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A Shaped Reflector Antenna for 60-GHz Indoor Wireless LAN Access Points

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Abstract—This paper addresses the design of a 60-GHz shaped reflector antenna that has to illuminate a predefined circular area without substantial spatial variation. At the boundary of this coverage area, the field strength has to fall off rapidly. Such efficient and confined illumination may be required in wireless networks that have to cope with a stringent link budget and/or require low channel dispersion. Typical examples are the emerging broadband wireless networks for customer premises and residential applications that will operate in the millimeter-wave frequency region. The particular property of the considered reflector is its diverging surface instead of the commonly applied converging shape. It is shown that the spatial variation within the defined coverage area can be within 1 dB, provided that the antenna is perfectly constructed. It is also shown that practical imperfections such as axial and lateral feed displacement and mispointing of the feed on top of effects due to blocking by the feed can contribute to spatial field variations on the order of a few decibels.

Index Terms—Shaped reflector antenna, 60 GHz, wireless LAN.

I. INTRODUCTION

WIRELESS local-area networks (LANs) that operate in the millimeter frequency range, especially around 60 GHz, may offer a large information transport capacity in pico cells. However, the state-of-the-art millimeter-wave technology for the 60-GHz range poses serious constraints with respect to feasible radio-frequency (RF) transmit power as well as front-end noise figure. Especially in case orthogonal frequency-division multiplex is applied, as proposed for broadband wireless systems, the linearity of the RF transmit amplifier should be within stringent limits that may necessitate considerable backoff. Consequently, a broadband wireless system has to cope with a critical link budget. Therefore, the antenna of a broadband wireless access point should have a radiation pattern that efficiently radiates toward the portable stations. The transmit power has to be distributed efficiently in the sense that the spatial fluctuation of the field strength has to be as small as possible within the defined coverage area, whereas outside this area the field strength has to fall off rapidly. Ideally, we would like to achieve a rectangular illumination profile across the coverage area. In principle, a good approximation of such a confined beam can be provided by an array antenna with properly weighted elements. Such

antennas, however, exhibit considerable antenna loss when operating at frequencies as high as 60 GHz. A more power-efficient alternative is the use of an aperture-type antenna. The design procedure for millimeter-wave biconical horn antennas presented in [1]–[3] yields a radiation pattern that provides a more or less uniform coverage, but such an antenna does not radiate efficiently toward the portable stations as required, since only half of the transmit power goes downwards. In principle, a biconical antenna having a bent horn could provide a beam that is directed more downwards. However, such an antenna is difficult to construct. This is clearly a disadvantage with respect to 60-GHz wireless LAN employment because radiowaves at 60 GHz do not propagate well through inner walls so that in each room to be covered at least one antenna would be necessary. Since many antennas have to be applied, it is important to consider antennas that can be produced with acceptable costs. An obvious candidate is the shaped reflector antenna that can be readily produced in high volumes by application of cost-efficient molding techniques.

At first, we will present the general design approach as far as it concerns the shaping of the reflector (Section II). Then we apply this shaping approach in a practical example (Section III). In Section IV, we treat the feed and strut construction of an antenna that has been manufactured to operate according to the scenario presented in Section III. Measured return loss as well as field strength patterns produced by this antenna are presented and discussed in Section V. In Section VI, a summary and the conclusions are given.

II. DETERMINATION OF THE REFLECTOR SHAPE

The reflector shape is determined on the basis of the theory of a shaped double reflector antenna with the help of geometrical optics (GO) [4] and the uniform geometrical theory of diffraction (UTD) [5]. GO is based on the assumption that the wavelength approaches zero, whereas UTD assumes that the wavelength is small in comparison with the dimensions of the objects the electromagnetic wave interacts with. GO predicts zero fields in shadow regions. The geometrical theory of diffraction (GTD) supplies the GO with rays diffracted by edges or corners of objects [6]. The major limitation of GTD is its failure at reflection and shadow boundaries, where it predicts infinite fields. UTD is in this context the wanted extension; it predicts smooth continuous fields at the boundaries. In principle, alternative methods as physical optics or the uniform asymptotic theory of diffraction could be used as well. However, these methods give less physical insight and require considerable computational effort when computing the fields. For these reasons and because UTD

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Fig. 1. Ray geometry of the shaped reflector antenna.

is well described in the literature, we applied UTD to incorporate diffraction in our considerations.

