RESEARCH ARTICLE

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A Bidirectional Antenna Using a Probe Excited Rectangular Ring

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ABSTRACT This paper presents a simple and cost-effective bidirectional antenna using a probe excited rectangular ring. Radiation characteristics, such as radiation pattern and directivity, and impedance of this antenna are investigated. Radiated fields are calculated from the Fourier transform of the aperture field that is derived from the field inside the ring by using Green's function. Impedance of this antenna is realized by using induced EMF method. The impedance of a probe with optimum ring length that provides the single mode is firstly determined. Then, the resultant input impedance of the antenna is the reciprocal of the combination of the probe admittance and the both apertures admittance. From our investigations, for a specific ring dimension, the optimum ring length that yields the maximum directivity is calculated and chosen as a design parameter. Experimental results, verifying the bidirectional radiation pattern and impedance, agree very well with the theoretical predictions. This antenna is suitable to be a bidirectional base-station antenna in a street cell.

KEYWORDS: bidirectional antenna, probe, rectangular ring.

INTRODUCTION

In a cellular mobile system, the service area is divided into small cells. Generally, the area is approximated by a circle where the omnidirectional antennas are employed at the base station.[1] For a microcell mobile communication system, the communication follows the street and is usually called a "street cell". The zone size can be efficiently increased by using bidirectional antenna, which preferentially radiates the antenna beam along the street. Hence, bidirectional antennas are employed instead of the omnidirectional ones. A simple bidirectional antenna may be made up by combining two unidirectional antennas such as Yagi pointed in opposite directions or the omnidirectional antenna such as monopoles excited by appropriate phase.[2] The antenna constructed by this technique suffers from feeder loss and complicated structure that results in expensiveness. Therefore, research and development on bidirectional antennas have been continuously conducted. The bidirectional narrow patch antenna (BNPA), which has narrow patches on both sides of a narrow dielectric substrate fed by a parallel stripline is easily fabricated by printing patches and feeding network on a substrate. However, BNPA has low radiation efficiency. The radiation efficiency can be improved by adding two opposing parasitic patches to a BNPA to form the so-called BNPA-P.[3] It was found that gain is higher than a collinear antenna of the same length. For a wide street about the width ranging from 30 to 60 meters, a BNPA element is developed to be a bidirectional rod antenna (BIRA) that possesses an optimum beam shape.[4] Furthermore, a bidirectional antenna using two notch antennas cut in a sheet of conductor above a ground plane was proposed to extend the coverage of a relay station in booster system inside tunnel.[5] To suppress the cross polarization in the H-plane of this notch antenna, the crank shaped antenna modified from the original notch antenna was proposed.[6] It was found that the radiation patterns of these antennas are tilted up from the mounting wall and they should be tilted downward in order to cover the service area. This was accomplished by using the crank shaped antenna with the parasitic elements for gain enhancement.[7] From this aforementioned literature, it is evident that development of a bidirectional antenna that has suitable characteristics for a particular application is desired. Moreover, cost effectiveness must be considered since the number of microcells is very large. The authors have proposed a bidirectional antenna using a linear probe excited rectangular ring.[8] It was pointed out that a moderate gain bidirectional antenna could be easily realized with good cost effectiveness. However, only some results of radiation characteristics were presented in that work.[8]

This paper presents a cost-effective and simple structure bidirectional antenna using a probe excited rectangular ring. Characteristics of this antenna such as radiation pattern, directivity and impedance are analyzed. The aperture field is derived from the field inside the ring, with the feed probe excited in it, by using Green's function. Then, the radiated field is calculated from the aperture using Huygen's principle. Finally, superpositions of the fields from the two apertures are performed to investigate the radiation characteristics. Input impedance of the antenna is represented as the reciprocal of a shunt admittance of the probe in a ring, regardless of reflection, and two aperture admittances. These characteristics are analyzed to clarify the optimum dimension that yields suitable characteristics for practical application. They are verified by experiments.

