LOW-COST TRANSMIT ANTENNA WITH BEAM-SHAPING PROPERTIES FOR RF ENERGY TRANSPORT

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Abstract: Far-field RF energy transport is an alternative for powering wireless sensor nodes. The major issues concerning the technology are path loss and transmitted power restrictions. After optimizing all subsystems of a rectifying antenna (rectenna) the power incident upon the rectenna can be increased without increasing the transmit power. Thereto the transmitted energy must be directed to the rectenna but also to the reflecting surrounding, such that all paths - direct and reflected - add in-phase at the rectenna. A cost-effective transmit antenna, capable of adaptively creating such a radiation pattern, is offered by a switched-array antenna. The concept is proved experimentally and by modeling and simulation.

Keywords: RF energy transfer, antenna, rectenna, switched array, dipole, mutual coupling

INTRODUCTION

For reducing energy consumption [1] as well as for realizing assisted living, wireless sensors need to be applied for creating (retrofit) smart houses and offices. A widespread use of wireless sensors has been halted so far by the problem of powering these sensors. Cabling is too expensive and cumbersome [2], batteries have unacceptable maintenance and environmental issues and energy harvesting is not always possible.

A way of overcoming the powering problem is provided by employing rechargeable batteries. These batteries, while being active, are being recharged remotely by means of radio waves. An antenna, positioned on the wireless sensor, intercepts part of the Radio Frequency (RF) energy in the radio waves and this RF energy is converted - through a fast-switching rectifying circuit - into usable DC energy. The rectifying circuit in combination with the antenna it is connected to is known as a *rectenna*, see Figure 1.

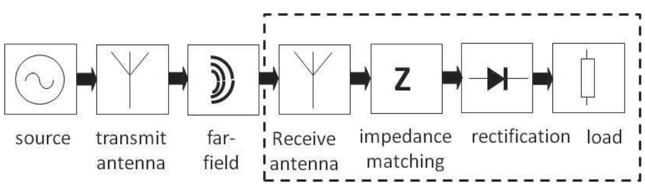

Fig. 1: RF power transmission system (rectenna inside the dashed box).

For the indoor applications we are dealing with, we do not only have control over the rectifying antenna (rectenna) [3]. Through the transmit antenna, we also have - to a certain extend - control over the wave propagation and the power density at the position of the rectenna.

Through exploiting reflections in an office environment we may obtain a better than free-space path loss as is illustrated in Figures 2 and 3 [4]. Figure 2 shows the received DC power of a rectenna connected to a voltage boost converter as a function of distance in an office corridor for a fan-beam transmit antenna (see inset), transmitting an Effective Isotropic Radiated Power (EIRP) of 32W. Figure 3 shows the received DC power as a function of distance for a broad-beam horn antenna (see inset) transmitting an EIRP of 10W. The frequency used in both experiments is 2.45GHz.

The Figures clearly show that with a 'proper' illumination of the sidewalls of the corridor, power may be delivered over a larger distance, employing a lower EIRP.

While the 'proper' illumination in different environments is currently being investigated, we have simultaneously started with the development of a low-cost transmit antenna with beam-shaping properties. These characteristics may be found in a switched array antenna.

SWITCHED ARRAY ANTENNA MODEL

From the above we see that we need a transmit antenna that establishes a Line Of Sight (LOS) link with the receiving rectenna. Next to that, the transmit antenna needs to illuminate the walls of the corridor. The exact illumination and thus the exact transmission antenna beam shape depend on the rectenna location(s) and the reflective environment.

An antenna with adjustable beam-steering capabilities may be realized by a phased array antenna in which the element phases or phases and amplitudes can be manipulated [5]. However, this is a solution requiring expensive phase-shifters and attenuators and requiring a bulky (and expensive) array feeding network.