First, we will apply GO for shaping the reflector in such a way that it provides a rectangular illumination function as a result of GO reflections. Because of the use of GO, the design of the reflector antenna must satisfy the following conditions.

- 1) *Snell's law for a reflecting surface*: angle of incidence is equal to angle of reflection with respect to the normal vector.
- 2) *Law of conservation of power*: the energy per unit of time that passes through a surface within a ray tube is independent of that surface. The energy in the circle surface on the reflector is equal to the energy in the circle surface on the coverage plane-section. So the power flow in a ray tube is constant.

The ray geometry of the shaped reflector antenna is shown in Fig. 1. There are two coordinate systems in this figure: one describes the coordinates (x_r, y_r) of the reflector and the other one describes the coordinates (x_c, y_c) of the coverage plane. The parameters used in this figure are described below. Because of the rotational symmetry with respect to the vertical axis of the antenna system, only the situation for $x_r > 0$ is described:

- (x_r, y_r) coordinate point on the reflector surface;
- (x_c, y_c) coordinate point on the coverage plane;
- ρ^i ray length from the feed to the reflector surface;
- $\rho_{\max}^i$ maximum ray length from the feed to the reflector surface;
- ρ^r length of the reflected ray;
- $\rho_{\max}^r$ maximum length of the reflected ray;
- Ψ^i angle between the vertical axis and the ray from the feed;
- $\alpha_{\max}$ maximum angle between the vertical axis and the ray from the feed;
- Ψ^r angle between the vertical axis and the reflected ray;

$\Psi_{\max}^r$

D

D_c

F

h

maximum angle between the vertical axis and the reflected ray;

diameter of the reflector;

diameter of the coverage area;

distance between the feed and the origin of the (x_r, y_r) coordinate system;

distance between the origin of (x_c, y_c) coordinate system and the origin of the (x_r, y_r) coordinate system.

Application of Snell's law of reflection for the reflector leads to the following differential equation:

$$\frac{dy_r}{dx_r} = \tan \left[\frac{1}{2} \Psi^i - \frac{1}{2} \Psi^r \right]. \quad (1)$$

Because of the rotational symmetry of the antenna system, the relative power radiated by the feed between the angles 0 and Ψ^i can be modeled by

$$P_f = 2\pi \int_0^{\Psi^i} G_f(\Psi) \sin \Psi d\Psi \quad (2)$$

with $G_f(\Psi)$ the gain function of the feed. In the following, we assume that the feed is a corrugated horn so that its gain function can be written as:

$$G_f(\Psi) = \begin{cases} 2(n+1) \cos^n(\Psi), & \text{for } 0 \leq \Psi \leq \frac{\pi}{2} \\ 0, & \text{for } \Psi > \frac{\pi}{2}. \end{cases} \quad (3)$$

According to the second condition, the relative power given in (2) is equal to

$$P_f = 2\pi \int_0^{x_c} H(r) \cos(\Psi^r) r dr \quad (4)$$

Fig. 2. Field distribution for -10 dB edge illumination.

with $H(r)$ the power illumination function across the coverage plane.

Normalizing (2) and (4) to the total radiated power by the feed in the direction of the reflector and combining the results according to the second condition yields

$$\frac{\int_0^{x_c} H(r) \cos(\Psi^r(r)) r dr}{\int_0^{D_c/2} H(r) \cos(\Psi^r(r)) r dr} = \frac{\int_0^{\Psi^i} G_f(\psi) \sin \psi d\psi}{\int_0^{\alpha} G_f(\psi) \sin \psi d\psi}. \quad (5)$$