Analysis of a Bidirectional Antenna Using a Probe Excited Rectangular Ring

Radiation Characteristics

A bidirectional antenna using a probe excited rectangular ring consists of a linear probe of length l aligned along the y axis, and this probe is surrounded by a rectangular ring that the surface is represented by ($-a/2 \le x \le a/2$, $y = -b/2$, $-c/2 \le z \le c/2$), ($-a/2 \le x \le a/2$, $y = b/2$, $-c/2 \le z \le c/2$), ($x = -a/2$, $-b/2 \le y \le b/2$, $-c/2 \le z \le c/2$), ($x = a/2$, $-b/2 \le y \le b/2$, $-c/2 \le z \le c/2$). At the ends of the ring, there are two apertures on the planes $z = -c/2$ and $z = c/2$, respectively, as shown in Fig 1.

To estimate the antenna characteristics, electromagnetic fields inside the ring must be firstly calculated. Green's function, a response at an observer from the unit point source, is a powerful tool to obtain the electromagnetic field in the source region. The Green's function of this antenna configuration was derived as shown in reference 9 and will not be repeated here for brevity. This Green's function is subject to the boundary condition that it vanishes at the conducting surface of the ring. In this work, we neglect the reflection at the edge of the ring. In this fashion, total radiation from the two apertures of the ring is considered. Electric field in this antenna structure can be derived by integrating the current on the probe as derived in reference 10 with the Green's function inreference 9. The resultant field can be expressed as

$$E_y(x,y,z) = A(l)\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\frac{1}{mk_z}\sin\left(\frac{m\pi}{2}\right)\cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)\cos(k_z z)$$

$$\cdot\left(e^{-j\frac{k_z c}{2}}-1\right)\left[Sa\left(\frac{kb+n\pi}{2}\right)+Sa\left(\frac{kb-n\pi}{2}\right)\right], \quad (1)$$

where k denotes the wave number of the free space at the operating frequency, $k_z^2 = k^2 - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b}\right)^2$, $A(l) = j\frac{4\omega\mu}{\pi}\sin(kl)$, ω and μ are the angular operating frequency and permeability of the medium, respectively and $Sa(x) = \frac{\sin(x)}{x}$.

When the fields in the ring are completely derived, the aperture surface current density can be determined by using Huygen's principle.[11] Then by using Fourier transformation[11], the radiated field of an aperture on the z=0 plane can be expressed as

$$\overline{E}(r,\theta,\phi) = jk\frac{e^{-jkr}}{2\pi r}\left[\hat{a}_\theta f_y \sin\phi + \hat{a}_\phi f_y \cos\phi\right], \quad (2)$$

where

$$f_y = \frac{abA(l)}{4}\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\frac{1}{mk_z}\sin\left(\frac{m\pi}{2}\right)\left(e^{-j\frac{k_z c}{2}}-1\right)\left[Sa\left(\frac{kb+n\pi}{2}\right)+Sa\left(\frac{kb-n\pi}{2}\right)\right]$$

$$\cdot\left[Sa\left(\frac{ka\sin\theta\sin\phi+m\pi}{2}\right)+Sa\left(\frac{ka\sin\theta\sin\phi-m\pi}{2}\right)\right].$$

The radiated field in (2) was derived when the aperture is located on the $z = 0$ plane. When the

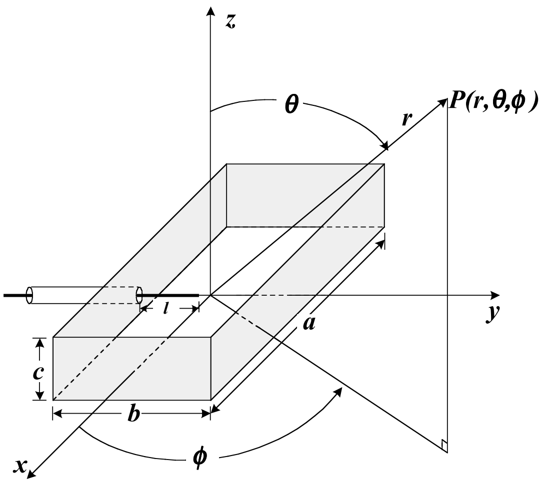

Fig 1. A probe excited rectangular ring.

apertures are removed from the $z = 0$ plane to $z = \pm c/2$, the radius r is substituted by r_1 and r_2, respectively as represented in Fig 2. These radii, r_1 and r_2, can be approximated[10], respectively, as follows:

$r_1 \approx r - \frac{c}{2}\cos\theta$ and $r_2 \approx r + \frac{c}{2}\cos\theta$ for phase variation and $r_1 \approx r_2 \approx r$ for amplitude variation.

