The Overall Antenna Bandwidth with an Application to the Improved Study of Radial Discone

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Abstract

Broadband antenna characterization is usually referenced implicitly to SWR bandwidth, which is often reported to have an unrealistically huge value without consideration of any other antenna property. The definition of the Overall Antenna Bandwidth is introduced in order to generalize the broadband characterization to include simultaneous broadband antenna properties - in our classification: field, circuit, or field-circuit - needed in practical situations. As an application, a radial discone antenna, i.e. a radial outline of the well-known broadband discone, was studied computationally, for its broadband operation improvement. Simulation was performed using the [RichWire] program. To adequately serve UHF non-GPS wireless 50 Ohm applications, normal/tight criteria were imposed on appropriate antenna properties for their value variations. The resulted bandwidths of 4:1 for horizontal directivity/power gain greater than –3dB (field), 6:1 for mismatch loss ML greater than –0.5 dB or SWR less than 2 (circuit), and 4:1 for horizontal radiation intensity greater than –3dB (field-circuit), define a simultaneous broadband operation in 800-3000 MHz. Web animations demonstrate the results of the generalized broadband antenna characterization using the definition of the overall antenna bandwidth.

Keywords

Broadband antennas, overall antenna bandwidth, wireless applications, antenna simulation

Introduction

Broadband antennas can be used, among others, in wireless applications where still a large number of bands lie above 800 [MHz] [1], [2], in

UHF. Simple wire (or patch) loaded monopole disc antennas for multi-broadband wireless applications were proposed by Suh et al. in 2003. However, from the just three given radiation patterns concluded that there are low normalized radiation intensity values (band-gap), of the order of –20 to –30 dB, from ~2000 [MHz] to ~2400 [MHz] operating sub-bands [3]. Notably, this behavior of low SWR in connection with high band-gaps is observed in the work of Kim et al. who presented an extraordinary ultra-wide band 100:1 Double Discone Antenna With the Tapered Cylindrical Wires but with radiation intensity band-gaps [4].

Observing the practical deviation between high broadband SWR characteristics and radiation band gaps we unified the circuital and field properties in the broad bandwidth formation of an antenna by introducing the definition of the overall antenna bandwidth. This definition was then applied to design a simple variation of the discone – a radial discone antenna – for wireless applications from copper wire fed by an N-type female connector for operation from 800 to 3000 [MHz] [5], and can be used as a guide.

An extensive investigation has been carried out for the radial discone antenna that covered: 1) the possible cone flare-angles from 15° to 180°, 2) three different values of the gap between the disc and the cone part of the antenna which proved to be a very important parameter and 3) two different values for the disc diameter.

Simulation was based on a suite of developed by us visual tools supported by a fully analyzed, corrected and redeveloped edition of the original thin-wire computer program by J.H. Richmond [6].

Broadband definition

First of all, we downgrade the common, currently in use, definition of "antenna bandwidth", to what it really is, that is as its "SWR-bandwidth" only. Next, in order to form the Overall Bandwidth of an Antenna by taking into account any number N of its frequency dependent properties Q_i, $1 \le i \le N$, we like, we give the following definition of Q-Bandwidth of any Q of these Q_i:

If a frequency dependent antenna property Q is mathematically expressed by a real valued function of frequency f, that is as: $Q = Q(f)$ or by $Q : \mathbb{R}_+ \rightarrow \mathbb{R}$ and we want to get the interval of Q property values $I_Q = [Q, Q'] \subset \mathbb{R}_+$, then the Q-bandwidth Q-BW can be always defined as the set of f frequency values for which the Q has values between Q and Q', or as the inverse image of I_Q by Q: $\text{Q-BW} = Q^{-1}[I_Q]$.

This definition stands for any real quantity, i.e., the norm of a vector function, the dimensionless quantities for example those expressed in dB, for the real or imaginary part of impedance or the magnitude of impedance. It is possible to be used even for complex "quantities", if we combine it with the concept of the circular region in $\mathbb{C}$.

Notably, the theoretically resulting Q-BW set of frequencies may happen to be any subset of $\mathbb{R}$, e.g. a single frequency, a number of frequencies, a finite interval of frequencies, a combination of them, or even the whole $\mathbb{R}_+$, or the empty set $\varnothing$. But, in practice, since the operating frequencies of the source feeding the antenna are just those representable by rational numbers with a given finite length of digits, the domain of function Q is just a subset of a finite interval [f, f'], so the same will be hold for the Q-BW itself, it will be just a subset of this practically well-known set of operating frequencies.

After that, for more than one antenna properties, that is for Q_i quantities with $1 \le i \le N$, we define the Overall Antenna Bandwidth as the common intersection of all Q_i bandwidths:

$$\bigcap_i Q_i = Q_1 \cap Q_2 \cap \ldots \cap Q_N \tag{1}$$

In this study, three quantities were selected, the usually most interesting in antennas, in order to estimate the bandwidth of the examined radial discone antennas, as an attempt to quantify their broadband property. These Q_i are:

a) Q_1: the 50-Ω Voltage Standing Wave Ratio SWR, as the most common used circuit characteristic,

b) Q_2: the Power Gain G_p at the horizontal plane where $(\theta = \pi/2, \varphi)$, as the field property and

c) Q_3: the Radiation Intensity U at the horizontal plane, as the mixed circuit-field characteristic.

To avoid excessive repetition of theory we consider as granted that $Z = R + i\,X$ as input impedance and G_p as power gain are the given output of Thin-Wire (RichWire) computer program via simulation, Z_0 the characteristic impedance and $\dot{V}_s$ the input source voltage. Then the radiation intensity is given [7 – 9] by

$$U(\theta,\varphi) = \frac{1}{4\pi}|\dot{V}_s|^2 G_p(\theta,\varphi)\frac{R}{(R+Z_0)^2+X^2}$$

$$= \frac{1}{4\pi}\frac{|\dot{V}_s|^2}{4Z_0} G_p(\theta,\varphi)\frac{4}{2+\mathrm{SWR}+\frac{1}{\mathrm{SWR}}} \quad (2)$$

Discone and Simulation

The design parameters of a discone (more exactly, a disc over a frustum cone) is shown in Fig. 1, where D is the disc diameter (t is its radius), d is the small (upper) diameter of the frustum cone, C is the large (lower) diameter of the frustum cone, s is the slant height, a is the flare-angle and g is the spacing (gap) between disc and cone. While this antenna was an invention of Kandoian [10], the first design relations was given by Nail [11]:

$$s = u\,(\lambda_1/4),\ D = v\,C,\ g = w\,d \quad (3)$$

where λ_1 is the wavelength at the lowest "operating frequency" f_1, and the parameters are:

$$u = 1,\ v = 0.7,\ w = 0.3 \quad (4)$$

It is worth mentioning that Nail also stated the following hypothesis: "although no investigation has been made, it appears that the larger flare-angle discones (a ≥ 90°) give better performance in the horizontal plane over large frequency bands than the smaller-flare-angle discones".

Later Rappaport designed discones using an N-type male connector feed and suggested other values for the parameters [12]:

$$u = 1.15,\ v = 0.75,\ w = 0.5 \quad (5)$$

The implementation of the discone antenna outline with wire radials may be called, among other names, a "radial discone" and Cooke observed that the following u parameter value is more appropriate for such antennas [13]:

$$u \approx 1.33 \quad (6)$$

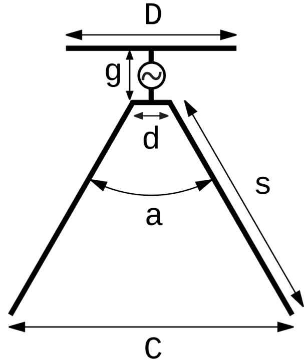


Fig. 1: Discone antenna

Although there are authors proposed different, rather slight, modifications on the parameter values, those of (3)-(5) may considered as the most accepted ones.