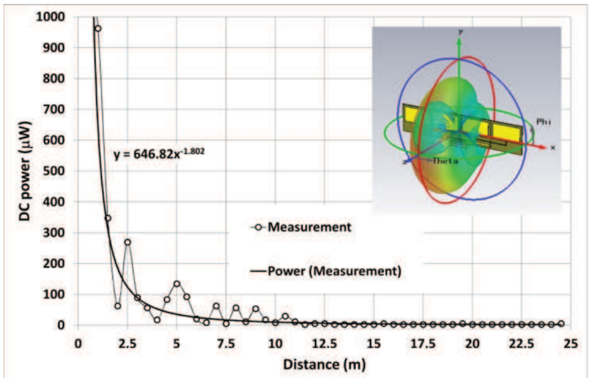

Fig. 2: DC power vs. distance in an office corridor. Transmission by a 2.45GHz, EIRP=32W fan-beam antenna, 50cm above the ground, receiver also 50cm above ground.

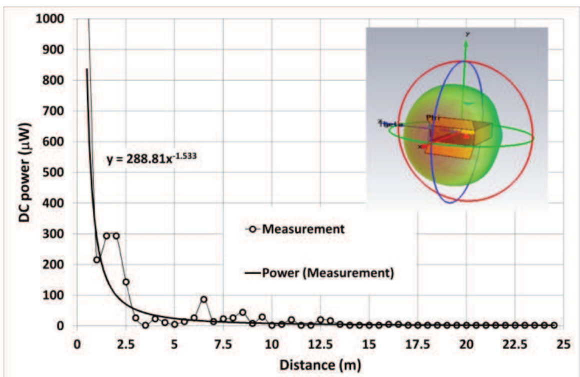

Fig. 3: DC power vs. distance in an office corridor. Transmission by a 2.45GHz, EIRP=10W broad-beam horn antenna, 50cm above the ground, receiver also 50cm above ground.

We may get rid of the feeding network by using a reactively loaded array antenna [6], see Figure 4.

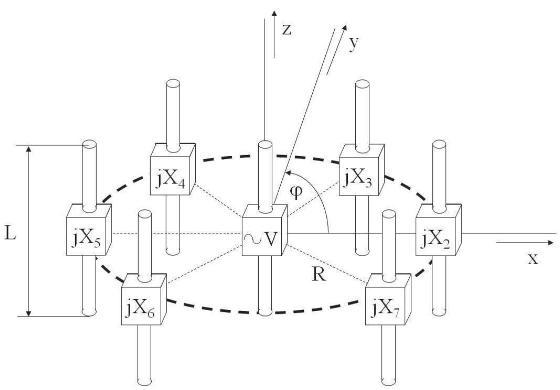

Fig. 4: Reactively loaded dipole array antenna.

By having the centre element in this shown array configuration driven and the surrounding elements being loaded with the appropriate reactive load, the antenna beam may be steered to a desired azimuthal direction φ. To change the beam direction or shape, the reactive loadings need to be adjusted.

One step further in realizing a low cost array antenna with beam-shaping properties is to replace the adjustable reactive loadings with switches; i.e. create a switched array antenna [7].

For an array antenna consisting of N elements, where the first element is the driven one (as the one shown in Figure 4), the voltage V is related to the antenna element currents through [8]:

$$V_1 = Z_{11}I_1 + Z_{12}I_2 + \cdots + Z_{1N}I_N \,. \qquad (1)$$

If the other N-1 elements are short-circuited, we may write

$$\begin{pmatrix} -Z_{21} \\ -Z_{31} \\ \vdots \\ -Z_{N1} \end{pmatrix} = \begin{pmatrix} Z_{22} & Z_{23} & \cdots & Z_{2N} \\ Z_{32} & Z_{33} & \cdots & Z_{3N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N2} & Z_{N3} & \cdots & Z_{NN} \end{pmatrix} \begin{pmatrix} I_2/I_1 \\ I_3/I_1 \\ \vdots \\ I_N/I_1 \end{pmatrix}, \qquad (2)$$

or, in a shorter notation

$$[V] = [Z]\cdot[I]. \qquad (3)$$

When the non-driven elements are loaded, a voltage drop over the load is created and a series impedance must be added to every one of these elements. Equation (3) then changes into

$$[V] = ([Z]+[Z_L])\cdot[I], \qquad (4)$$

where

$$[Z_L] = \begin{pmatrix} Z_{L2} & 0 & \cdots & 0 \\ 0 & Z_{L3} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Z_{LN} \end{pmatrix}. \qquad (5)$$