The far-field pattern of the antenna can be expressed, by neglecting mutual coupling, as a superposition of the field from these two apertures. Since the fields radiated from the two apertures have the same phase but in opposite directions; therefore, they are combined, and the resultant field can be written as

$$\overline{E}_t(r,\theta,\phi) = \overline{E}(r,\theta,\phi) \cdot 2\sin\left[\frac{1}{2}\left(kc\cos\theta + k_z c\right)\right]. \quad (3)$$

IMPEDANCE CHARACTERISTICS

In order to transfer the power from a transmitter to the antenna or from the antenna to a receiver efficiently, impedance of the antenna must be characterized so that appropriate matching is achieved. In this paper, input impedance of the antenna is considered to be the reciprocal of resultant shunt admittances consisting of admittance of the probe with disregarding reflection from the two apertures and two aperture admittances. The admittance of the probe can be determined by using the induced EMF method[12] from the relationship

$$Y_p = \left[Z_p\right]^{-1} = \left[\frac{1}{I_m^2}\int \overline{E}\cdot\overline{J}\,dy'\right]^{-1}, \quad (4)$$

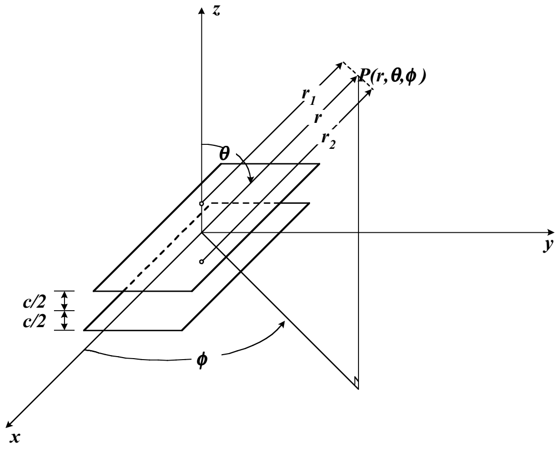

Fig 2. Far-field observation of the two apertures.

where $\overline{E}$ is the field calculated on the probe surface and $\overline{J}$ is the current distribution as shown in.[10] The probe impedance after substituting the field and the current as written above can be expressed as

$$Z_p = -j\frac{4\omega\mu\sin(kl)}{\pi}\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\frac{1}{mk_z}\sin\left(\frac{m\pi}{2}\right)\left(e^{-j\frac{k_z c}{2}}-1\right)\left[Sa\left(\frac{kb+n\pi}{2}\right)+Sa\left(\frac{kb-n\pi}{2}\right)\right]$$
$$\cdot\left[\begin{array}{l}\frac{1}{2}\sin(kl)\left\{Sa\left(\left(\frac{kb+n\pi}{b}\right)l\right)+Sa\left(\left(\frac{kb-n\pi}{b}\right)l\right)\right\}+\\ \frac{1}{2}\cos(kl)\left\{Ca\left(\left(\frac{kb+n\pi}{b}\right)l\right)+Ca\left(\left(\frac{kb-n\pi}{b}\right)l\right)\right\}\end{array}\right], \quad (5)$$

where $Ca(x) = \frac{\cos(x)}{x}$. In addition, aperture admittance (Y_a) can be calculated by using this relation[12],

$$Y_a = \frac{1}{V^2}\int_{-\frac{a}{2}}^{\frac{a}{2}}\int_{-\frac{b}{2}}^{\frac{b}{2}}\left(E_t^a \cdot H_t^a\right)\,dydx, \quad (6)$$

where E_t^a is the tangential electric field on the apertures. It can be considered from (1) whereas H_t^a is the aperture magnetic field which can be derived by substituting E_y from (1) into Maxwell's equation (Ampere's law). V is the voltage across the aperture. Y_a after manipulating as described can be expressed as

