A New Class of Antenna Arrays with Passive Elements

Boro M. Reljic, Branka Jokanovic

Abstract. **The paper summarizes a research effort related to construction of a new antenna class – Broadside Antenna Arrays with Passive Elements (BAAPE). First, beneficial properties of this antenna class have been investigated, based on its structure analysis. After that, possibility of realization of simple and multielement antennas of such a type has been considered. Basic geometric relations and performances have also been specified. Encountered problems have been described and with two realized antennas the idea was verified. The research results have shown that it is possible to construct the BAAPE and that this antenna has a number of suitable properties: a simple planar structure, high directivity and efficiency, good matching and medium frequency bandwidth. Therefore it has great potential for applications in wireless communications, which primarily cover high frequencies bands, especially upper microwave and millimeter wave bands. Also, using this antenna as an antenna element in a bigger planar antenna system with high gain and high efficiency is a very interesting application.**

Keywords: **Antenna arrays, broadside arrays, endfire arrays, passive arrays, classic arrays, Yagi antenna.**

I. INTRODUCTION

According to relative position of radiation pattern with respect to geometry of the antenna array, the arrays are divided into two main classes: arrays with endfire radiation pattern and arrays with broadside radiation pattern.

According to the technology of realization of the antenna array, two characteristic cases could also be distinguished: classic and passive antenna arrays. In classic antenna arrays all elements of the array are fed, i.e. they are active. Unlike the classic arrays, majority of elements in passive antenna arrays are not supplied directly (i.e. by transmission lines or waveguides). Such elements are called passive (or parasitic) and their currents are induced by the near field.

Main advantage of passive over the classic antenna arrays is their simple structure, as they do not require complex network for supplying and phasing elements.

Consequently, RF energy losses from generator to antenna elements are smaller and thus efficiency of the antenna is higher. Described advantage of passive arrays is most distinguished if only one element is fed.

Passive antenna arrays have been known since the beginning of the 20th century, but only as arrays with endfire radiation pattern. These antennas are treated as structures for surface electromagnetic wave guidance and they are best known as Yagi antennas.

This paper shows that it is also possible to realize other boundary case of passive antenna arrays - broadside antenna arrays with passive elements.

In the following text suitable features of BAAPE, based on its structure and known features of Endfire Antenna Arrays with Passive Elements (EAAPE), i.e. Yagi antenna, are considered firstly.

By means of combined analytical and numerical methods on simple structures, it is shown that realization of passive antenna arrays with bidirectional and unidirectional broadside radiation pattern is possible. Necessary relation between geometrical parameters has also been defined to ensure proper antenna operation.

Performances of simple structures have been found and problems to be solved have been pointed out. The idea has been verified by realization of a unidirectional 3-element antenna.

Next, a possibility of construction of a multi-element antenna with unidirectional broadside radiation pattern with a reflector plate has been investigated. The problems of construction have been analyzed and geometrical relations necessary for operation of multi-element antennas have been defined. To check conclusions about the multielement antenna, another antenna has been realized and tested.

Finally, characteristics of this class of antennas have been summarized and they have been compared to other antenna classes with respect to various electrical and geometrical parameters. Parameters of realized multielement antenna have also been given.

II. PROBLEM FORMULATION

As it was said, passive antenna arrays are known only as class of arrays with endfire radiation pattern i.e. in the form of EAAPE (Yagi antennas).

We shall first consider advantages of BAAPE (based on its structure analysis) and than we shall analyze the possibilities for their realization. Foremost, BAAPE will have similar constructional and electrical advantages over the classic antenna arrays as EAAPEs have, that are simplicity and efficiency. On the other hand, compared to EAAPE, advantages of arrays with broadside radiation pattern are the following:

- possibility of planar realization and integration with front-end components in telecommunication equipment;
- application in a bigger antenna system in order to replace groups of elementary radiators and thus simplify the structure while the array remains planar (note: use of arrays with endfire radiation pattern produces 3D (*spacious*) antenna array)

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From the above, we can conclude that construction of these antennas is very interesting with regard to their applications in wireless communications

III. REALIZATION OF SIMPLE BAAPES

Let us now investigate the possibilities of realization of BAAPEs. In order to reach this aim, we shall start from the simplest passive array structure, which is a two-element array.