Additionally, since the lower f_1 and upper f_2 "broadband" frequency limits result as the most distant frequencies for which a designer-selected quantity is bounded between two designer-selected values, it is not possible to have in advance a guaranteed broadband zone. These facts keep open the discone and radial discone investigation of which the [f_1, f_2] zone is rather an unknown result than a given datum.

To the best of authors' knowledge:

(a) The radial discone antenna study is more or less experimental and there is no systematic study, which combines analysis, simulation, construction and measurements.

(b) There is no definite value for the flare-angle, of either radial or ordinary discone, other than the one resulting from the obvious trigonometric relation:

$$C = 2s \sin(a/2) \qquad (8)$$

(c) The broadband characterization is given usually by circuital SWR, while the radiation properties of the antennas are either neglected or limited to pattern illustrations in a number of spot frequencies into the claimed bandwidth. Thus, if the main interest is for a base station scanner antenna, with omnidirectional radiation pattern near-by the horizontal plane, as in the case of [14], care must be taken in order to achieve a rather constant radiation pattern.

d) For applications such as wireless communication, with the demand for operation on an increased frequency band there is a need for an upper operation frequency directive.

A visual program was specifically developed to design a broadband radial discone with bare wires embedded in free space when the wire conductivity, the type of feeding connector and the frequency band are given. Constructional details of the used technique have been given analytical in [15].

The consideration of radial discone as an array of at least 8 V-dipoles produces a theta-polarized vector radiation pattern with magnitude a surface almost by revolution around z-axis. So the radial discone has indeed on horizontal plane xOy the basic properties of a vertically polarized almost omnidirectional antenna, a fact that encouraged design of a broadband model by simulation. The model that was used for the simulation is shown in Fig. 2.

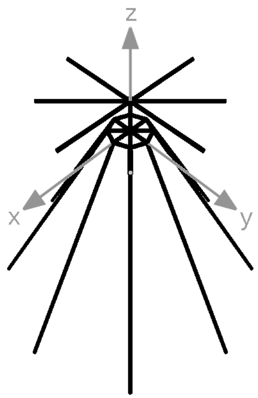


Fig. 2: Disc-Frustum Cone radial discone model

A unified study of any radial discone may be considered as parallel to the one of the following application: A constant slant height as $\lambda_1/3$, at the lowest desired frequency of 800 [MHz] that is 12.5 [cm], (equal to λ/4 at 600 [MHz]) and constant small cone diameter d equal to the N-type female connector diameter, 1.6 [cm] were considered. Three parameters were variable:

(a) The cone flare angle a in the range [15°, 180°] in steps of 15°.

(b) The disc diameter D with two v values as Nail (0.7 C) and Rappaport (0.75 C) proposed.

(c) The disc to cone distance g with three values: 3 mm as the minimum possible one, 6 mm approximately equal with that of (3) (~5 mm) and 8 mm as (4) suggests. Thus, there are 6 possible antenna models for each different cone flare angle.

Three arithmetic criteria were adopted for the broadband characterization of a model, as mentioned above:

a)the 50-Ω SWR is lower than 2, $Q_{SWR} = Q_1$: SWR ≤ 2 or similarly the mismatch loss is greater than –0.5 dB, –0.5 dB ≤ ML, where $ML = 10\log_{10}(1-\rho^2)$ with ρ the reflection coefficient,

b) the relative Directivity Gain G_d, or Power Gain G_p, is greater than –3 dB on horizontal plane where $G_p = e\,G_d = G_d$ for performance coefficient $e \approx 1$, as it is considered for a perfect conductor, $-3\text{ dB} \le G_{dH} \approx G_{pH}$: $Q_2 = Q_{Gp}$ and

c) the normalized radiation intensity $U/U_{max} = \mathcal{U}$, is greater than –3 dB on horizontal plane, $-3\text{ dB} \le \mathcal{U}_H$: $Q_3 = Q_{\mathcal{U}}$.

As a practical application of the broadband design, the 2G/3G band from 800 to 2500 [MHz], extend below to 600 [MHz] to cover the case of λ/4 slant height, was selected to begin with. Six sub-bands introduced, I: 806-960 MHz, II: 1429-1513 MHz, III: 1710-1900 MHz, IV: 1910-2025 MHz, V: 2110-2170 MHz and VI: 2400-2499 MHz.

The 50-Ω SWR, the normalized radiation intensity on horizontal plane and the relative Power Gain on horizontal plane are shown in Figs. 3 - 8, for the 12 x 6 = 72 simulated models in the frequency range [600, 2500] MHz. The vertical gray strips indicate the six sub-bands, light (I, II, III) and dark (IV, V, VI) correspondingly. It is obvious that for flare angles less than 45° and greater than 120° the frequency range with SWR ≤ 2 is reduced, the radiation intensity and even more the power gain on the horizontal plane are rapidly decreased below −3dB with frequency, especially for the larger flare angles (> 135°). Therefore Nails claim, mentioned above, for better performance in the horizontal plane over large frequency bands of the larger flare-angle discones (a ≥ 90°) [11], which led on our research to cone flare angle greater than 90°, seems that it is not verified at least for radial discones. To validate this conclusion, Fig. 9 gives the maximum of 50-Ω SWR for all the simulated models in the considered frequency range while Fig. 10 and Fig. 11 give the minimum values of radiation intensity and power gain on the horizontal plane, respectively.

Results

Eighteen models were selected to be constructed with cone flare angles 60° (with the best performance), 90° (marginal case) and 120° (the greater cone angle with satisfactory characteristics) by applying the mixture of directives from (3)-(5), as was aforementioned. Analytic results will be presented in a forthcoming work.

In Fig. 12 (a)-(c) typical simulation radiation intensity 3D patterns are given for these antennas at the center of each sub-band, which confirm the horizontal omnidirectional radiation properties of the broadband models.

It is obvious from Figs. 3 - 11 that the better broadband performance, with respect to the three adopted criteria, was achieved by the 60° radial discones. Fig. 13 shows the horizontal mean value in [dB] versus the horizontal range between min and max value in [dB], for all the 72 simulated models. The magnified little rectangle in the upper left corner contains the four 60° radial discones with the best values.