$$Y_a = -\frac{1}{V^2}\int_{-\frac{a}{2}}^{\frac{a}{2}}\int_{-\frac{b}{2}}^{\frac{b}{2}}\left\{j\frac{k_z}{\omega\mu}\left[A(l)\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\frac{1}{mk_z}\sin\left(\frac{m\pi}{2}\right)\cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)\right.\right.$$
$$\left.\left.\cdot\left(e^{-j\frac{k_z c}{2}}-1\right)\left(Sa\left(\frac{kb+n\pi}{2}\right)+Sa\left(\frac{kb-n\pi}{2}\right)\right)\right]^2\cos(k_z z)\sin(k_z z)\right\}dxdy \quad (7)$$

By transforming these admittances, from the ends of the both apertures ($z = \pm c/2$), along the waveguide to the probe position ($z = 0$), the combination of these two aperture admittances and the probe admittance provides the input admittance of a probe excited rectangular ring. Then, the input impedance of this antenna can be found by taking inverse of this input admittance. This transformation is conducted only in case of the optimum ring length that yields a single mode distribution.

From the results of these two subsections, antenna characteristics are expressed explicitly in terms of antenna parameters. We can analyze the condition that the optimum characteristics are obtained. The parameters from the optimum condition will be utilized as a design parameter.

Antenna Characteristics

Radiation Characteristics

According to the total field radiated by this antenna as shown in (3), it is obvious that the radiation characteristics of the antenna depend on the following parameters, ie, the probe length (l), the ring width (a), the ring height (b) and the ring length (c). Since the antenna structure is the same as a rectangular waveguide, in this circumstance the width and the height of the ring are chosen to be the dimension of a standard waveguide operating in a dominant TE_{10} mode. However, if the ring length is short, the field at the aperture which is closed to the probe will consist of several modes and the evanescent wave of the higher order mode near the probe still have a significant level. Therefore, they contribute to the aperture field and, consequently, the radiated field.

Fig 3 shows the aperture field distribution for the wavegide dimension of $a = 0.69\lambda$, $b = 0.35\lambda$, $l=0.28\lambda$ as a function of the ring length. When c equals 0.075λ, which is very short, the aperture field distribution is complex according to combination of higher order modes. As the length c is increased to 0.1λ these higher order modes attenuate rapidly, and the aperture field distribution is smoother than the previous one. When the ring length is further increased to 0.15λ these higher modes vanish at an expense of the long aperture separation. It is noteworthy that since the antenna acts as the array of two apertures, the distance between the apertures contribute on the radiation pattern.

Radiation patterns of the antenna with different ring lengths are compared in Fig 4. The E-plane ($\phi = \pi/2$) and H-plane ($\phi = 0$) patterns are depicted in Fig 4(a) and Fig 4(b), respectively. The short ring antenna, ie, c equals 0.075λ and 0.1λ possesses the splitbeam pattern according to the multimode aperture field. This results in the decreased directivity. The optimum ring length that provides the highest directivity must be clarified.

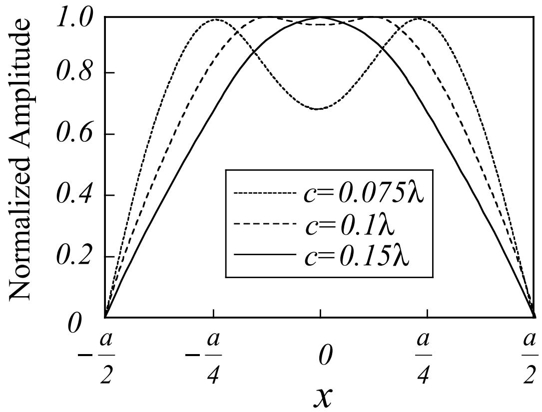

Fig 3. Aperture field distribution for various ring lengths ($a = 0.69\lambda$, $b = 0.35\lambda$, $l = 0.28\lambda$).