This, together with the two boundary conditions

$$\tan \alpha = \frac{D}{2F} \quad (6)$$

and

$$\tan(\Psi_{\max}^r) = \frac{D_c - D}{2h} \quad (7)$$

determines the total system. If, for instance, x_c is given, then x_r , y_r , and further Ψ^i , Ψ^r can be calculated. For the simple case of a rectangular illumination function, i.e., $H(x_c) = 1$ for $0 \leq x_c \leq D_c/2$ and zero elsewhere, we obtain

$$\begin{aligned} & \frac{\int_0^{x_c} \cos \left[\arctan \left(\frac{r - x_r}{h - y_r} \right) \right] r dr}{\int_0^{D_c/2} \cos \left[\arctan \left(\frac{r - x_r}{h - y_r} \right) \right] r dr} \\ &= \frac{\cos^{n+1} \left[\arctan \left(\frac{x_r}{F - y_r} \right) \right] - 1}{\cos^{n+1} \left[\arctan \left(\frac{D}{2F} \right) \right] - 1}. \end{aligned} \quad (8)$$

The surface function of the reflector can be obtained by expressing Ψ^i and Ψ^r in x_r , y_r , h , and F , substituting these expressions in (1) and then solving the differential equation (nu-

merically) for a given value of x_c . The numerical procedure applied should produce a large number of (x_r, y_r) pairs that must be substituted into the power equation (8). If a pair of (x_r, y_r) coordinates satisfies the power equation with a small relative difference between the left and right part (e.g., within 0.1%), then these coordinates can be considered as a unique point of the reflector that is valid for the given x_c value. For these calculations, the value of n has to be known. This value is related to the illumination from the feed. Note that for the determination of the edge illumination at the reflector, the free-space loss from the feed to the reflector edge must be taken into account.

In practice, the illumination function will be the vectorial sum of a component that results from these GO reflections (in what follows, denoted as the GO component) and a component that results from diffraction from the reflector edges (in what follows, denoted as the diffraction component). The diffraction component occurs as a spatial variation (ripple) of the field on top of the GO component.

III. PRACTICAL EXAMPLE

As an example, the field distribution over the coverage area is shown in Fig. 2 for a shaped reflector having $D = 0.3$ m, $F = 0.15$ m, $h = 3$ m, and $D_c = 8$ m. These values represent an access point antenna with acceptable dimensions intended for providing coverage in a moderately sized room. The antenna feed is a corrugated horn, which illuminates the reflector edge with -10 dB when compared with the illumination at the center of the reflector. The figure of -10 dB edge illumination may be considered as a compromise between the amount of spillover, on the one hand, and efficient illumination of the reflector surface on the other. The diffraction component is calculated on the basis of the UTD according to [5]. This method fails near the caustic of the edge. This caustic position, however, falls within the shadow that is caused by the feed. With an outer diameter of 1.6 cm, the feed produces a circular shadow region having a

Fig. 3. Field distribution for -20 dB edge illumination.

diameter of about 30 cm at 3 m below. As can be seen in Fig. 2, this region is excluded from the calculations. (An impression of these shadowing effects can be obtained, nevertheless, by considering the far-field measurement results in Section V.) From Fig. 2, we can conclude that the maximum ripple (top-top) is about 2.5 dB, whereas the field strength at both edges is exactly 6 dB below. These -6 dB dips at the boundary of the coverage area are unavoidable as long as the GO component is a rectangular illumination function with field strength equal to zero outside the coverage area. This is because the physics requires field transitions at GO reflection boundaries to be continuous. Therefore, the diffraction component has to compensate the discontinuity of the GO component yielding the smooth transition at the boundary of the coverage area shown in Fig. 2. One could argue that the ripple could be lowered by decreasing the edge illumination in order to decrease the edge diffraction. However, if we insist that the illumination function must be rectangular, then we have to reshape the reflector in order to take this into account. Fig. 3 shows the field pattern in case the edge illumination is lowered to -20 dB. This figure shows that the dip at the boundary is still -6 dB, as expected, and that the ripple has become larger instead of smaller. An obvious way to avoid at least the boundary dips is to base the reflector shape on a coverage area diameter that is slightly larger than that of the actual coverage area. As a consequence, some radiated power comes outside the coverage area so that it is wasted. A more effective way to lower the spatial field variation is to take a power illumination function with smooth continuous transitions, which extend outside the actual coverage area. As such, we propose

