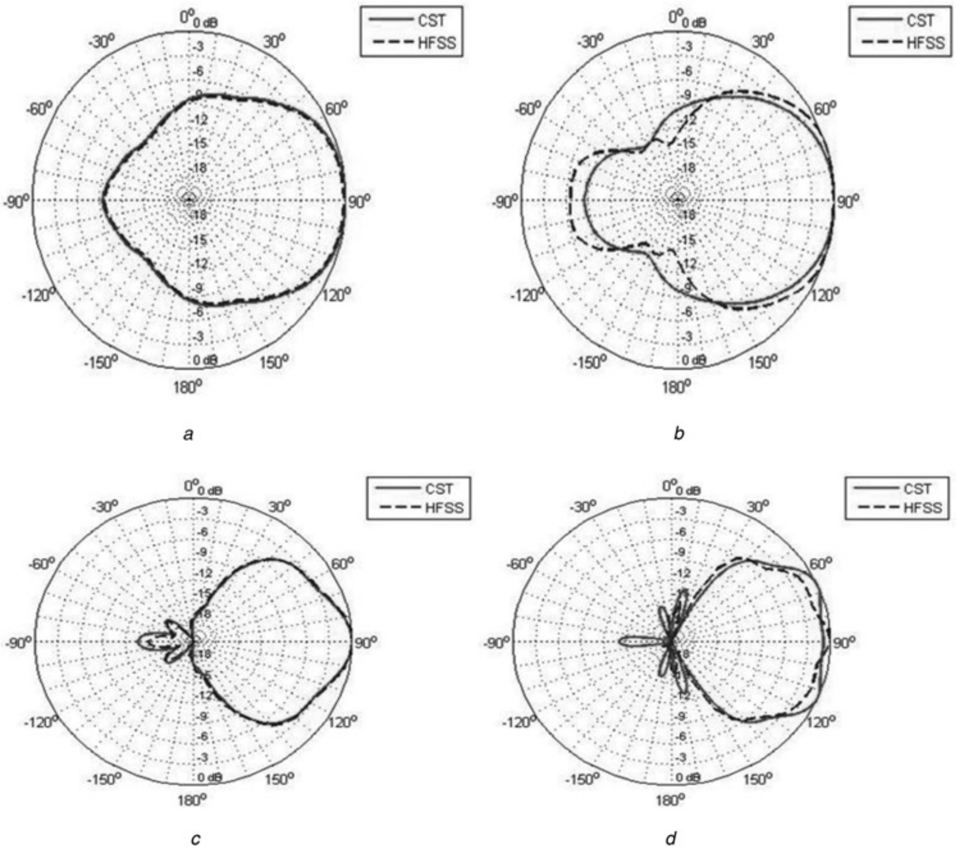


Fig. 3 *Directivity of the DREBT antenna at φ = 90° for*

a 500 MHz
b 1 GHz
c 2 GHz
d 3 GHz

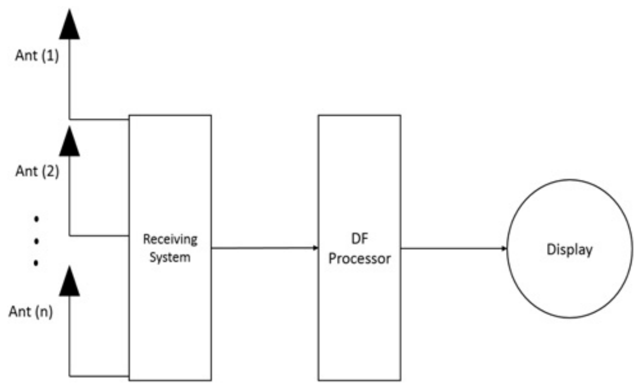


Fig. 4 *Essential components of a DF system*

constructed with known configuration for all wave angles and frequencies. Then, the voltage vectors at the antennas are detected from the obtained digitised signal. The voltage vector is correlated with lookup table to find AoA [30, 31].