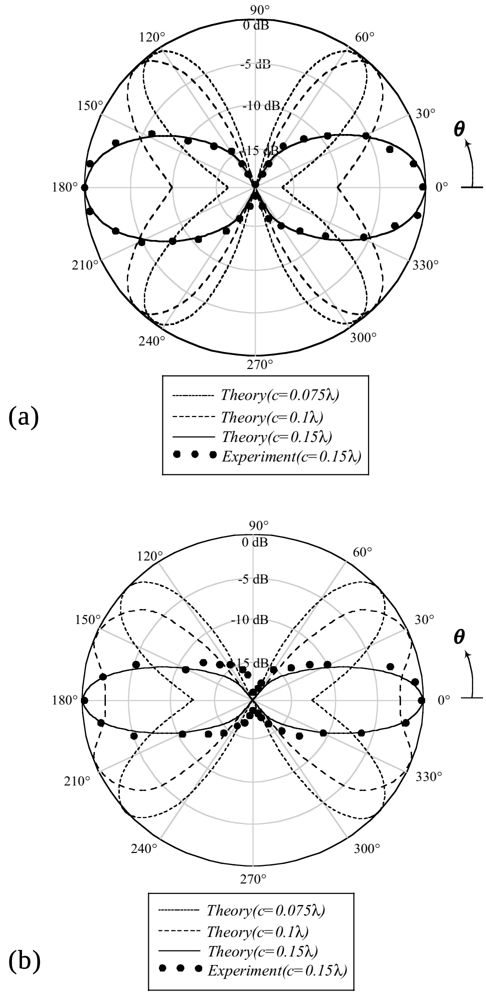

Fig 4. Radiation patterns for various ring lengths in two principal planes ($a = 0.69\lambda$, $b = 0.35\lambda$, $l = 0.28\lambda$).
(a) E-plane pattern
(b) H-plane pattern

Fig 5 shows the directivity as a function of the ring length when *l* is fixed at *0.28λ*, *a=0.69λ* and *b=0.35λ*. We can observe that at the ring length of *0.15λ*, the highest directivity of 9.3 dBi is achieved. Radiation patterns of the antenna when the ring length is *0.15λ* that illustrate the bidirectional pattern in E-plane and H-plane, are also posed in Fig 4(a) and Fig 4(b), respectively. The beamwidth in the E-plane and H-plane are *54* degree and 36 degree, respectively. From this investigation, it is realized that we have to choose the ring length of *0.15λ* as a design parameter.

Impedance Characteristics

To investigate impedance characteristics of this antenna, the ring dimension was fixed at one which provides the highest directivity, ie, *a* equals *0.69λ*, *b* equals *0.35λ* and c equals *0.15λ*. Then the input impedance was calculated by using (7) and plotted for various probe lengths on the graph in Fig 6(a). When the probe length is short, *l* equals *0.2λ*, for instance, the antenna acts as inductive impedance with low resistance and reactance. The longer the probe length, the higher the resistance and reactance. It is noted that, in Fig 6(b), the SWR is the lowest at the probe length is around *0.28λ*. Therefore, this length is employed as a design parameter.

When the antenna is designed to operate at the frequency of *1.9* GHz (*a=10.92* cm, *b=5.46* cm, *c=2.37* cm, and *l=4.41* cm), the variation of impedance and SWR as a function of frequency are illustrated in Figs 7(a) and 7(b), respectively. It is obvious that the antenna provides a wide bandwidth. The *8%* bandwidth where SWR is less than 1.5 are observed. The results shown in Fig 5 and Fig 7 reveal that this antenna provides a wide bandwidth of *8%* for the directivity of over 8 dBi and SWR less than *1.5*.

Communication Range

When the antenna was installed on the roadside, its pattern will cover the road as shown in Fig 8. If the space is free of reflection and scattering from

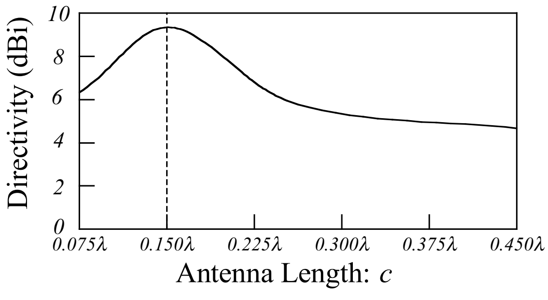

Fig 5. Directivity versus ring length (*a = 0.69λ*, *b = 0.35λ*, *l = 0.28λ*).

