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An applicable 5.8 GHz wireless power transmission system with rough beamforming to Project Loon☆

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Abstract

In recent, Google proposed the Project Loon being developed with the mission of providing internet access to rural and remote areas using high-altitude balloons. In this paper, we describe an applicable prototype of 5.8 GHz wireless power transmission system with rough beamforming method to Project Loon. From the measurement results, transmit beamforming phased array antenna can transmit power more efficiently compared to a horn antenna and array antenna without beamforming with increasing the transmission distance. For the transmission distance of 1000 mm, transmit beamforming phased array antenna can obtain higher received power about 1.46 times compared to array antenna without transmit beamforming.

Keywords: Wireless power transfer; Rectenna; Beamforming; High-altitude balloons; Phased array

1. Introduction

The majority of people in the world lack access to the internet. They cannot afford a connection or none exists where they live. Google proposed the Project Loon being developed with the mission of providing Internet access to rural and remote areas [1]. The project uses high-altitude balloons placed in the stratosphere at an altitude of about 32 km to create an aerial wireless network with 3rd generation (3G) speeds. The project considers solar power for high-altitude balloons. However, the usage of solar power is limited due to time and place. In the night time, since solar power system cannot produce electricity, it is impossible to use high-altitude balloons as an aerial wireless network. To overcome this problem, we focus on the wireless power transmission technology.

Wireless power transmission technology via microwave was advanced from 1960s [2]. This technology is the transmission of electrical energy from a power source to an electrical load without artificial interconnecting conductors. In the original form of this technology, solar cells would use a satellite in space to capture the suns energy and send the energy back to Earth. This concept would help to solve the major energy crisis. However, since the transmitted power would be spread in wide area, we should consider the effect on the human body and environment. If we transmit an electrical energy from earth to air, the above-mentioned problem can be reduced, significantly. Moreover, this concept would help the energy problem of the Project Loon.

Previously, the prototype of 5.8 GHz wireless power transmission system with high performance rectenna was developed for an electric vehicle system [3]. However, without transmission beamforming, the incident power density is not uniform for a large array. Therefore, not all of the rectenna elements have the same output voltage due to their different positions. From this reason, transmit beamforming is necessary to increase the received power density at the receiver side. In this paper, we describe the applicable developed prototype of 5.8 GHz wireless power transmission system with rough beamforming method to Project Loon. Here, the rough beamforming means that the transmit beamforming is operated with small number of phased array antennas. This paper is organized as follows. Wireless power transmission with rough beamforming is described in Section 2. In Section 3, we show

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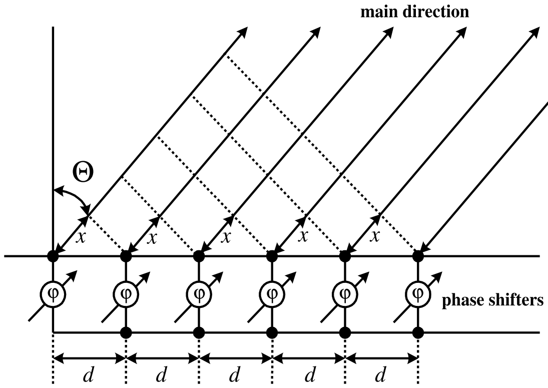

Fig. 1. Phased array antenna.

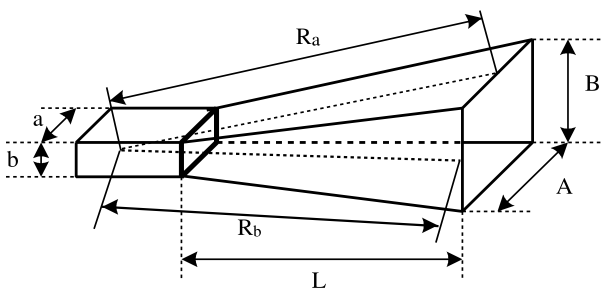

Fig. 2. Geometry of a horn.

the system experimental results. Finally, the conclusion is given in Section 4.