A. *Basic model description.*

Fig. 1 shows a model of two-element antenna. The structure consists of two dipoles, one being fed and the other being passive. In the middle of the passive element, the lumped reactance *jXp* has been inserted by means of which current of the passive element is adjusted.

The parameters of the model are length *l*, radius *r*, elements spacing *s* and value of inserted reactance *Xp*.

Matrix parameters of these coupled dipoles are *Zii*, *i*=1,2 and *Zij*= *Zji*, *i*, *j*=1,2, *i*≠*j*. Mutual impedance of dipoles is *Zij*= *Zij*(*s*, l_1, l_2, *r*), whereas for thin dipoles, *Zii* may be approximated with self impedance of *i*-th dipole, if dipoles are not too close.

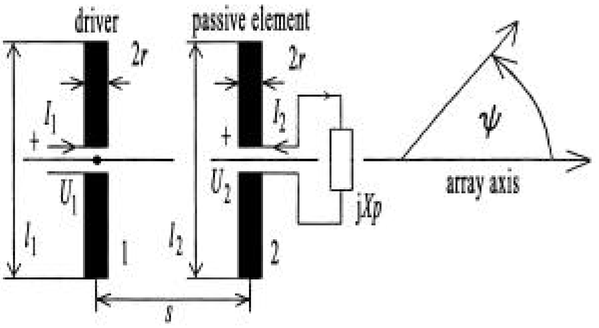

Fig. 1. Two-element passive array

By means of the antenna array theory we can calculate directivity *D* and (two-element) array amplification A_2 as

$$D = D_l \cdot \frac{|F_2|^2}{\dfrac{R_z}{R_l}} = D_l \cdot A_2 \,, \tag{1}$$

where D_l is directivity of a thin dipole i.e. antenna element.

After calculation A_2 is obtained in form

$$A_2 = \frac{1 - 2\cos g \dfrac{|Z_{21}|}{|Z_{22}^{tot}|} + \dfrac{|Z_{21}|^2}{|Z_{22}^{tot}|^2}}{1 - \dfrac{|Z_{12}|^2}{|Z_{22}^{tot}|^2}\left[\cos(2\arg Z_{12}) + \sin(2\arg Z_{12})\dfrac{X_{22}+X_p}{R_{11}}\right]} \,, \tag{2}$$

where

$$g = m + b\, s \cos y \tag{3}$$

$$m = \arg Z_{21} - \arg Z_{22}^{tot} \,, \tag{4}$$

$$Z_{22}^{tot} = Z_{22} + \mathrm{j}X_p = R_{22} + \mathrm{j}X_{22}^{tot} \,. \tag{5}$$

b is phase coefficient and F_2 is array factor,

$$F_2(z) = \frac{-1}{z_0}(z - z_0) \,, \tag{6}$$

where

$$z_0 = -a = -\frac{I_a}{I_p} = \frac{Z_{22}^{tot}}{Z_{21}} \tag{7}$$

$$z = e^{+\mathrm{j}f} \,, \tag{8}$$

$$f = b\, s \cos y \,. \tag{9}$$

Variable *z* is called a visible range and the same name is used for variable f as they are related by (8).

Relation (1) implies that

$$D \propto |F_2|^2 \tag{10),}$$

whereby F_2 is a factor depending on the array construction.

It is apparent that F_2 gives the space dependence for *D* for the antenna array. (6) implicates that

$$|F_2(z)| \propto |z - z_0| \tag{11}$$

A clearer picture of the situation and implication of particular parameters on the radiation pattern shape is obtained when the diagram of the visible range and F_2 zero loci are presented in a complex plane.

Fig. 2 shows two lines in &plane, which are loci of array factor zero z_{01} (*s* - fixed, *Xp* - parameter). The right line corresponds to EAAPE for *s*=0.1 λ, while the left one corresponds to BAAPE, *s*=0.5 λ.