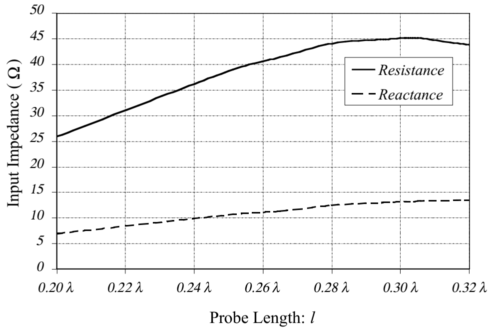

Fig 6. (a) Input impedance for various probe lengths (*a = 0.69λ*, *b = 0.35λ*, *c = 0.15λ*).

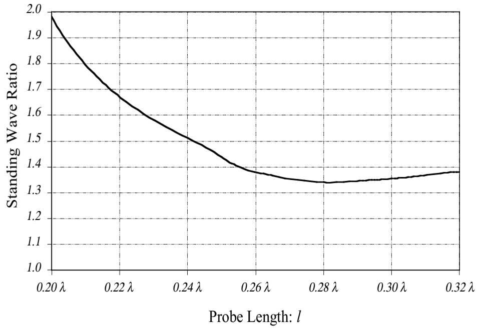

Fig 6. (b) Standing wave ratio for various probe lengths (*a = 0.69λ*, *b = 0.35λ*, *c = 0.15λ*).

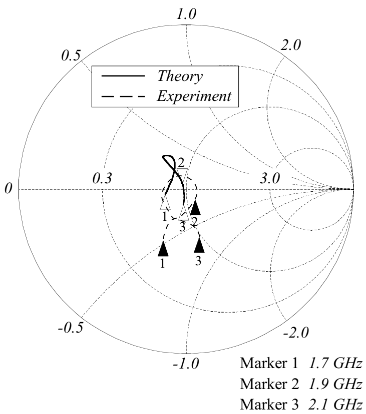

Fig 7. (a) Input impedance as a function of frequency (*a = 10.92* cm, *b = 5.46* cm, *c = 2.37* cm, *l = 4.41* cm).

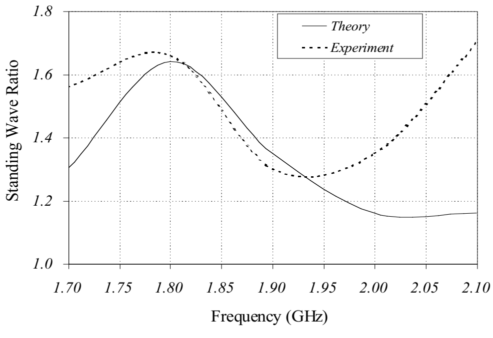

Fig 7. (b) Standing wave ratio versus frequency (*a = 10.92* cm, *b = 5.46* cm, *c = 2.37* cm, *l = 4.41* cm).

objects, the free space is considered. We can estimate the communication range by calculating the power received by the mobile unit when the bidirectional antenna using a probe excited rectangular ring is employed as a base-station antenna. In this demonstration, the operating frequency is chosen to be *1.9* GHz. When the transmitted power from the base station is fixed at *20* mW, and the gain of the mobile antenna is assumed to be unity in dimensionless, by utilizing the well-known Friis transmission equation[10], the relationship of power received by the mobile antenna (P_r) is

$$P_r = EIRP \cdot G_r \cdot \left(\frac{\lambda}{4\pi R}\right)^2, \qquad (8)$$

where *EIRP* stands for Effective Isotropic Radiated Power which is the product of the transmitted power and the directive gain of the base-station antenna, G_r is the gain of the mobile antenna (unity in dimensionless), λ is the operating wavelength (m) and R is the communication range (m).