For a reactively loaded array antenna, $Z_{Li}=jX_i$, $i=2,\ldots,N$. For a switched array antenna, $Z_{Li}=0$ or $Z_{Li}=\infty$.

For the self-impedances Z_{ii}, $i=1,\ldots,N$, the approximation as given in [9] and corrected in [8] is being used

$$R_{ii} = \mathrm{Re}\{Z_{ii}\} = \sum_{m=0}^{4}\sum_{n=0}^{4} a_{mn}(2kl_i)^m \left(\frac{a}{\lambda}\right)^{-n},$$
$$X_{ii} = \mathrm{Im}\{Z_{ii}\} = \sum_{m=0}^{4}\sum_{n=0}^{4} b_{mn}(2kl_i)^m \left(\frac{a}{\lambda}\right)^{-n} \qquad (6)$$

where k is the wave number, λ is the wavelength, a is the radius and l_i is the half-length of the dipole element. The coefficients a_{mn} and b_{mn} may be found in [8] and [9].

For the calculation of the mutual impedance between two dipoles we assume the dipole elements to be infinitely thin. The mutual impedance $Z_{12}=R_{12}+jX_{12}$ for two dipoles of half-lengths l_1 and l_2, separated a distance $_d$ is then calculated as [10]

$$R_{12}=30\left\{\begin{array}{l}\cos k_0(l_1+l_2)\begin{bmatrix}Ci(u_0)+Ci(v_0)\\-Ci(u_1)-Ci(v_1)\\-Ci(w_1)-Ci(y_1)\\+2Ci(k_0d)\end{bmatrix}+\cos k_0(l_1-l_2)\begin{bmatrix}Ci(u_0')+Ci(v_0')\\-Ci(u_1)-Ci(v_1)\\-Ci(w_1)-Ci(y_1)\\+2Ci(k_0d)\end{bmatrix}\\+\sin k_0(l_1+l_2)\begin{bmatrix}-Si(u_0)+Si(v_0)\\+Si(u_1)-Si(v_1)\\-Si(w_1)+Si(y_1)\end{bmatrix}+\sin k_0(l_1-l_2)\begin{bmatrix}-Si(u_0')+Si(v_0')\\+Si(u_1)-Si(v_1)\\+Si(w_1)-Si(y_1)\end{bmatrix}\end{array}\right\}$$

$$X_{12}=30\left\{\begin{array}{l}\cos k_0(l_1+l_2)\begin{bmatrix}-Si(u_0)-Si(v_0)\\+Si(u_1)+Si(v_1)\\+Si(w_1)+Si(y_1)\\-2Si(k_0d)\end{bmatrix}+\cos k_0(l_1-l_2)\begin{bmatrix}-Si(u_0')-Si(v_0')\\+Si(u_1)+Si(v_1)\\+Si(w_1)+Si(y_1)\\-2Si(k_0d)\end{bmatrix}\\+\sin k_0(l_1+l_2)\begin{bmatrix}-Ci(u_0)+Ci(v_0)\\+Ci(u_1)-Ci(v_1)\\-Ci(w_1)+Ci(y_1)\end{bmatrix}+\sin k_0(l_1-l_2)\begin{bmatrix}-Ci(u_0')+Ci(v_0')\\+Ci(u_1)-Ci(v_1)\\+Ci(w_1)-Ci(y_1)\end{bmatrix}\end{array}\right\}, \tag{7}$$

where $Si(x)$ and $Ci(x)$, are the sine and cosine integral of argument x. The arguments used in (7) are specified in [10].