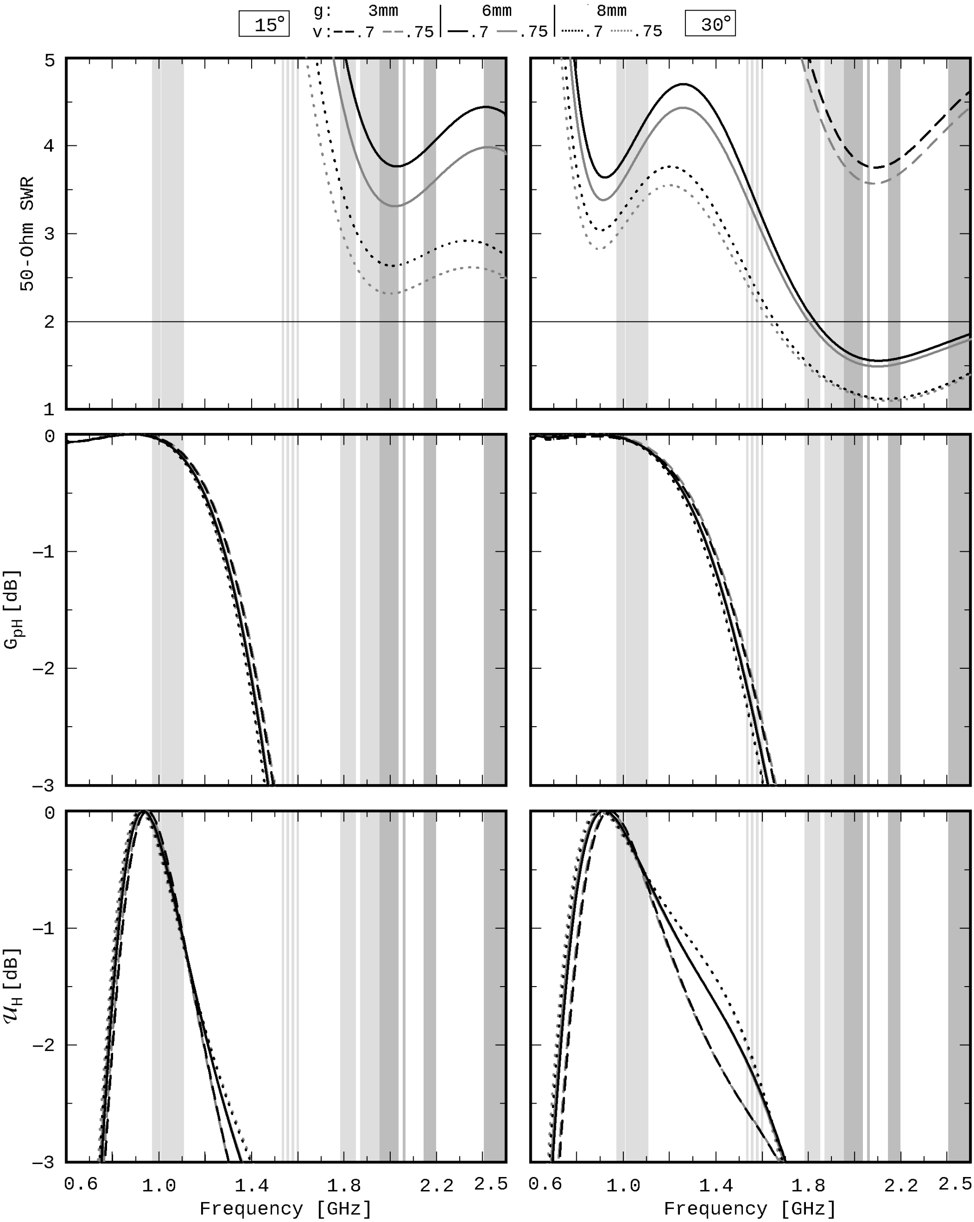


Fig. 3: SWR, G_{pH}, $\mathcal{U}_H$ for a = 15° and a = 30°

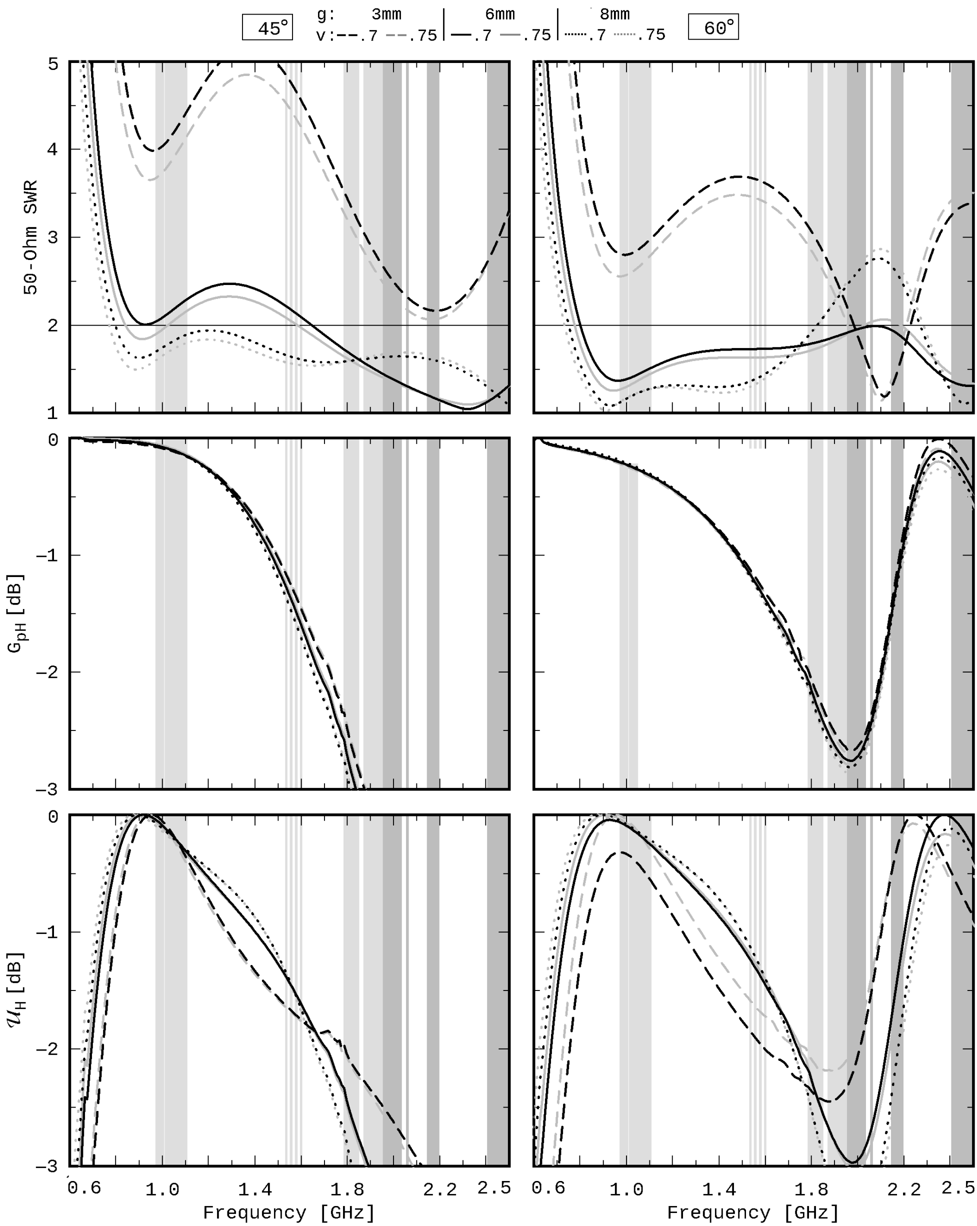


Fig. 4: SWR, G_{pH}, $\mathcal{U}_H$ for a = 45° and a = 60°

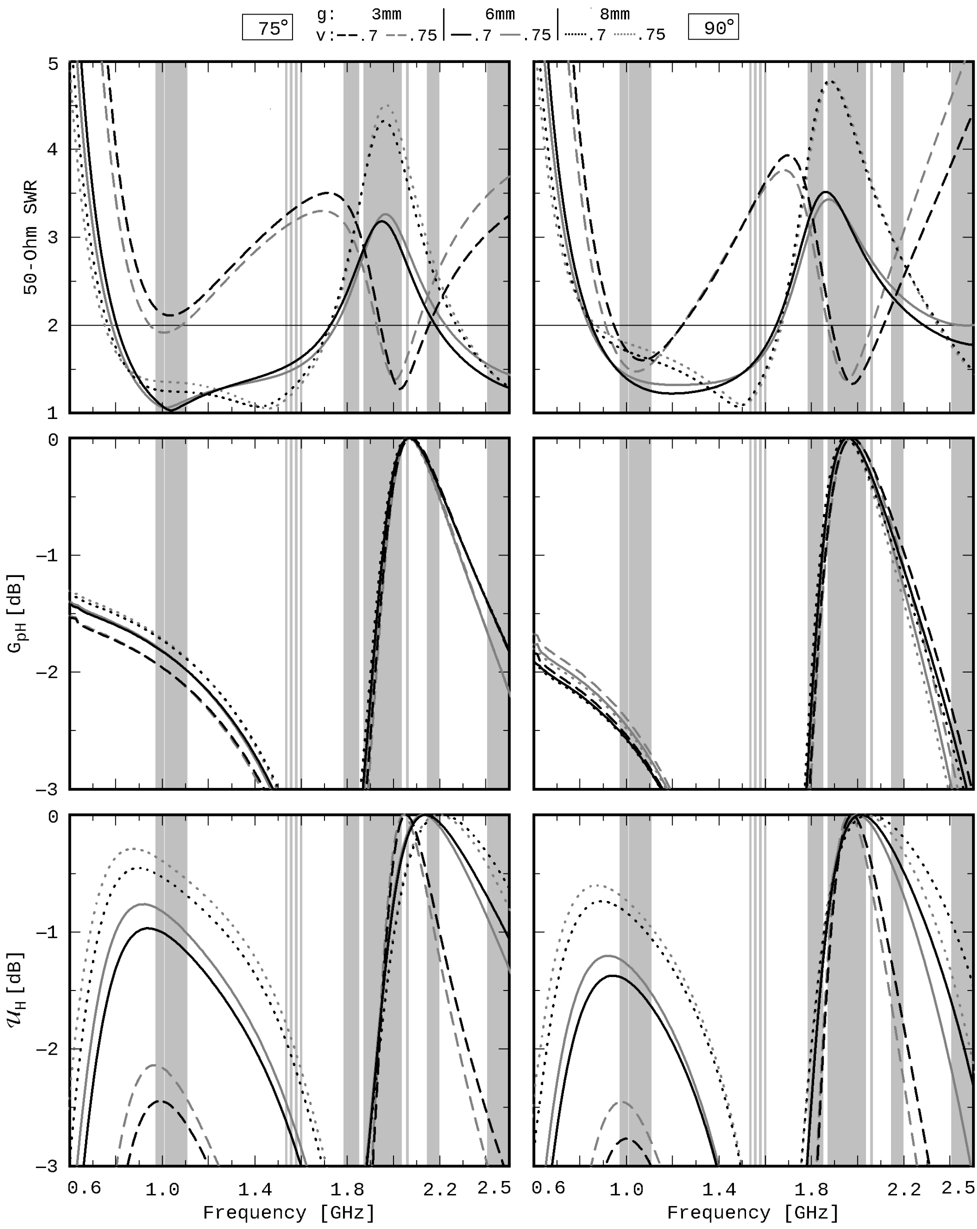


Fig. 5: SWR, G_{pH}, $\mathcal{U}_H$ for a = 75° and a = 90°

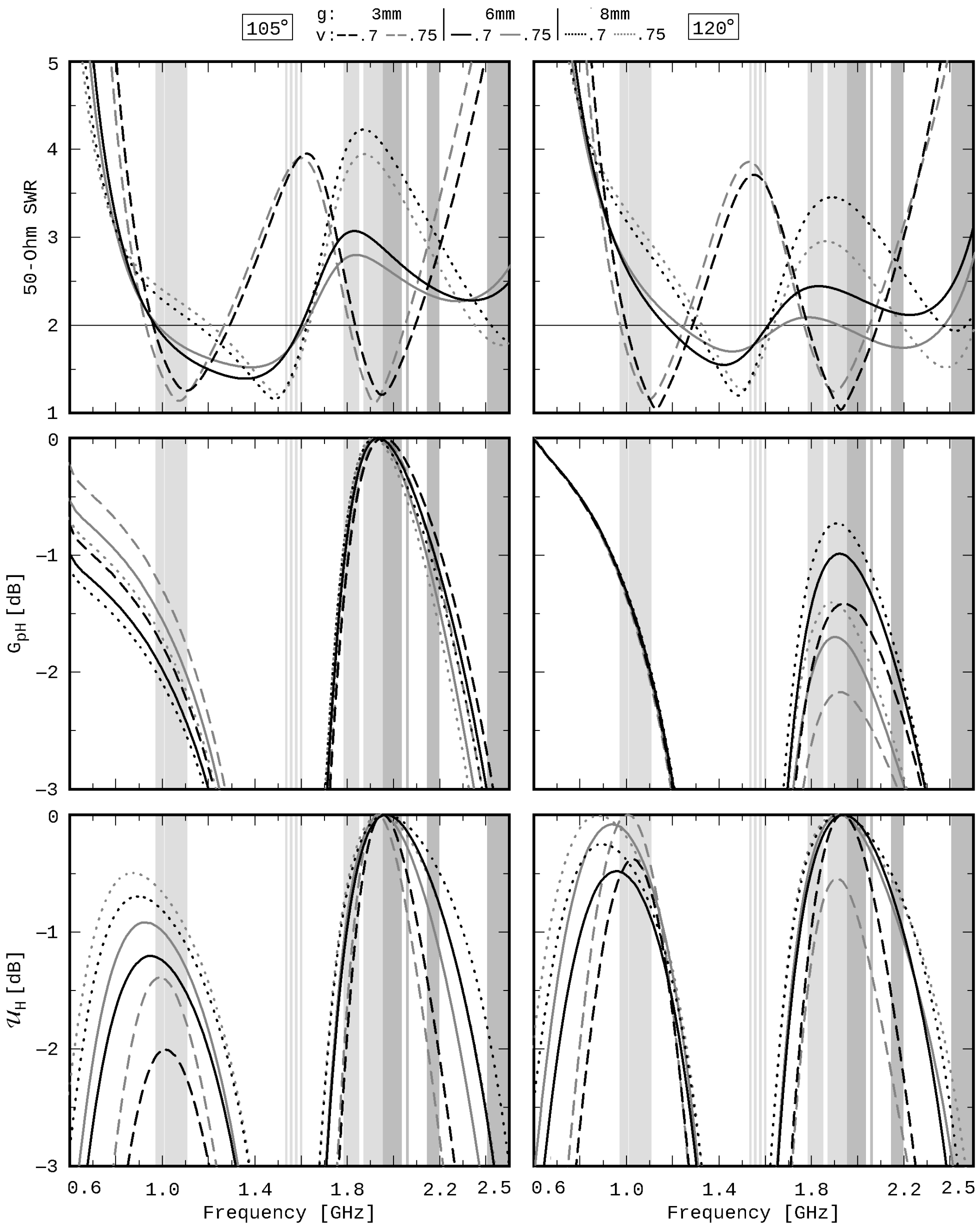


Fig. 6: SWR, G_{pH}, $\mathcal{U}_H$ for a = 105° and a = 120°

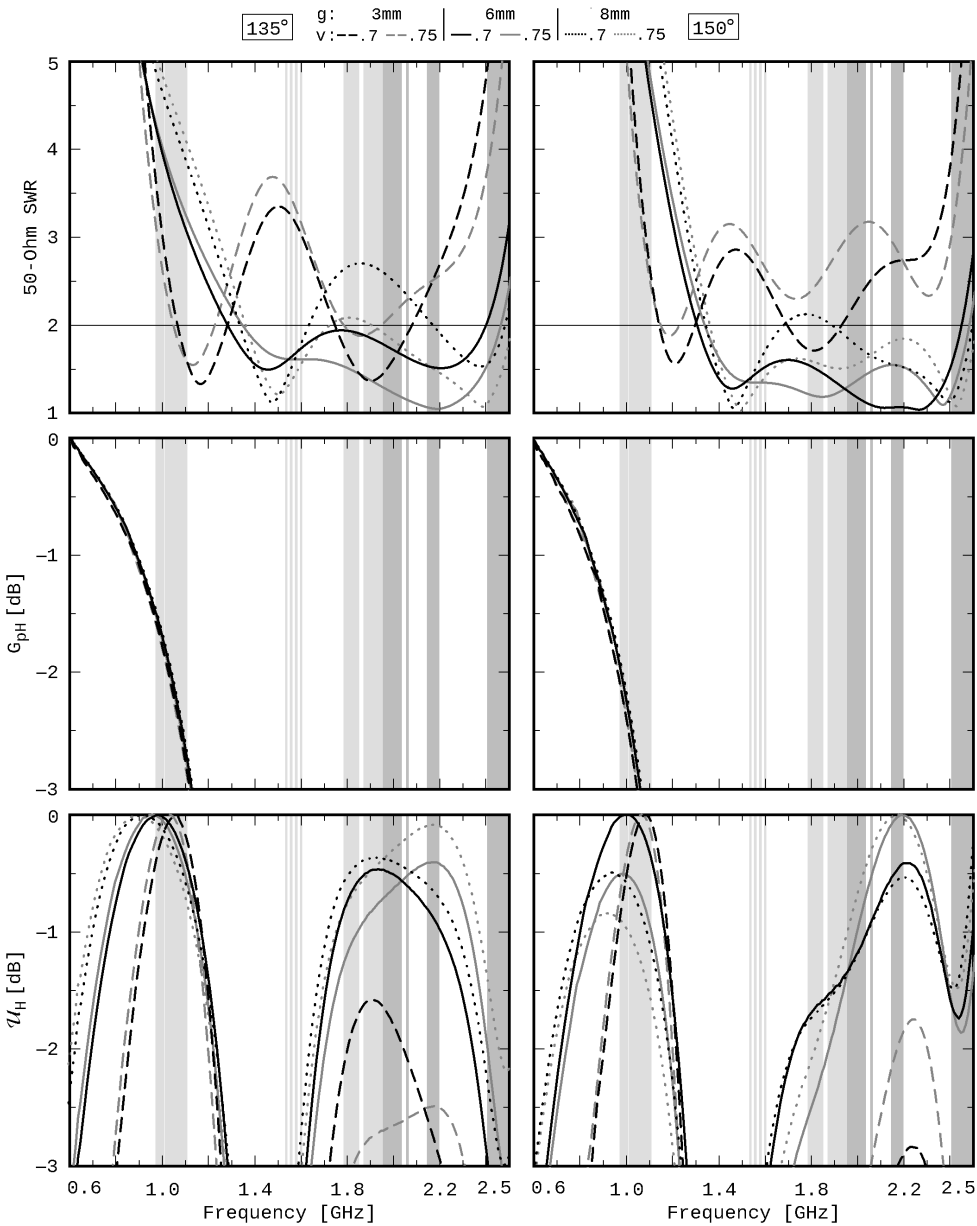


Fig. 7: SWR, G_{pH}, $\mathcal{U}_H$ for a = 135° and a = 150°