In addition to the correlative interferometer technique, amplitude of the incident signal is considered to calculate AoA. First, the direction of the maximum amplitude value of the signal that occurs at the antennas is found. Then, correlative interferometer operation is taken around at the ±25° of the maximum amplitude. Afterwards, *k*-means clustering, well defined in the literature, is used to minimising the error.

While speaking of DF accuracy, root-mean-square (RMS) error is one of the tools that show us the DF system goodness. RMS of the AoA of DF system is defined as

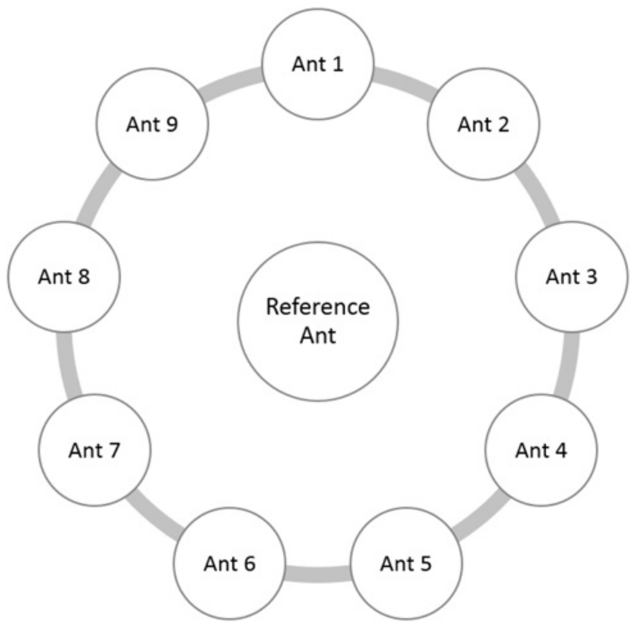


Fig. 5 *Array antenna configuration of a DF system*

$$\mathrm{RMS}_{\mathrm{err}} = \sqrt{\frac{\sum_{i=1}^{n} \left(e_i - e_{\mathrm{A}}\right)^2}{n}} \tag{3}$$

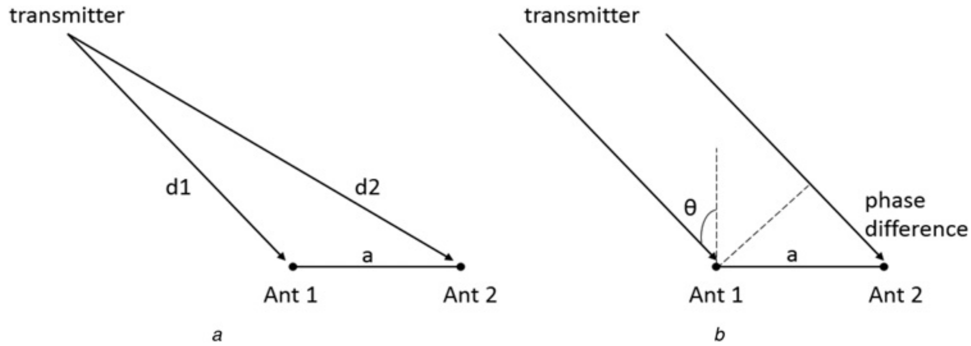


Fig. 6 *Geometry of two antenna phase comparison of a DF system (a) actual state (b) assumed state*
a Actual state
b Assumed state