Wider arc on the unit circle represents visible range for *s*=0.1 λ, while the whole unit circle is visible range for *s*=0.5 λ (visible range points correspond to y angles, Fig. 1, (8), (9)).

For *s*=0.1 λ and for z_{01} above Re(*z*) axis passive element is a reflector, while for z_{01} under Re(*z*) axis passive element is a director.

For example, if zero is at z_{01}^{ef} position, it is clear from Fig. 2 that distance <z_{01}^{ef}, $z(y=0)$> is greater than distance <z_{01}^{ef}, $z(y=\pi)$>. As $D(y)$ is proportional to the square of this distances (in &plane), according to (1), (6), (10) and (11) the array functionates as Yagi antenna and passive element is a director.

Fig. 2 also implies that parameter choice for ideal BAAPE are as follows: *s*=0.5 λ, z_{01}= -1. According to (1) and (6) in this situation there is no radiation in endfire direction, while there is finite radiation in broadisde direction (compare corresponding distances <z_{01}, $z(y)$>). However, this ideal case can not be fulfilled as it requires R_{22}= -R_{21} (for thin dipoles of length *l*≈λ/2 R_{21}(*s*=0.5 λ)= -12.5Ω, but R_{22}≈70Ω).

Although ideal situation is not possible, above conditions can be approximately fulfilled when z_{01} is set near *z*= -1 point in a complex plane on line, which corresponds to element spacing *s*=0.5 λ.

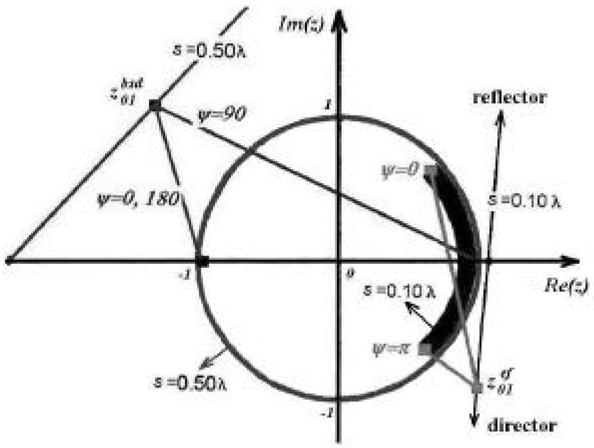

Fig. 2. Visible range with zero loci of array factor (lines s=0.1λ and s=0.5λ, Xp parameter) for two-element BAAPE.

Additional analysis revealed that the best antenna performances are obtained for s=0.6 λ, $Xp\approx 0$ and then broadside to endfire radiation ratio is B/E=5÷7 dB and directivity is D=5.3 dBi, which is a good directivity for a two-element bidirectional array.

B. Three-element array

Described two-element antenna is asymmetrical. By adding one more identical passive element, symmetrically on the other side of the driving element, a symmetrical three-element antenna with bidirectional radiation pattern is obtained. Directivity of such antenna is

$$D_3 = D_{l/2} \cdot A_3 \qquad (12)$$

where $\grave{A}_3$ is calculated analytically (similarly to $\grave{A}_2$ for two-element antenna) and when we analyze it we can conclude that the best antenna performance is achieved for s=0.6 λ, $Xp\approx$ -15 Ω and $D\approx$ 7 dBi, B/E=9.5 dB.

C. Unidirectional array

All aforementioned antennas have (symmetrical) bidirectional radiation pattern, as their structure is also symmetrical with respect to the plane with antenna elements.