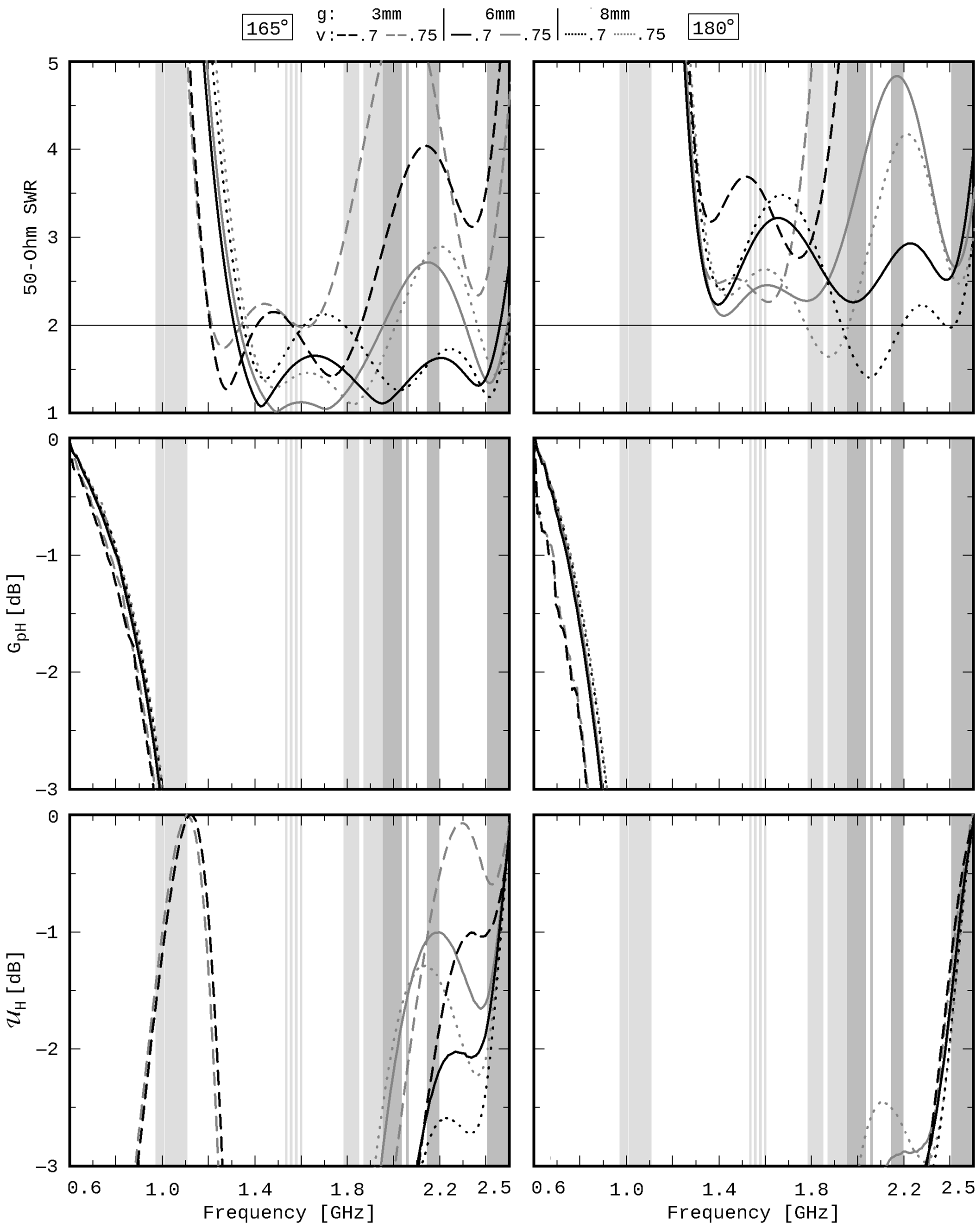


Fig. 8: SWR, G_{pH}, $\mathcal{U}_H$ for a = 165° and a = 180°

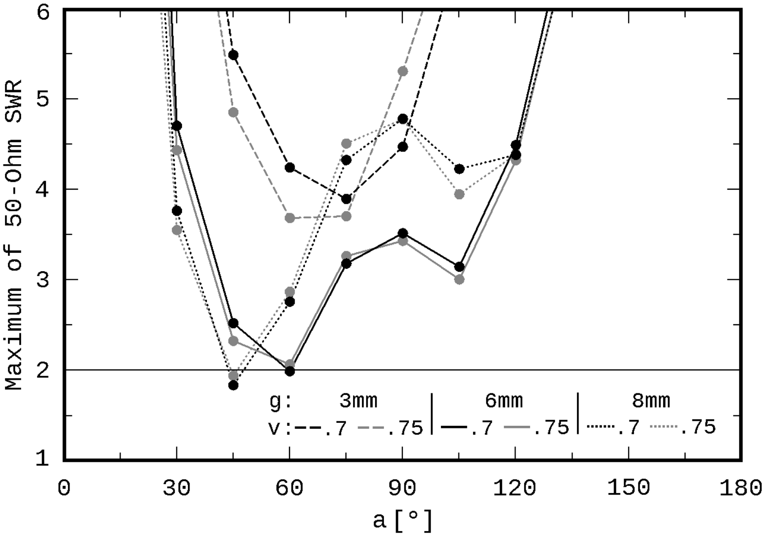


Fig. 9: Maximum 50-Ω SWR of overall 600-2500 MHz

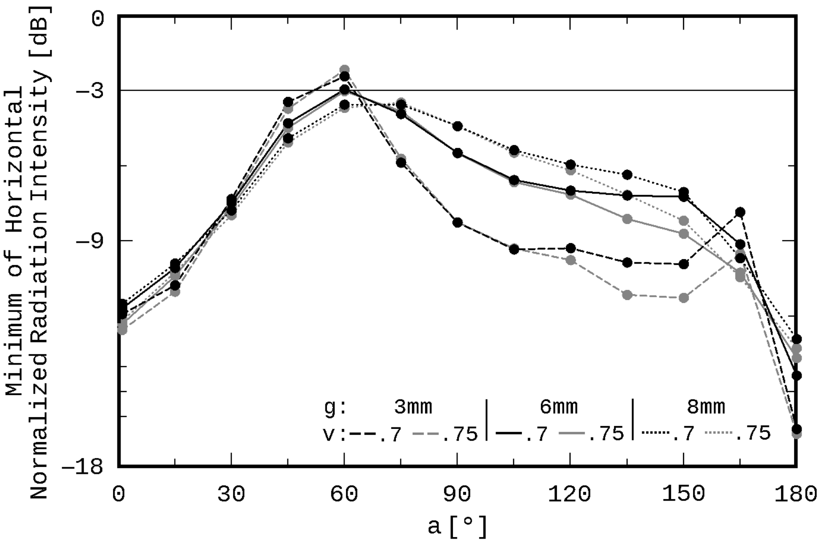


Fig. 10: $\mathcal{U}_{\mathrm{H}}$ minimum values of overall 600-2500 MHz

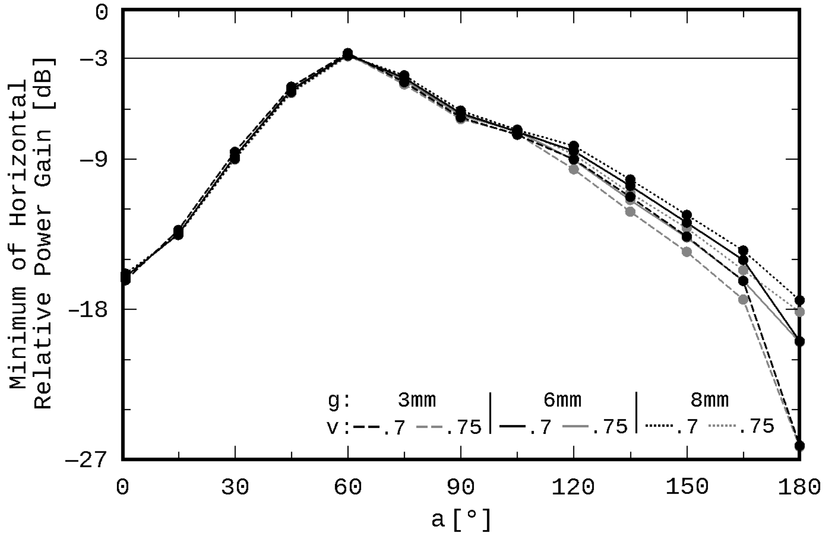
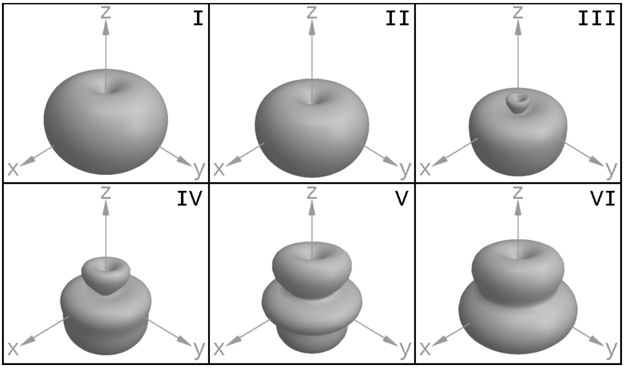


Fig. 11: G_{pH} minimum values of overall 600-2500 MHz