2. Wireless power transmission with rough beamforming

2.1. Transmit beamforming

Fig. 1 shows a linear arrangement of phased array antenna by isotropic radiating elements spaced $\lambda/2$ where λ is the wavelength of the center frequency f_0 of array. The directivity pattern, i.e., the relative sensitivity of response to signals from various directions, is in a plane over an angular range of $-\pi/2 < \Theta < \pi/2$ for frequency of f_0. The directivity pattern is symmetric due to the angle of Θ. If $\Theta = 0$, the main lobe is centered at $\Theta = 0$. If $\Theta \neq 0$, the directivity pattern has its main lobe at an angle of Θ radians (beam steering angle). In this case, the output of each element is delayed in time. The delay distance of each element is calculated as

$$\xi = d \cdot \sin\Theta, \tag{1}$$

where d is the spacing between antenna elements. The relationship between the phase different φ and the beam steering angle Θ is calculated by

$$\frac{2\pi}{\varphi} = \frac{\lambda}{\xi} = \frac{\lambda}{d \cdot \sin\Theta}. \tag{2}$$

The maximum steering angle is obtained with $\varphi = \pi$ as $\Theta_m = \sin^{-1}(\lambda/2d)$. As a result, the maximum steering angle is inverse-proportionally depending on the spacing between antenna elements.

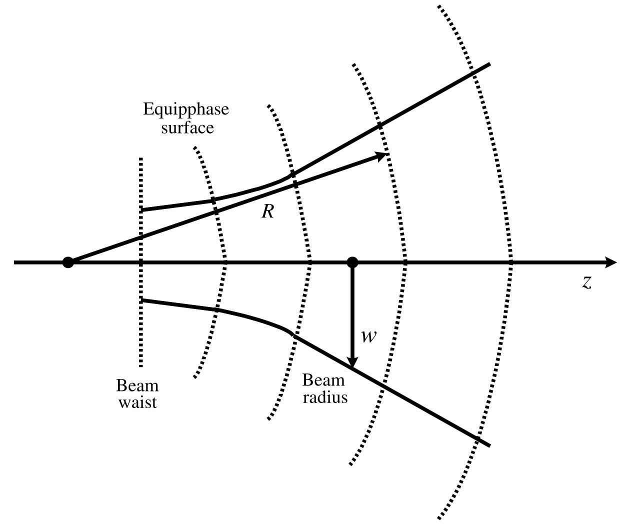

Fig. 3. Schematic diagram of Gaussian beam propagation.

2.2. Phased array with horn antennas

Fig. 2 shows the general geometry of a horn. The rectangular horn flares out of a rectangular or square waveguide with flat metal walls. In general, the slant radiuses along the sides will be unequal. The waveguide dimensions are width a and height b. The aperture has width A in the magnetic plane and height B in the electric plane. Each aperture coordinate has its own quadratic phase distribution constant as $S_e = \frac{B^2}{8\lambda R_a}$, $S_h = \frac{A^2}{8\lambda R_b}$, where R_a and R_b are the distance from the junction of the projected sides to the aperture center of the magnetic plane and the electric plane, respectively. The lowest-order waveguide mode has the field distribution as $E = E_0 \cos\frac{\pi x}{a}$. Combining these ideas, the aperture electric field changes gradually at the horn end and the aperture electric field is approximated by [4]

$$E = E_0 \cos\frac{\pi x}{A} \exp\left\{-j2\pi\left[S_e\left(\frac{2y}{B}\right)^2 + S_h\left(\frac{2x}{A}\right)^2\right]\right\}. \tag{3}$$

Here, each element of phased array with horn antenna was assumed as a diffraction-limited Gaussian beam. At $z = 0$ (transmitter surface), electric field distribution [5] is to be $E(r_i, 0) = E(0,0)\exp\left[-\left(\frac{r_i}{\omega_0}\right)^2\right]$, where ω_0 denotes the beam radius at $z = 0$, which is called beam waist radius, and r_i represents the perpendicular distance of the ith element from the axis of propagation as $r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$, where (x_i, y_i) is a center position of the ith element. Fig. 3 shows the behavior of the radius of curvature. As you can see, the radius of beam waist is the same value as the minimum radius of beam, where the radius of curvature is infinite, characteristic of a plane wave front. If we take the amplitude on-axis at the beam waist to be unity, the expression for the electric field of the ith element can be obtained by using the fundamental Gaussian beam mode as

$$E(r_i, z) = E(0,0)\frac{\omega}{\omega_0} \times \exp\left(\frac{-r_i^2}{\omega^2} - \frac{j2\pi z}{\lambda} - \frac{j\pi r_i^2}{\lambda R} + j\phi_0\right), \tag{4}$$