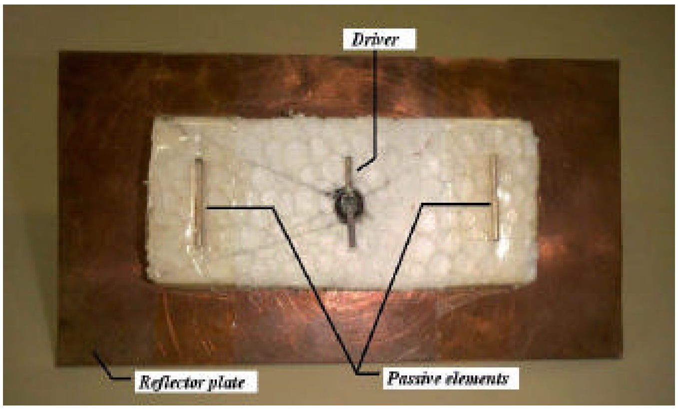

Fig. 3. 3-element unidirectional BAAPE realized at X band.

However, most common antenna applications cover the use of unidirectional radiation pattern antennas. To obtain a unidirectional radiation pattern with described antennas, a reflector plate could be added.

In the case of a three-element antenna with unidirectional radiation pattern (added reflector at the distance of ~λ/4), directivity obtained by simulation [4] is $D\approx$ 11.5 dBi, while for realized antenna $D\approx$ 11.3 dBi.

Ideally, if influence of plate reflector on current distribution over elements is neglected, by adding a reflector plate to bidirectional array, directivity of $D\approx$13 dBi could be obtained.

The antenna is shown in Fig. 3.

IV. MULTIELEMENT BAAPES

A. Construction possibility

Described structures have medium values of directivity - between 6 and 12 dBi, depending on whether it is an array with bidirective or unidirective radiation pattern. These values of directivity in some applications may be low.

By adding new passive elements, development of multielement passive antenna arrays with broadside radiation patterns can be investigated. As unidirectional radiation pattern antennas are most commonly applied, we will pay attention only to them.

However, adding of new elements to a simple antenna does not increase directivity notably. A three-element unidirectional BAAPE does not reach ideal directivity because of the strong impact of the reflector. It is 1.5 dB less than the ideal one.

When a 5-element antenna is built by adding two new elements, we obtained no significant increase of directivity compared to that of a three-element unidirectional BAAPE. This is because of the nearness of the reflector and the strong coupling between passive elements and the reflector.

In case of EAAPE (Yagi antennas), conditions that are set for geometrical parameters of the structure, in order to enable propagation of endfire mode of waves along the structure, are not critical. Namely, it is necessary that elements' lengths are around λ/2, distance between the elements is around λ/4, while the radii of the elements are not critical. Most frequently used are thin elements with radii of order about 0.001 λ and spacings between 0.1 - 0.25 λ. As none of these dimensions are critical, conditions for propagation of the endfire mode are practically always fulfilled in this structure. This fact has led some authors [1], [2], [3], [15] and [16] to the conclusion that passive antenna arrays are inherently arrays with endfire radiation pattern i.e. they are always Yagi antennas.

In order to find whether propagation of suitable broadside wave mode is possible in a multielement passive array of dipoles above the reflector plate, a sequence of experiments was performed by means of an electromagnetic simulator [5] and results of [11] and [14]. In this research 3-7 element BAAPEs have been analyzed.

All antennas have been situated in the vacuum. Special attention has been given to influence of a reflector as it was previously found that its influence is predominant on antenna performance. Antennas with element radii of 0.001 and 0.01 λ placed on previously determined spacing of ~λ/2 have been analyzed. For the purpose of more efficient RF energy distribution and enhancement of coupling between elements, dipoles around full wavelength were used. Distance of the reflector in the experiment varied from 0.25 to 0.75 m, i.e. approximately from 0.25 to 0.75 λ, as the central frequency was around 300MHz.

The following antenna parameters were monitored: directivity in broadside direction D and side lobe level (relative to maximum directivity) SLL. It was required that antennas have

SLL [dB] $\geq SLL_{min}$ = 5dB.

The experiments have shown that when thin elements are used, adding new elements causes no noticeable increase of the antenna directivity, i.e. it keeps at the value around 12-13dBi, regardless of the reflector distance.

If thicker elements are used, experiments reveal that for (infinite) reflector distance of around 2/3λ there is a considerable increase of directivity by adding new elements. Shortly, it could be concluded that there is a condition for propagation of a suitable broadside wave mode in the structure (that gives maximal directivity of the antenna in the broadside direction).