As the mobile unit moves along the road from *A* to *B* and on to *E* as shown in Fig 8, the directive gain is slightly changed; however, the received signal is considerably changed according to the long distance.

Table I shows received signal at corresponding positions. The distance from the antenna to the mobile unit at point A is 3 m. Morever, the distances between the antenna to point B, C, D and E are slightly longer than the distance between each point of the mobile unit. We can realize that, for a conventional receiver with 12 dBμv sensitivity, the maximum range is in excess of 2.0 km. The maximum range in case of the 2.15 dBi omnidirectional antenna is employed in place of the bidirectional one is also calculated. It should be pointed out that the maximum range of the proposed bidirectional antenna is twice longer than that of the system that employs the omni-directional antenna.

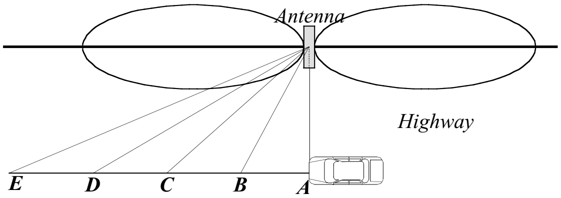

Fig 8. Antenna coverage on the highway (not to scale).

Experimental Results

To verify the theoretical results, a probe excited rectangular ring was fabricated to operate at the frequency of 1.9 GHz. The ring is cut from the part of the available brass waveguide. The probe is made of the copper rod. The dimensions are as follows: a equals 10.92 cm, b equals 5.46 cm, c equals 2.37 cm and l equals 4.41 cm. The probe diameter is 1 mm. The radiation patterns were measured and plotted on the same graph of the calculated results in Fig.4. It is obvious that the two results agree very well. There are slight errors due to neglecting the reflection at the end of the ring and assuming the current distribution along the probe to be sinusoidal function in the calculation. For the impedance characteristics, the antenna was measured by using a HP8720C Network Analyzer and compared with theoretical results as illustrated in Fig. 7(a). We can realize that the measured impedance is more sensitive to the frequency variation than the calculated results according to a single mode transformation of aperture admittance in calculation. However, both of the results show the same trend that we can be confident that this proposed principle is reliable. Comparison of SWR versus frequency with the measured counterpart is depicted in Fig. 7(b). It is obvious that the experimental results are slightly higher than the theoretical ones at the frequencies higher than the designed frequency. The bandwidth which SWR less than *1.5* is *8%*.

The field test was conducted to check the communication range by using the proposed antenna as a base-station antenna of the Personal Cordless Telephone (PCT) system in Thailand. The base station was installed on an elevated highway in the city of Bangkok. This environment is assumed to be free of multipath fading. The system specification is as represented in Table I. the mobile unit moved on the highway and it was connected to the base station. The longest range that the mobile unit can keep contact to the base station is around *2.0* km.

Table I. Estimation of communication range.

Position	Directive Gain (dBi)	Distance (m)	EIRP (dB_W)	Field Strength ($dB_{\mu V}$)
A	0	-	-	-
B	7.5	100	-9.5	26.3
C	8.0	500	-9.0	19.5
D	8.4	1000	-8.6	16.7
E	8.8	2000	-8.2	13.9

Generally, if an omnidirectional antenna is employed the communication range is about *1.0* km. This field test confirms that the proposed antenna can extend the communication range of the PCT system on an elevated highway.

CONCLUSION

We have proposed a simple structure bidirectional antenna using a probe excited rectangular ring. The expressions in this paper are derived by considering that the probe is thin for the sake of thorough understanding of the dependence of parameters on the antenna characteristics in addition to the simplicity that depends on the length of the ring, we can realize that for a specific ring dimension, there is an optimum length that provides the gain of more than *8* dBi with SWR less than *1.5* over the bandwidth of *8%* which is essential for a mobile communication on a highway, in a tunnel and in a corridor. However, in such a multipath environment, diversity charac-teristics must be taken into account in characterizing this antenna. This is left for further study. The input impedance can be varied by adjusting the probe length which makes it very easy to match. The measured results verify the proposed principle. According to the simple structure and low cost material, this antenna is acceptable as a cost-effective antenna.

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