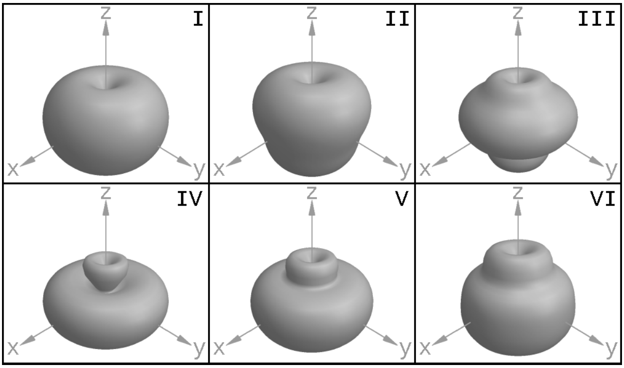
Their measured and simulated SWR with DERs (Differential Error Regions) as gray clouds are shown in Fig. 14 in separate frame for each antenna with its dimensions.

Thus, the application of the broadband criteria for the selected frequency range resulted to the design of radial discone, model 3 in Fig. 13 and Fig. 14, with D = 8.8 [cm], g = 0.6 [cm], s = 12.5 [cm], d = 1.6 [cm] and a = 60° which operates from 800 to 3000 [MHz], exceeding the initial range and it was initially presented in [5], yet using only two criteria. Fig. 15 shows the analytical predicted, simulated and measured radiation intensity on a vertical plane at the center frequency of the measurement band, at 950 [MHz], with a good agreement. Fig. 16 shows the reflection coefficient in the smith chart for this antenna, from simulation and measurement with the DERs as gray cloud for the measurement band. The small open circular points indicate the corresponding explicitly given frequencies.