$$H(x_c) = \begin{cases} 1, & \text{for } 0 \leq x_c \leq 4 \\ 1 - a(4 - x_c)^2, & \text{for } 4 \leq x_c \leq 5 \end{cases} \quad (9)$$

in which x_c denotes the radial distance to the center of the coverage area, whereas parameter a represents the slope of the function with $0 < a < 1$. A small diffraction ripple is achieved in case a is close (but not equal) to one. The result for $a = 0.99$ is depicted in Fig. 4, which shows that the ripple has become within 1 dB. It can be felt that a further (slight) improvement is possible by starting the smoothed transition of the GO component already within the coverage area.

IV. ANTENNA CONSTRUCTION

The antenna reflector has been shaped to provide the field pattern shown in Fig. 4. A picture of the constructed antenna is shown in Fig. 5. The antenna feed is a corrugated conical horn that has been designed (according to standard design rules) to provide a circular symmetrical radiation pattern $2(n+1)\cos^n(\Psi)$. It illuminates the reflector edge with -10 dB when compared with the illumination at the center of the reflector (thus $n = 6.6$). This feed is connected via a transition to standard WR-19 waveguide. The transition transforms the TE_{10} mode, supported by the (rectangular) WR-19 waveguide into the TE_{11} mode supported by the circular entrance of the feed antenna. The antenna strut has been made from the WR-19 waveguide. The WR-19 waveguide has been applied as antenna strut instead of the WR-15 waveguide since it provides a more stable support of the feed antenna.

In order to avoid the necessity of polarization alignment, the polarization of the radiated field has been made circular. The linearly polarized TE_{11} mode that exists in the entrance of the feed horn is transformed into the circularly polarized TE_{11} mode (and vice versa). This is achieved by a polarizer, i.e., a dielectric slab with a critical length (of about 12 mm) placed in the feed entrance at an angle of 45° relative to the polarization vector

Fig. 4. Field distribution for -10 dB edge illumination and a smooth illumination function.

Fig. 5. Geometry of the shaped reflector antenna.

of the incoming TE_{11} mode. The polarizer has been made of 0.5-mm-thick Teflon ($\epsilon_r = 2$). Its ends are 2 mm tapered to a point in order to reduce reflections. The incoming TE_{11} mode may be decomposed into two orthogonal TE_{11} modes, polarized parallel and perpendicular to the polarizer, respectively. The parallel mode has a larger propagation constant than the perpen-

dicular mode, which results in the desired differential phase of about 90° . The difference in amplitude of these two modes was about 0.7 dB.

V. MEASUREMENT RESULTS

A. Measurement Results of Return Loss

Return loss (S_{11} parameter) measurements have been performed at the WR-19 waveguide input in the frequency range of 61–62 GHz. These measurements revealed frequency dips below -30 dB. It occurred that the frequency position of these dips could be tuned to the desired frequency by shifting the polarizer slightly (fraction of a millimeter). This is an interesting fact, since it eliminates the need of tuning stubs for the case that stringent requirements with respect to return loss have to be met. Shifting the deepest dip toward 61.2 GHz yields the plot of Fig. 6. The return loss of about -30 dB does not depend on the antenna environment. Even the removal of the reflector did not introduce a change. This complies with our expectation because the reflector has a diverging shape so that those reflections that come back in the feed horn via the reflector surface are significantly attenuated.

B. Measurement Results of Field Patterns

Field measurements were carried out in a compact antenna test range (CATR). Figs. 7–9 show, respectively, the far-field patterns measured at 0° , 45° , and 90° with regard to the strut, together with the theoretic GO illumination function [translation of (9) to the far field in polar coordinates yields the $\sec^2$ characteristic across the actual coverage area and the smooth rolloff at its boundaries]. The steepness of the pattern edges and the angular positions of these edges confirm that the antenna efficiently illuminates the target area to be covered. The dip in the pattern boresight of about 3 dB is caused by feed blockage. At most places the diffraction ripple remains within 1 dB, which

Fig. 6. S_{11} measured at the WR-19 entrance parallel to strut.