When the impressed current I_1 and the induced currents I_i, $i=2,\ldots,N$, are known, the radiation pattern of the antenna may be calculated. Therefore, we – again – assume infinitely thin dipole elements, supporting currents of the form

$$I_{di}=I_i\sin\left[k\left(l_i-|z_i|\right)\right] \quad \text{for} \quad -l_i<z_i<l_i\ . \tag{8}$$

The far electric field of the array antenna is then found to be

$$E_\vartheta=j\frac{60}{\sin\vartheta}\frac{e^{-jkr}}{r}\cdot\sum_{i=1}^{N}I_i\left[\cos(kl_i\cos\vartheta)-\cos(kl_i)\right]\cdot e^{jk(x_i\sin\vartheta\cos\varphi+y_i\sin\vartheta\sin\varphi)}, \tag{9}$$

where x_i and y_i are the positions of the elements in the $z=0$ plane, see Figure 4.

Now we have the tools ready for investigating the influence of switching elements on or off in a (thin) dipole array antenna. Furthermore, we can see how we may create desired antenna beam shapes by varying the number of elements, the positions of these elements in the array and the lengths of the dipole elements.

SWITCHED ARRAY ANTENNA ANALYSIS

For the switched array configuration shown in Figure 4 (reactive loads replaced with switches) we have limited beam shaping possibilities. By switching two elements on, we can direct the beam into azimuthal angles that are multiples of 60 degrees. Switching on elements 3 and 6 for example, will direct the beam in the directions $\varphi=60^0$ and $\varphi=-120^0$. Then by choosing the radius R and the dipole length L we may influence the beamwidth as is shown in Figure 5.

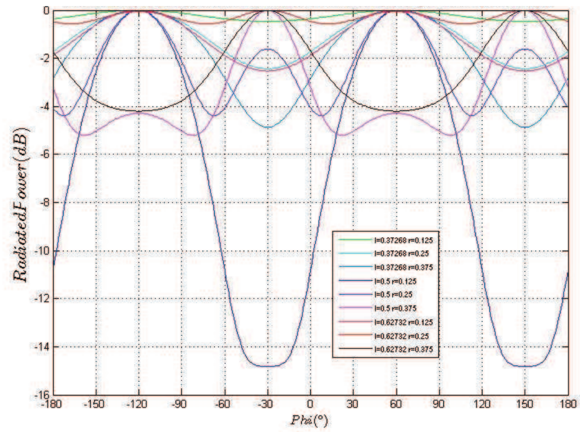

Fig. 5: Normalized radiated power for a switched dipole array antenna as shown in Figure 4 for different values of R and L, relative to the wavelength.

Once the radius and dipole lengths have been fixed, the adaptive properties of the antenna are very limited. To increase the beam-shaping properties of the antenna, more elements, arranged in two rings around the driven element, are added, see Figure 6.

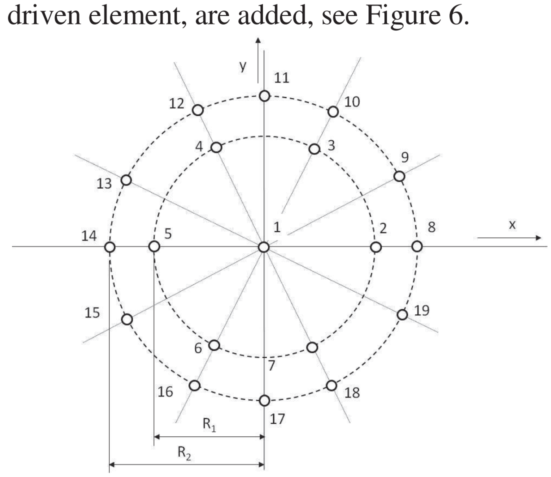

Fig. 6: Two-ring dipole switched array antenna. The centre element (1) is driven, the other elements may be left open or may be short circuited.