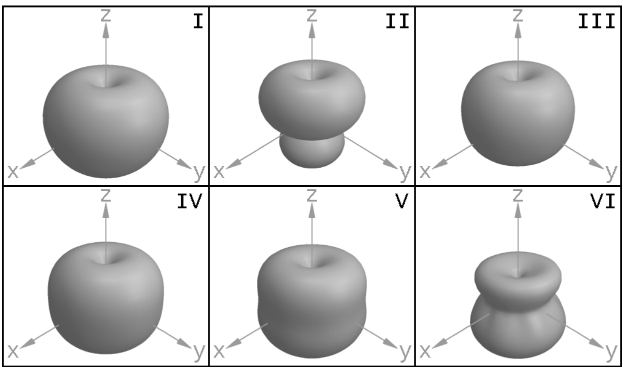
In order to test the limits of this antenna Fig. 17 shows its Directivity while Fig. 18 shows the four quantities of $\mathcal{U}$, SWR, G_p and mismatch loss ML at the extended frequency band from 300 to 6000 [MHz].



(a) 120°



(b) 90°



(c) 60°

Fig. 12: Predicted normalized radiation intensity patterns at the center of each sub-band for 120°, 90° and 60° flare-angles

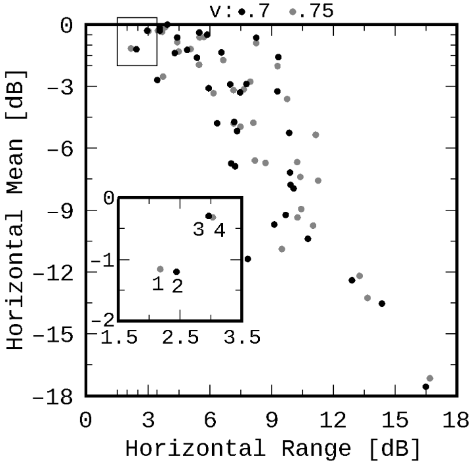


Fig. 13: Horizontal mean and range values for all 72 simulated models

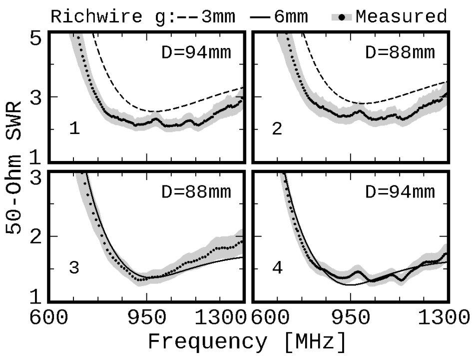


Fig. 14: Four antennas - measured and simulated SWR

The resulted bandwidths of 6:1 for ML ≤ 0.5 dB or SWR ≤ 2 and 4:1 for −3 dB ≤ $G_{dH} \approx G_{pH}$ and 4:1 for −3 dB ≤ $\mathcal{U}_H$ considered continuously excluding the frequency gaps, proved the successful design of the selected radial discone antenna as a broadband antenna with almost omnidirectional antenna pattern on the horizontal plane for the whole band 800 to 3000 [MHz] by applying the introduced generalized broadband characterization.

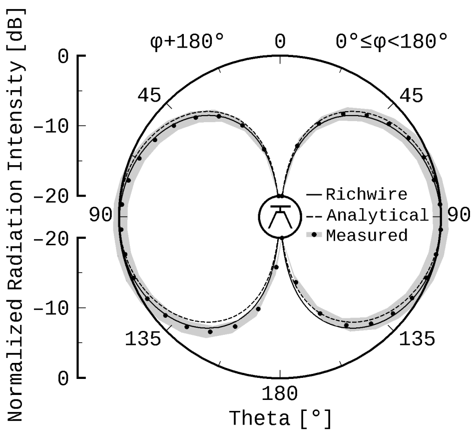


Fig. 15: $\mathcal{U}$ pattern on a vertical plane at 950 [MHz]

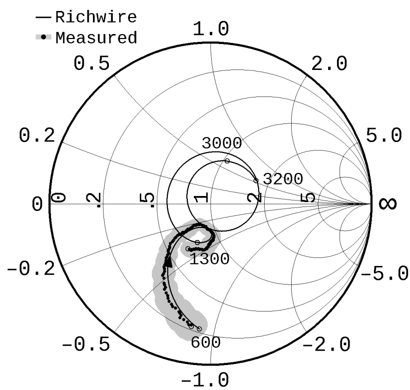


Fig. 16: ρ̇ in the Smith chart

Tab. 1 contains the frequency intervals where the three considered criteria are satisfied and their corresponding Q_i bandwidths while in Fig. 19 the resulted Q-BW is shown, as their intersection.