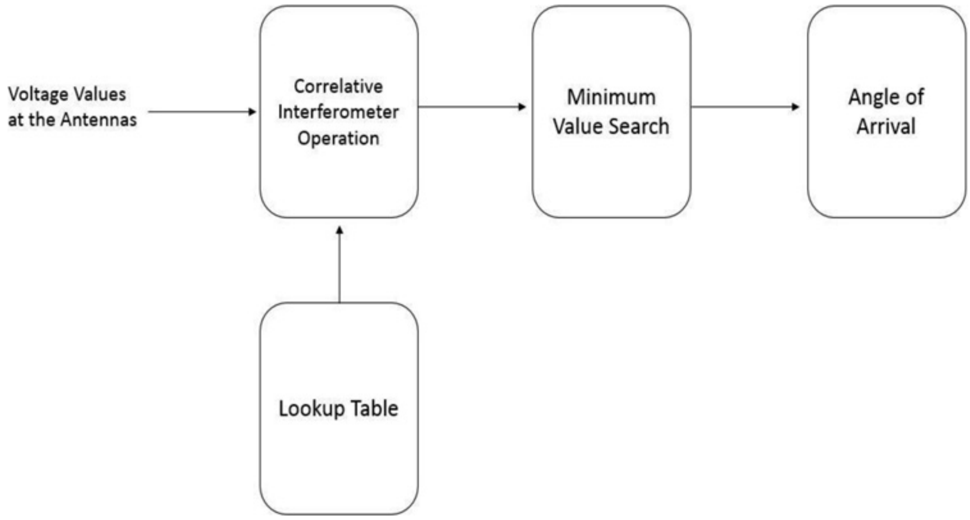


Fig. 7 *Correlative interferometer blog diagram*

where e_i is the error at the ith azimuth angle, n the number of azimuth angles and

$$e_A = \frac{\sum_{i=1}^{n} e_i}{n}$$

is the normalised azimuth angel [32].

For a 300 number of data the calculated AoA's with correlative interferometer results are shown in Fig. 8. Where high errors can be eliminated by using of *k*-means clustering. Example is given for four frequency (430, 750, 1500 and 2500 MHz) while the results for other frequencies are similar.

5 Measurements

Measurement of the mobile DF system with proposed antenna is performed both indoor in an anechoic chamber and outdoor in open field.

First, we evaluated the performance of the DF system with the proposed DRBET antennas by conducting measurements in an anechoic chamber. In the measurement setup shown in Fig. 9*a*, we performed AoA calculations of the DF system under 5, 10 and 15 dB noise. In the anechoic chamber, the turntable was used to turn the DF antenna array between 0° to 359° with 1° incremental steps. After that RMS error calculated from the estimated AoA's for all rotated positions. Commercial bi-conical, log-periodic and horn antennas are used as unknown sources. As can be seen in Fig. 10, we obtained very good results for the whole frequency band covering from 150 MHz to 3 GHz.

Second, we performed outdoor measurements in open field with a mobile DF system mounted on top of a vehicle as shown in Fig. 9*b*. The test fields is about 4 km^2 forestry rough field with including power lines. To have a fair evaluation the system is not only tested for the line of sight but also at different positions including near the power lines, inside the high trees and hills. Diverse test positions were used, for example, unknown signal source was standing among the high trees or bottom of a hill while DF system was not at line of sight to target the source.

In Figs. 11*a–d*, elevation profile of the tests scenarios that are executed from Google Earth program are shown. DF system tests are taken under many test scenarios because of the limitations, some of them are only shown. Distance between two edges, signal source to DF system, is 244 to 1470 m. Altitude is 44 to 119 m.

During test, 20 sample AoA is recorded for all test scenarios. Then, RMS error of the system is calculated. Measurement is taken under 100 MHz frequency step.

As clearly seen in Fig. 12, using *k*-means clustering reduces the DF error. Under 1 GHz, interferometer that is only included phase difference information is working well. As the frequency increases the distance between the antennas is increasing with respect to wave length, for frequencies higher than 1 GHz results obtained by only phase difference calculations is not reliable.