Fig. 4 shows results of an experiment with a seven-element antenna with thicker elements. Directivity, side lobe level (relative to maximum directivity) and reflector distance in λ are shown for partially optimized antennas for a set of reflector distances in mm. The figure shows that small reflector distances give antennas with low directivity (12-13dBi) because of the strong reflector influence. For the reflector distances of 0.4λ to 0.65λ, antennas of high directivity (around 17 to 18dBi) could be obtained.

If the reflector distance is over 0.7λ maximally obtained directivity considerably falls (to around 13dBi). Additional optimization also shows that for that reflector distances side lobe level (due to presence of the ground) cannot be sufficiently lowered. Thus, these reflector distances are also unfavorable as well as those below 0.4λ.

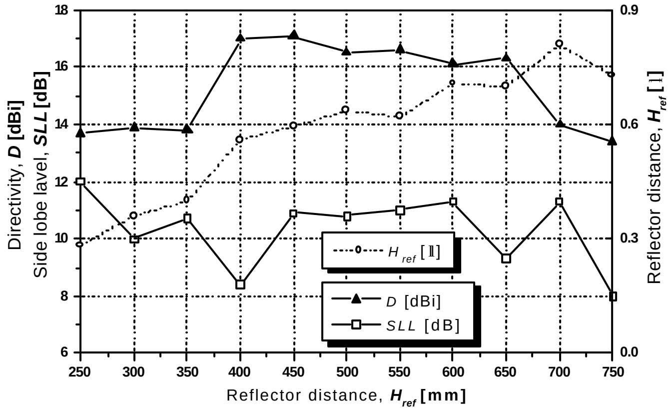

Fig. 4. Directivity (broadside) D, side lobe level SLL and H_{ref}[λ], for a set of reflector distances H_{ref}[mm], for thicker dipoles, N=7.

Thus, next conclusion on suitable geometrical parameters of unidirectional passive antenna array with broadside radiation could be made. Element

- radii are $r \sim 0.01\,\lambda$,
- length are $l_i \sim \lambda$,
- spacing are $s_{ij} \sim \lambda/2$
- reflector distance is $Href \sim \lambda/4$ and $Href \sim 2/3\lambda$.

B. Properties of multielement antenna

Further work comprised synthesis and optimization of group multielement antennas (N=7-11) as well as determination of their performance in order to check performance limits of unidirectional BAAPEs.

Results of these experiments are summarized in Fig. 5. The figure shows dependence of directivity, side lobe level and bandwidth versus the number of elements for the analyzed antenna class.

Beside aforementioned realized three-element antenna, in order to verify conclusions concerning multielement BAAPEs, one multielement antenna (N=7) has also been realized at X band. Parameters of realized seven-element antenna are shown on Fig. 5, while Fig. 6 shows the structure of the realized antenna. Diagrams on Fig. 5 show good agreement between experimental results and those obtained by electromagnetic simulation.

While other antennas are with an infinite reflector, the realized antenna has a finite reflector with much reduced size (slightly bigger than the antenna array dimensions, ~2.8 λ x 4.2 λ), Fig. 6. Realized antenna has front to back ratio above 20dB in the whole frequency range.

Higher suppression of backside radiation could be obtained by using bigger reflector plate.

According to the geometrical surface they occupy (S_{ant}), comparison between BAAPE, EAAPE (Yagi antenna) and uniformly illuminated aperture is shown in Fig. 7

In the case of classic Yagi antennas and considered passive antenna arrays with broadside radiation, geometrical surface