In the first example, we take $R_1=0.5\lambda$ and $R_2=1.0\lambda$. The dipole length of the driven dipole is 0.5λ, the lengths of the dipole antennas on the first ring is 0.45λ and the lengths of those on the second, outer ring is 0.54λ. Then, with element 1 driven and elements 2, 8 and 11 till 17 switched on, i.e. short-circuited, the normalized radiation pattern as shown in Figure 7 is created.

We see a radiation pattern with a forward directed lobe and two strong lobes in the directions of the walls when this antenna would be installed in a corridor.

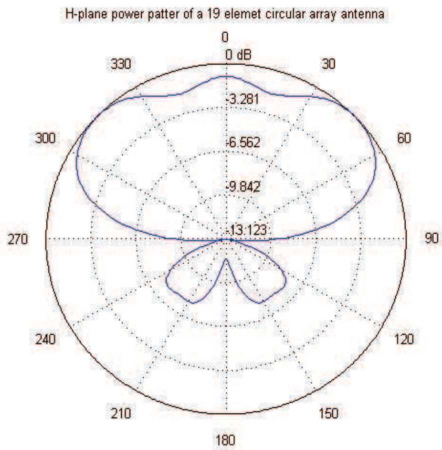

Fig. 7: Normalized radiation pattern of the two-ring dipole switched array antenna shown in Figure 6. Elements 2,8 and 11 till 17 short-circuited.

It is very likely, see Figures 2 and 3, that such a pattern will aid in increasing the power transfer distance. If, applying the same antenna configuration, we have element 1 being active and we switch on elements 2, 8 and 10 till 18, we may strengthen the forward lobe, at the expense of more back radiation, see Figure 8.

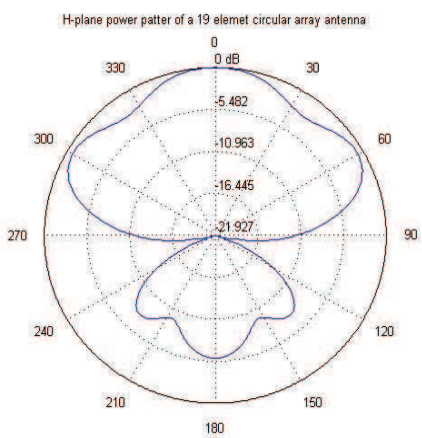

Fig. 8: Normalized radiation pattern of the two-ring dipole switched array antenna shown in Figure 6. Elements 2,8 and 10 till 18 short-circuited.

By switching on elements 2.3.7 and 11 till 17 we may create a broad beam with a minimum radiation in the backward direction, see Figure 9. The lengths of the dipole elements are as in the previous two examples.

CONCLUSION

Through an approximate modeling it has been shown how a switched array of vertically directed wire dipole antennas, positioned in two concentric rings may be used for adaptively shaping the radiated beam. Only the centre dipole element is driven, all other elements may be left open or may be short-circuited through the use of switches.

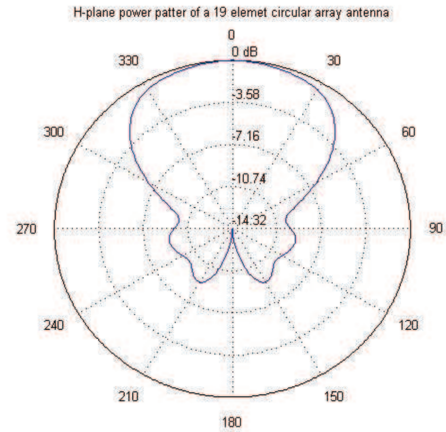

Fig. 9: Normalized radiation pattern of the two-ring dipole switched array antenna shown in Figure 6. Elements 2,3, 7 and 11 till 17 short-circuited.

By choosing different lengths for the dipole antennas on the different rings, elements may be switched as reflectors or directors as in a Yagi-Uda antenna. The demonstrated concept may be applied in transmitting antennas for RF energy transfer in an office environment where is necessary, next to the establishing a LOS link, to illuminate the walls in the environment.

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