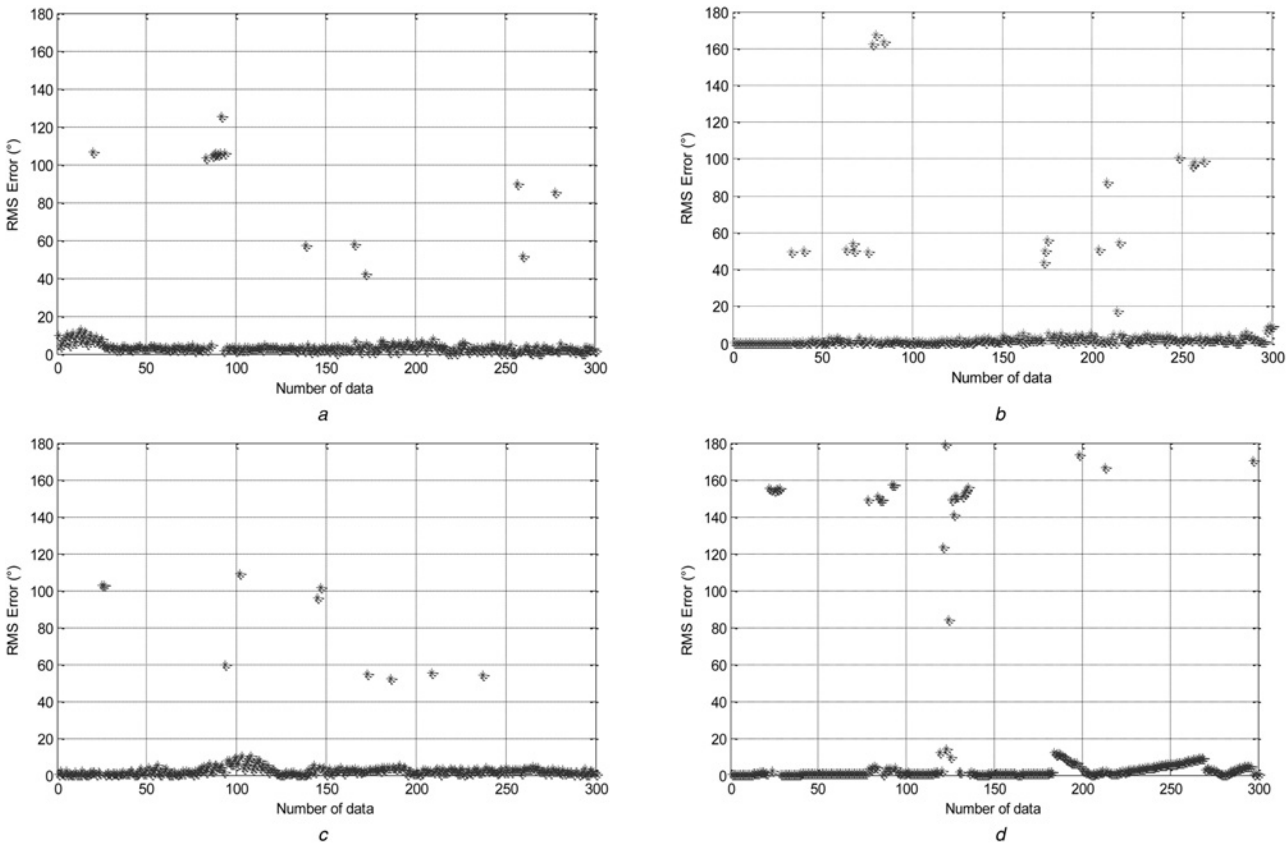


Fig. 8 *Example of calculated AoA's results*

a At 350 MHz
b At 750 MHz
c At 1500 MHz
d At 2500 MHz

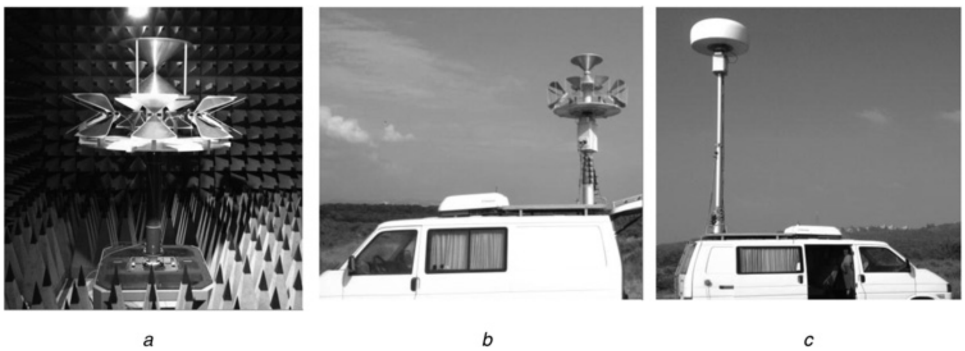


Fig. 9 *DF antenna system*

a In a chamber
b In a field at the top of the vehicle
c DF-A0029 at the top of the vehicle