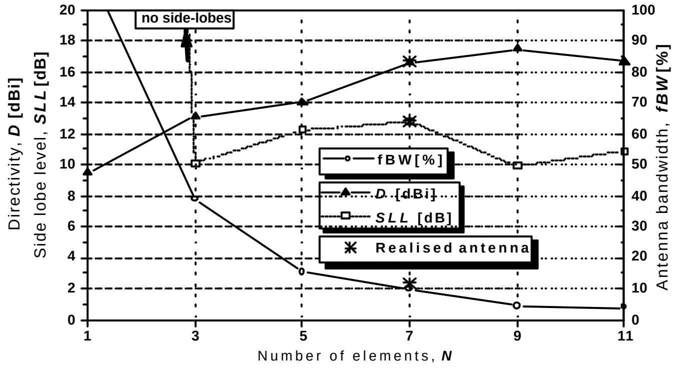

Fig. 5. Directivity, side lobe level and bandwidth of BAAPEs and the same parameters for realized N=7 antenna.

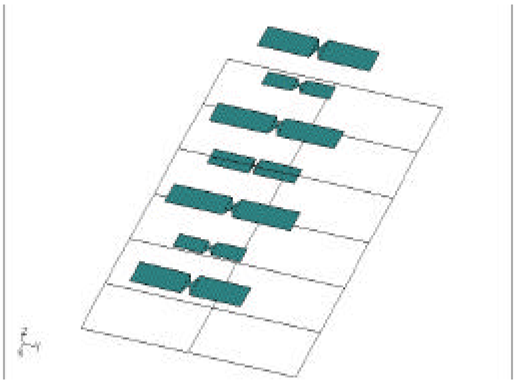

Fig. 6. Realized unidirectional BAAPE, *N*=7.

that the antenna occupies (S_{ant}) could be defined as a minimal rectangle in which antenna elements could be placed. For these antennas, it is equal to the product of the array length L_{ant} and the length of the longest array element.

Although EAAPE have higher directivity for the same surface of the array, the number of EAAPE antenna elements is 2 to 2.5 times higher than that of unidirective BAAPEs.

The difference between directivity of an unidirective passive array with broadside radiation and directivity of a uniform illuminated aperture is 1.5 – 3dB. So, aperture efficiency of the antenna is good.

Fig. 8 shows comparison between directivity of EAAPE (Yagi) and unidirectional BAAPE depending on number of used elements.

It can be seen that for the same number of antenna elements, directivity of the passive antenna array with broadside radiation is higher than directivity of EAAPE for about 4 – 6 dB. Upon comparison, it was not taken into consideration that the infinite reflector, used to simplify analysis of unidirectional passive antenna arrays with broadside radiation, doubles the number of elements. This means that the number of antenna elements is not the sum of the number of original elements and their images. As it can be seen in Fig. 6 (for realized seven-element antenna), unidirectional passive antenna arrays with broadside radiation can be realized with a reflector plate of finite (reduced) dimensions. Thus, the reflector plate should rather be considered as an additional element to the whole antenna array than as a group of images of original elements.

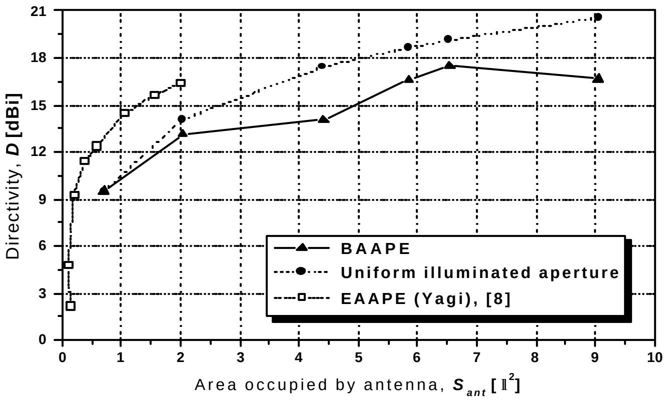

Fig. 7. Directivity of a unidirectional BAAPE, EAAPE (Yagi antenna) and the uniformly illuminated aperture vs. area occupied by antenna.

