

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

Chang-Jun Ahn

Graduate School of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba, 263-8522, Japan

Received 5 November 2015; received in revised form 21 December 2015; accepted 19 February 2016

Available online 27 February 2016

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.

© 2016 The Korean Institute of Communications Information Sciences. Publishing Services by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

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 sun's 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

[☆] E-mail address: junny@m.icee.org.

Peer review under responsibility of The Korean Institute of Communications Information Sciences.

[☆] This paper has been handled by Prof. Byonghyo Shim.

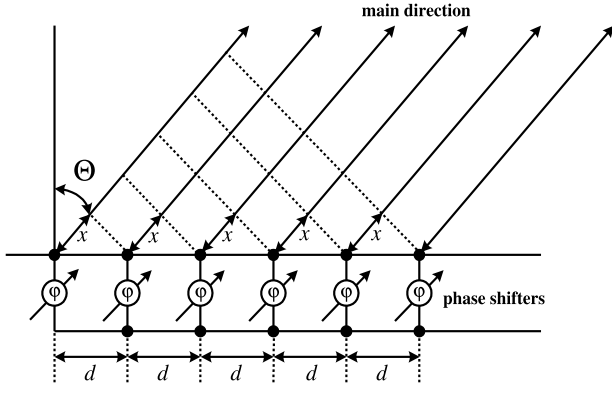


Fig. 1. Phased array antenna.

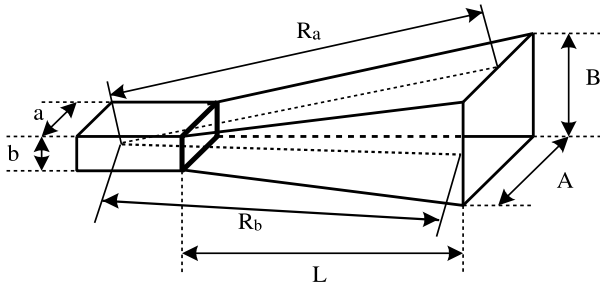


Fig. 2. Geometry of a horn.

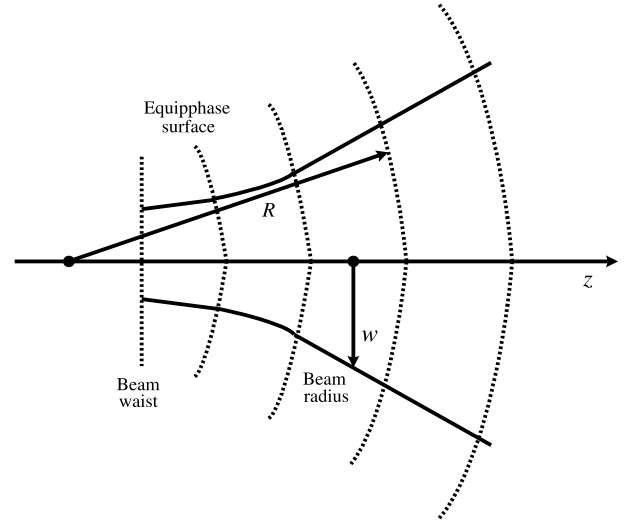


Fig. 3. Schematic diagram of Gaussian beam propagation.

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

$$\xi = d \cdot \sin \Theta, \quad (1)$$

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

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

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.

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 radii 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]

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

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 i th 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 i th 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 i th element can be obtained by using the fundamental Gaussian beam mode as