In final step of measurements, a commercial antenna (DF-A0029) that is claimed to work with interferometer DF algorithm is bought from Poynting Inc. The measurements are performed under the same conditions as the proposed DF array antenna. DF-A0029 antenna covers all tested frequencies with two different array antennas that contain dipole antennas for 150 MHz to 1 GHz and monopole antennas for 1 to 3 GHz. Test results of DF-A0029 antenna and comparison with proposed antenna are shown in Fig. 13. As can be seen the proposed antenna in general performs better than the measured commercial antenna for a DF application.

6 Conclusions

We proposed a compact DREBT antenna as a single element of a DF array antenna operating from 150 MHz to 3 GHz for mobile DF systems. We evaluated the performance of the proposed antenna in a DF system both in an ideal measurement setup in an anechoic chamber and in open fields. The measurements in open field were conducted not only at the line of sights but also at different conditions to obtain a fair evaluation. The results verify that the proposed DREBT antenna is a novel single antenna element for the mobile DF applications especially when considering its size,

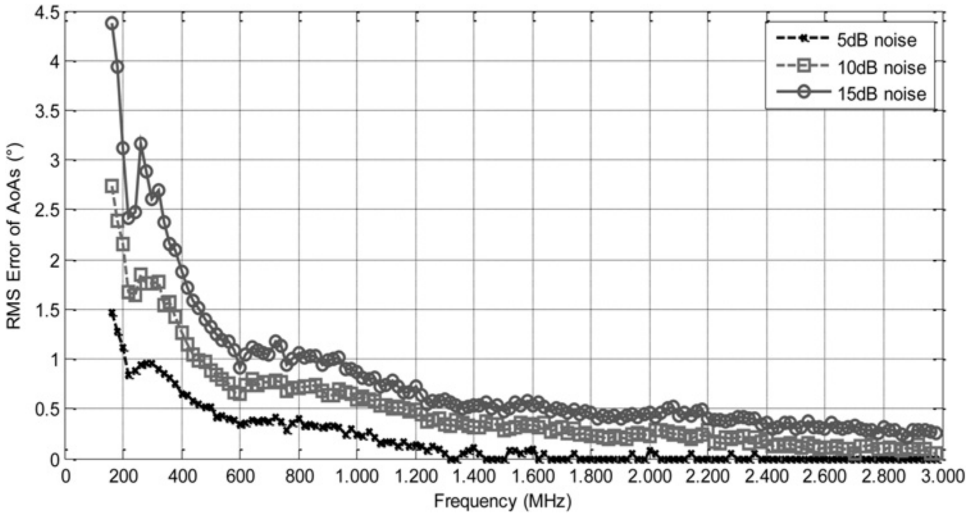


Fig. 10 *RMS DF-Error in a chamber with only interferometer algorithm*

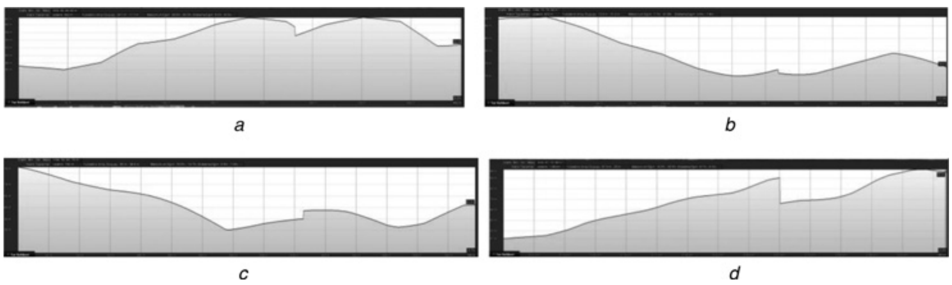


Fig. 11 *DF test scenarios (altitude is defined as highest point to lowest point and distance is between source to DF system)*

a Altitude 62–45 m and distance 452 m
b Altitude 94–70 m and distance 671 m
c Altitude 78–50 m and distance 744 m
d Altitude 96–47 m and distance 1.08 km