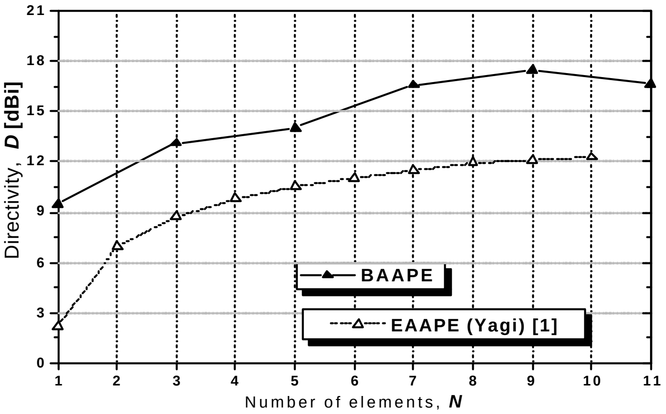

Fig. 8. Directivity of unidirectional BAAPE and EAAPE (Yagi antennas) vs. antenna element number.

Besides, this is a comparison of proposed class of antenna with classic Yagi antenna [1], [2], [7], [9] and [10] having only one wire as a reflector element. However, if higher values of front to back ratio of Yagi antenna are required in wider frequency range, a plane or corner reflector should be added instead of one wire reflector. This leads to 3D antenna construction [2], [7], [8] and [10].

In passive antenna arrays with unidirectional broadside radiation, the reflector is an inherent part of the antenna and it can easily reach sufficient front to back ratio in wider frequency range. In this way the antenna structure remains planar, which is an advantage in many applications.

The planar structure is an important feature of an antenna as photolitographic technique can be used and thus precise tolerance control is possible. Thus, antennas of uniform characteristics could be obtained, with better reproducibility. On the other hand, as far as assemblage is concerned, the planar structure is suitable for the following reasons:

- obtains low profile of the whole device,
- enables simple assemblage of the antenna on various objects (buildings, vehicles, masts, aircrafts, etc.)
- enables easier integration of the antenna and front-end components in a system [12].

V. CONCLUSION

In difference to well known class Yagi antenna, which are endfire arrays, a new class passive antenna arrays with broadside radiation is introduced. That is the Broadside Antenna Arrays with Passive Elements (BAAPE).

Geometrical parameters as well as performance of this new antenna class have been stated.

As it has been shown for good operation it is necessarily to choose geometrical parameters as follows. Element

- radii about 0.01 λ,

- length about λ,
- spacing about $\lambda/2$ and
- reflector distance about $\lambda/4$ or $2/3\lambda$.

Features of BAAPEs are the following: simplicity and planar construction, small number of elements (e.g. N=7 for D=17 dBi), high directivity (D=17-18dBi) and front to back ratio ($F/B \geq 20$dB), good aperture efficiency of the antenna and medium bandwidth (10-20%).

Given parameters vary in wide range, depending on the number of antenna elements and antenna size, so it is easy to choose appropriate antenna for a given application. Proposed antennas can be used as a single antenna or as an element of bigger planar antenna arrays.

In comparison to other antenna classes next conclusions could be made. Uniform illuminated aperture for same occupied area has directivity which is 1.5 – 3 dB greater than BAAPE, while directivity of Yagi antenna is about 3 dB grater than BAAPE.

On the other side for same number of elements BAAPE has 4 – 6 dB greater directivity than Yagi antenna. Thus for same directivity Yagi antenna has 2 – 2.5 times more elements than BAAPE.

Also, reflector is inherent part of planar unidirectional BAAPE construction and high front to back ratio could be obtained with its proper dimensioning. Opposite to BAAPE reflector in Yagi antenna results in 3D-antenna construction.

Finally, it could be concluded that BAAPE is very appropriate in designing of planar high gain and high efficiency antennas.

With aforementioned advantages, BAAPE has great potential for application in wireless communications.

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In this paper is described the invention of new antenna class, Broadside Antenna Arrays with Passive Elements.

The Fundamental principles of operations of Broadside Antenna Arrays with Passive Elements are covered in appropriate Boro Reljic's patent applications and is subject to Patent Low (Industrial Property Low), Patent Cooperation Treaty (PCT) and WIPO treaties.

VI. ACKNOWLEDGEMENTS

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