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

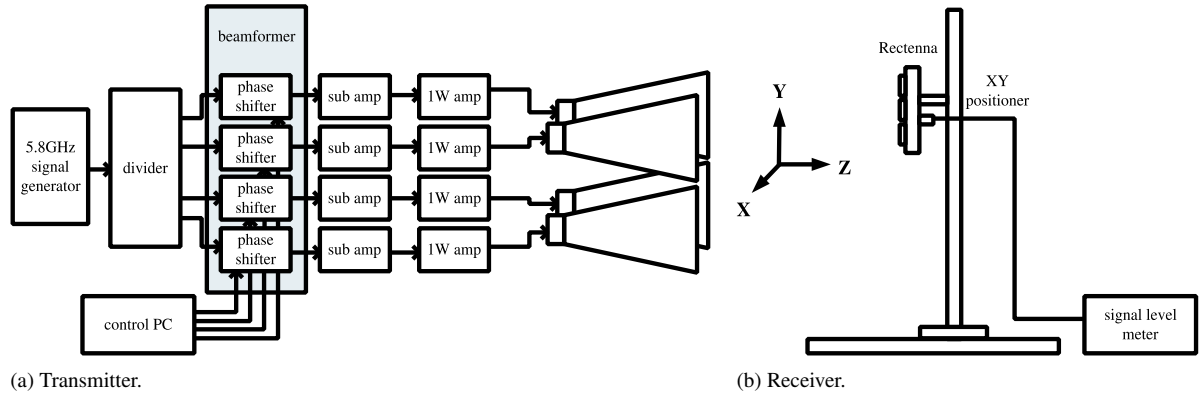


Fig. 4. Experimental configuration.

where ϕ_0 is the Gaussian beam phase shift as $\phi_0 = \tan^{-1}(\lambda z / \pi \omega_0^2)$, R is the radius of curvature as $R = z + \frac{1}{z} (\pi \omega_0^2 / \lambda)^2$, and ω is the beam radius at z as $\omega = \omega_0 \left[1 + (\lambda z / \pi \omega_0^2)^2 \right]^{\frac{1}{2}}$.

2.3. Rectenna

The rectenna, i.e. rectifying antenna, is one of the primary components in the wireless power transmission. The rectenna consists of antenna, matching circuit, and rectifying circuit. In the design of rectenna, microstrip dipole and patch antennas are widely used. In this paper, microstrip patch antenna is adopted due to its small-size manufacturing and no polarization characteristics. The rectifying circuit is a key element to improve the RF–DC conversion efficiency. A Schottky diode HSMS-8202 is chosen for the rectifying circuit. The developed rectenna shows the maximum gain as 6.2dBi at the frequency of 5.8 GHz with PTFT(Teflon) board of 10 dielectric constant and 1.6 mm thick [3]. Usually higher DC output voltage results in a smaller junction capacitance, which also gives better conversion efficiency. A broadband capacitor C08BLBB1X5UX is chosen as the DC pass filter.

3. Experimental results

Fig. 4 shows the experimental configuration of transmit beamforming wireless power transmission system. The system is provided by a field effect transistor (FET) oscillator and divided into four phase shifters using a power divider. The phase of each output signal is controlled by phase shifter. In this experiment, we used four phase shifters with 5.625 deg. resolution. Therefore, the phase is roughly controlled by a control PC. Furthermore, we did not use the any feedback information for calculating the phase of each output signal, since we already known the transmission distance to target object. Four FET amplifiers with each output power of 1 watt are used to have totally 4 watts. The size of a horn end is 112 mm × 85 mm and four horn antennas are arranged as shown in Fig. 4. Each horn antenna gain is 16dBi. The distances between the horn antenna and the center of rectenna array for measurement are 200 mm, 400 mm, 600 mm, 800 mm, and 1000 mm, respectively. The

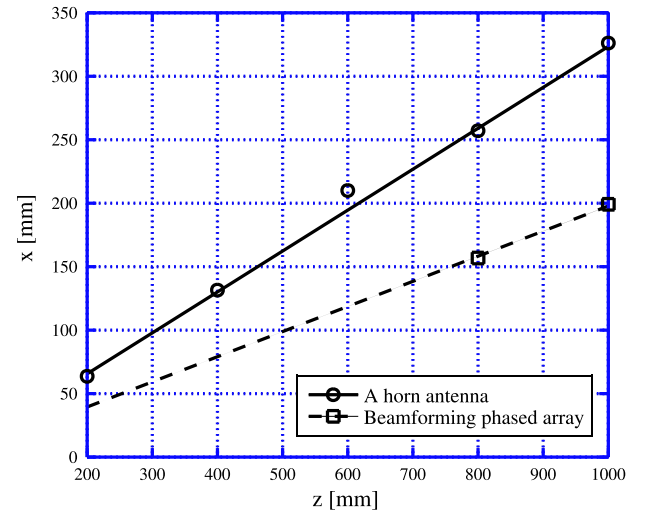


Fig. 5. Estimated beam characteristics.