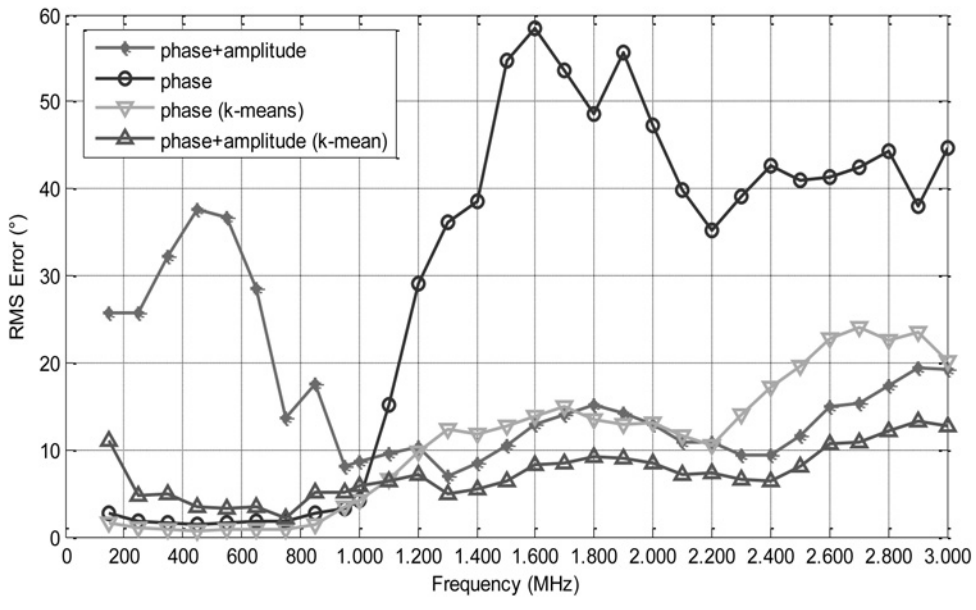


Fig. 12 *RMS DF-Error in outdoor*

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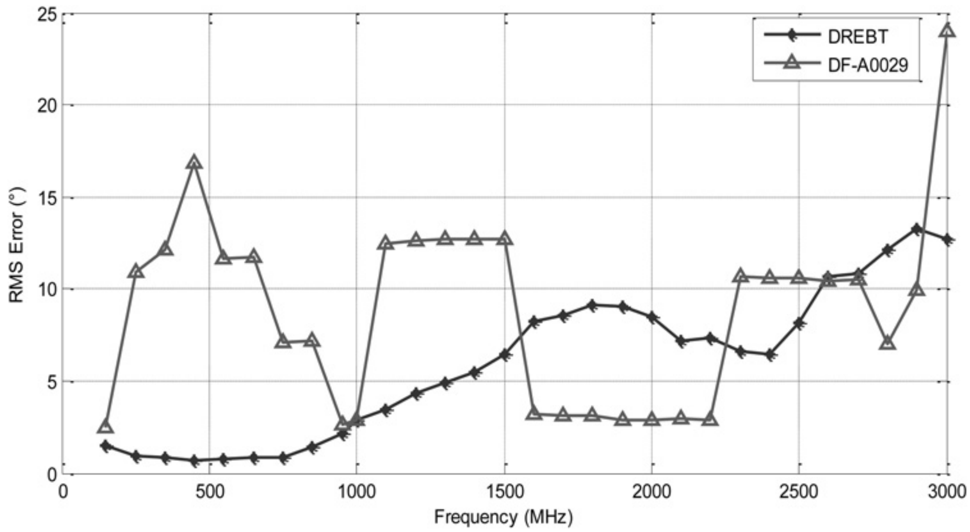

Fig. 13 *RMS DF-Error of Poynting DF-A0029 vs DREBT*

weight and easy manufacturing. Besides, proposed antenna has directional radiation pattern that makes possible to use not only phase comparison estimation methods to calculate AoA. Amplitude based estimation techniques can also be operated on the proposed DF array antenna.

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