Fig. 7. Far-field pattern in plane parallel to strut.

can be attributed to the smooth rolloff of the applied illumination function. However, the measured radiation pattern cut that was taken along the strut show a relatively much larger ripple of almost 3 dB in amplitude. This can be explained by reflections occurring between the strut and the reflector. An additional cause of asymmetry observed in the patterns is (the combination of) the small defocusing and mispointing of the feed, i.e., feed displacements and tilts. According to the radiation pattern produced by the feed, an error of about 0.5 dB per degree

of mispointing is made. Hence, per degree of mispointing, an asymmetry of 1 dB is introduced. If we compare the average levels of the curves, we observe a difference on the order of 1 dB. Furthermore, it can be noticed that the curves do not precisely have the steepness of the theoretic GO illumination function. This can be attributed to the fact that this function does not include the effects of diffraction.

The deviation of the measured far field from the target pattern remains within 2.5 dB, which may be considered as a favor-

Fig. 8. Far-field pattern in plane 45° to strut.

Fig. 9. Far-field pattern in plane perpendicular to strut.

able result. Further improvements can be obtained by reducing the mispointing of the feed as well as by reducing the lateral and axial feed displacement. The GO/UTD calculations indicate that, apart from feed blockage effects, the spatial field variation can be reduced to less than 1 dB. The feed blockage effect can be anticipated and can be taken into account by adapting the reflector shape. However, it may be questioned whether the associated design effort justifies the resulting improvement, since the corresponding illumination area is only less than 1% of the total coverage area and its position is well predictable, namely, just underneath the antenna.

VI. SUMMARY AND CONCLUSION

An approach is described according to which a shaped reflector antenna can be designed that has to illuminate a predefined circular area with substantial uniformity, whereas at the boundary of this coverage area the field strength has to fall off rapidly. Such efficient and confined illumination is required in wireless LAN systems that have to cope with a stringent link budget.

The results from analysis based on geometrical optics and uniform geometric theory of diffraction indicate that the spa-

tial variation within the defined coverage area can be limited to within 1 dB. However, these results do not take into account the effects due to practical antenna imperfections such as axial and lateral feed displacement, mispointing of the feed, and effects due to blocking by the feed. Therefore, we measured the field patterns produced by a practical antenna that has been designed and constructed according to the presented design approach. These field patterns show that the antenna produces a circular footprint in the far field. Within this footprint, the deviation from the average field strength remains within 2.5 dB.

It occurs that for the considered antenna, the blockage by the feed has only a slight effect on the spatial field variation across the coverage area. In addition, the blockage can only be experienced at a small spot (1% of the total coverage area) just underneath the antenna. So, in the design, this blocking effect does not need to be taken into account.

REFERENCES

- [1] P. F. M. Smulders and A. G. Wagemans, "Biconical horn antennas for near uniform coverage in indoor areas at mm-wave frequencies," *IEEE Trans. Veh. Technol.*, vol. 43, pp. 897–901, Nov. 1994.
- [2] —, "Millimeter-wave biconical-horn antennas for near uniform coverage in indoor pico cells," *Electron. Lett.*, vol. 28, no. 7, pp. 679–680, Mar. 1992.
- [3] P. F. M. Smulders, *Broadband Wireless LAN's: A Feasibility Study*, The Netherlands: Eindhoven University of Technology, 1995.
- [4] V. Galindo, "Design of dual-reflector antennas with arbitrary phase and amplitude distortion," *IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 403–408, 1964.
- [5] R. G. Kouyoumjian and P. H. Pathak, "An uniform geometrical theory of diffraction for an edge in a perfectly conducting surface," *Proc. IEEE*, vol. 62, pp. 1448–1461, 1974.
- [6] J. B. Keller, "Geometrical theory of diffraction," *J. Opt. Soc. Amer.*, vol. 52, pp. 116–130, 1962.

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