4×4 rectenna array consists of 16 patch antennas and each patch antenna size is 19 mm × 15 mm. We adopted 5.8 GHz rectenna since the frequency of 5.8 GHz is ISM band. In this case, no license is necessary to experimentalize the wireless power transmission. However, a possible transmission power is also limited. Thus, in this experiment, 4 watts are used as a transmitted power. The 4×4 rectenna array is used and the load resistance is chosen as 50 Ω .

Fig. 5 shows the estimated beam characteristics of a horn antenna and transmit beamforming phased array antenna. Without beamforming operation, a horn antenna shows wide beam characteristic as a beam divergence of 38 deg. On the other hand, the beamforming phased array antenna shows a narrow beam characteristic as a beam divergence of 22 deg. compared to a horn antenna. To clarify the beam characteristics, the beam quality (M^2) is defined as [6]

$$M^2 = \frac{w}{w_0} = \frac{\tan \theta_{\text{div}}}{\tan \theta_{\text{div},0}}, \quad (5)$$

where θ_{div} is the estimated beam divergence, and $\theta_{\text{div},0}$ is the beam divergence of the diffraction-limited Gaussian beam as $\tan \theta_{\text{div},0} = \lambda / (\pi \cdot d)$. From the result of $\theta_{\text{div}} = 10.87$ deg., and

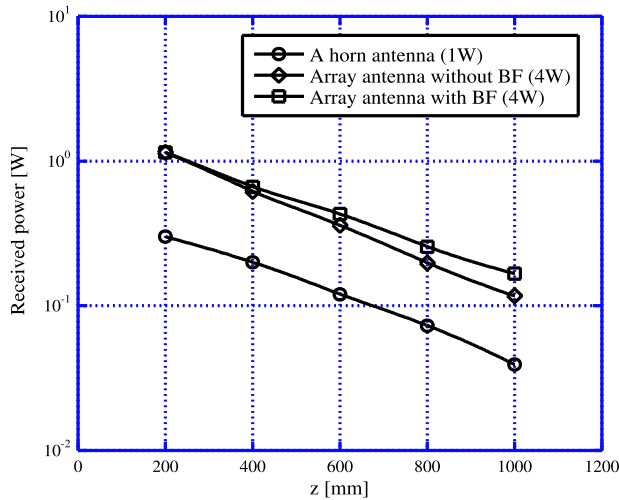


Fig. 6. Received power versus transmission distance.

$\theta_{\text{div},0} = 8.6$ deg., the beam quality is $M^2 = 10.87/8.6 = 1.26$. The transmit beamforming phased array antenna can achieve the improved beam quality. If we increase the area of phased array antenna, the beam quality can be improved significantly.

Fig. 6 shows the received power versus transmission distance for a horn antenna and array antenna with and without beamforming. 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 such as 800 m and 1000 mm. Particularly, for transmission distance of 1000 m, transmit beamforming phased array antenna can obtain higher received power about 1.46 times compared to array antenna without beamforming.

4. Conclusion

In this paper, we have developed 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 such as 800 m and 1000 mm. Particularly, for transmission distance of 1000 mm, transmit beamforming phased array antenna can obtain higher received power about 1.46 times compared to array antenna without beamforming.

Acknowledgment

This work is supported by the Grant of Scientific Research (C) No. 26420339 from the Japan Society for the Promotion of Science (JSPS).

References

- [1] <http://www.google.com/loon/>, accessed on October 11, 2015.
- [2] W.C. Brown, The history of power transmission by radio waves, *IEEE Trans. Microw. Theory Tech.* 32 (9) (1984) 1230–1242.
- [3] C. Ahn, T. Kamio, H. Fujisaka, K. Haeiwa, Prototype of 5.8 GHz wireless power transmission system for electric vehicle system, in: *Proc. of IEEE International Conference on Environmental Science and Technology, ICESS 2011, Singapore, 1 2011*, pp. 128–131.
- [4] T. Milligan, *Modern Antenna Design*, second ed., John Wiley & Sons, Inc., 2005, ISBN: 13 978-0-471-45776-3.
- [5] P. Goldsmith, *Quasioptical Systems: Gaussian Beam Quasioptical Propagation and Applications*, Wiley-IEEE Press, 1997, ISBN: 978-0-7803-3439-7.
- [6] K. Komurasai, T. Nakagawa, S. Ohmura, Y. Arakawa, Energy transmission in space using an optical phased array, *Trans. JSASS Space Tech. Japan* 3 (2005) 7–11.