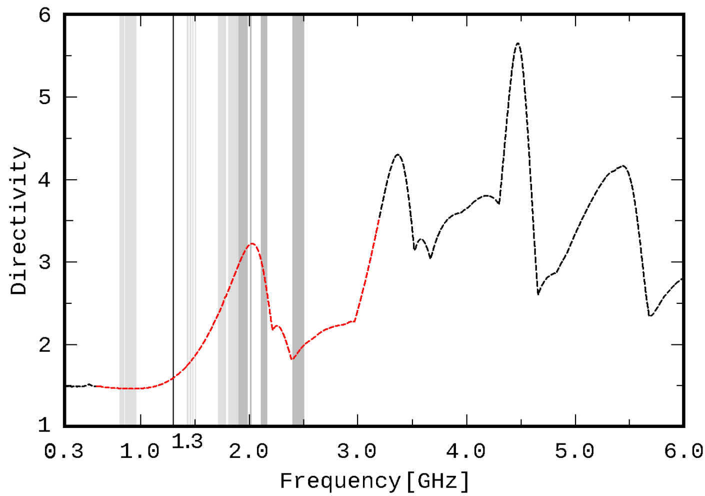


Fig. 17: Directivity at the extended frequency band

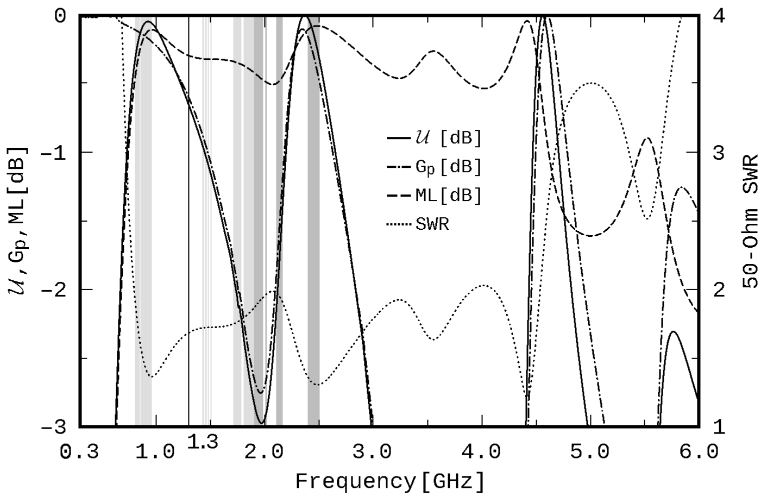


Fig. 18: $\mathcal{U}$, SWR, G_p and ML at the extended frequency band

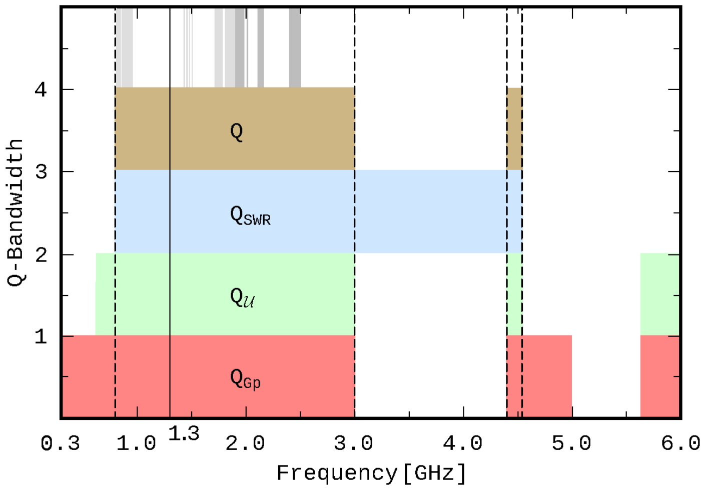


Fig. 19: Q-BW as intersection of Q_{SWR}, Q_{Gp} and $Q_{\mathcal{U}}$ bandwidths

Tab. 1: Q_i bandwidths

	Q_i [MHz]	Q-BW = $\cap Q_i$
Q_{SWR}	[800, 4540]	[800, 3000] $\cup$ [4400, 4540]
Q_{Gp}	[300, 3000]$\cup$[4400,4980]$\cup$[5640, 6000]	
$Q_{\mathcal{U}}$	[630, 3000]$\cup$[4400,4980]$\cup$[5640, 6000]	

Conclusion

During the investigation procedure an extended study of the radial discone antenna behavior for various flare angles, lower and higher of 60°, from 15° to 180° was performed.

To the best of the authors' knowledge it was the first time that data are presented for discones with flare angle a ≥ 90°, and such antennas were constructed and measured, although it was proved that the typical 60° antenna had the best performance for the purpose that have been set. All the measurements were performed according the presented previous authors' work [15] - [17].

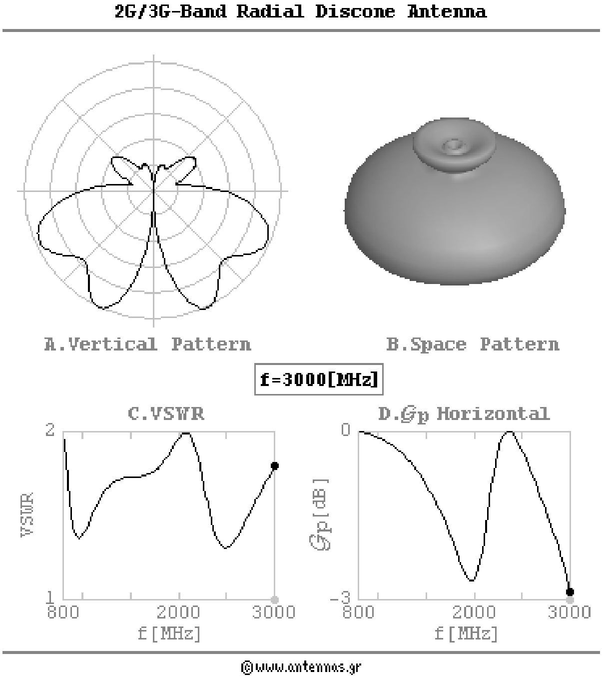


Fig. 20: 2D and 3D $\mathcal{U}$ pattern, SWR and G_{pH}

Unfortunately, Nail's claim in 1953 for better performance in the horizontal plane of discones with larger flare angles for broader frequency ranges than the smaller flare angles was not proved to be true, at least for their radial version. For instance the radial discones with 150° and 30° flare angle have both a low SWR but in a narrower frequency range and the most essential their pattern on the horizontal plane is almost zero for significant large sub-bands. In Fig. 7 although the 150° discone seems to be better for $\mathcal{U}_H$ than the discone with 30° flare angle in Fig. 3, this is not true since its horizontal gain G_{pH} is much worse. In the same time the slant height dimension as λ/3 at the lowest desired frequency of Cooke was justified.

The generalized broadband characterization of an antenna introduced here as the "Overall Antenna Bandwidth", combines for the specific application three quantities of different nature with the following demands:

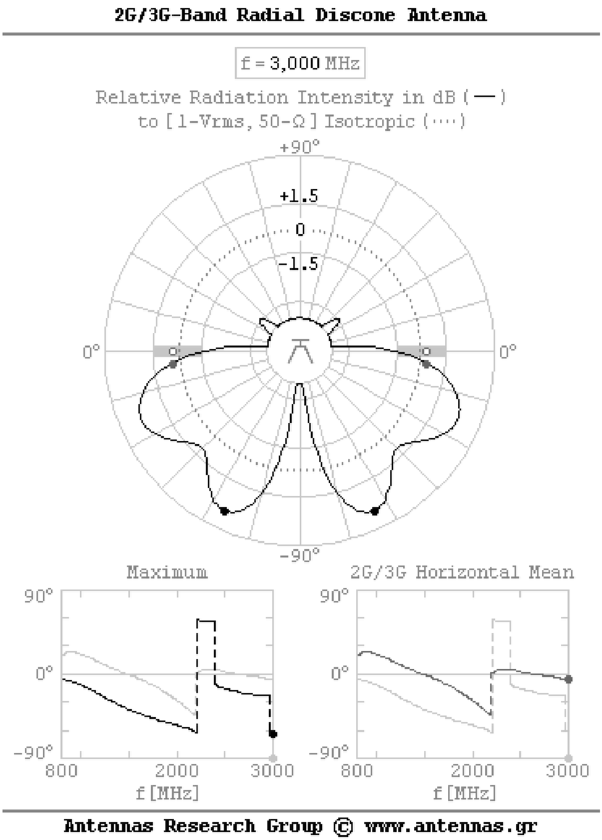


Fig. 21: 2D $\mathcal{U}$ pattern, direction of maximum and horizontal mean value

a) SWR (circuit quantity)

Q_{SWR}: SWR ≤ 2

b) the horizontal directivity/power gain G_{dH}/G_{pH} (field quantity)

Q_{Gp}: $-3\text{dB} \leq G_{pH}$

c) the horizontal radiation intensity $\mathcal{U}_H$ (field - circuit quantity)

$Q_{\mathcal{U}}$: $-3\text{dB} \leq \mathcal{U}_H$

Thus, the overall bandwidth results as

$$Q\text{-}BW = Q_{SWR} \cap Q_{Gp} \cap Q_{\mathcal{U}}$$

It was proved that a successful design of such an antenna is possible. Two animations was prepared for the proposed radial discone antenna from which the last frames are shown in Fig. 20 and Fig. 21 respectively. The $\mathcal{U}$ pattern on a vertical plane, the corresponding 3D patter, the SWR and the power gain G_p in the horizontal plane are given in Fig. 20. In Fig. 21 the $\mathcal{U}$ pattern in [dB] is compared with that of an Isotropic antenna. The grey and black points indicate the directions of mean value in horizontal plane and maximum value respectively, which are shown below with respect to frequency. The produced animations and all other updated material will be available in the authors' website [18].

Full results of the constructed and measured models as well as some details for their fixed construction and the performed analytical study will be presented by the authors as an extended report in a future paper, as well as a full description of the developed software for the radial discone antenna.

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