Multi-user Wireless Power Transfer through Time-Modulated Near-Field Focused Arrays

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***Abstract*—A novel approach for Near-Field Focusing is presented with the aim of simplifying the implementation of Wireless Power Transfer systems. It is based in the novel concept of Time-Modulated Arrays and it is especially intended for scenarios where multiple users are present, with devices to be fed and requiring a fast adaptation of the radiating system. Sime preliminary results are presented.**

***Index Terms*—Wireless Power Transfer, NF Focusing, Antenna Arrays, Time-Modulated Arrays.**

I. Introduction

Wireless Power Transfer (WPT) [1] is becoming a relevant state-of-the-art research topic as far as new techniques allow its implementation in different manners. It basically consists on concentrating energy onto a position where a device to be fed is located so that it may use such energy. Although different technologies may be considered into the WPT frame, one of the most extended ones is Near-Field Focusing (NFF) [2]–[4] using antenna arrays, which allows concentrating radiated field power on certain pre-assigned spots in the near-field (NF) region of an antenna.

Near-Field Multi-Focusing (NFMF) [5] has been proposed as an efficient technique able to create multiple focal spots in different positions of the near-field region. It has been formulated as an optimization problem whose inputs are the assigned positions, and whose outputs are the complex weights to be applied to the elements of the array so that the overall NF distribution is actually concentrated on those positions. Although NFMF has been shown to provide excellent results, one of the drawbacks of this approach is the complicated implementation of an adaptive system able to change the weights of the elements of the array to focus on other positions when moving devices are to be fed. Implementation technologies at the frequencies involved in usual WPT applications are far from simple and cheap adaptation of the phase shifting process required to modify the weights.

In this paper we propose a novel approach to NFMF based on a simpler implementation that allows digital control over the weights applied to each element of the array, so that modifying them becomes simpler. This approach is based on Time-Modulated Arrays (TMA) [6], which have been used in recent years as an alternative to conventional arrays for digital beamforming applications. TMAs are antenna arrays whose radiation patterns are controlled by periodically enabling and disabling the excitations of the individual array elements, what results not only in different radiated field distributions depending on some parameters associated to the control signals, but also in different radiated frequencies each one with a different radiated field distribution. A proper choice of the parameters defining the control signals may allow a certain control on the radiation properties of the array at each frequency. However, TMAs have only been formulated for far-field (FF) problems, and the previously proposed formulation has only been developed for their use as receivers. In this paper we extend the formulation so that it may be used in a more general case, hence widening the range of potential applications.

II. Time-Modulated Arrays: background

TMAs, in their simplest configuration, are antenna arrays whose radiation patterns are controlled by periodically enabling and disabling the excitation of the individual array elements, as illustrated in Figure 1 where the block diagram of a TMA with N elements implemented with radio-frequency (RF) switches may be observed, with I_n being a static excitation of the n-th element of the array. On the right side of the plot the periodic (T_0) pulse train that governs the n-th switch is plotted, denoted $g_n^{T_0}(t)$ and characterized by the normalized pulse duration $\xi_n = \tau_n/T_0$ and the normalized switch-on instant $\sigma_n = \delta_n/T_0$. In the existing literature, it is shown that the use of the aforementioned pulses results in side frequencies whose associated radiation patterns depend on the parameters of the pulses.

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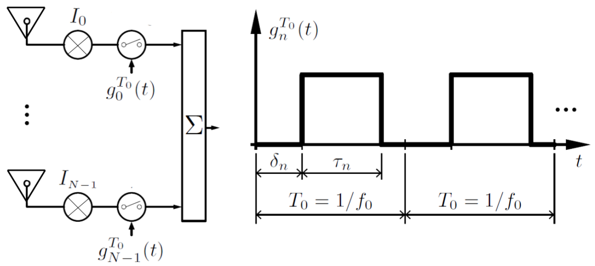

Fig. 1: Time-Modulated Array: basic concept and main parameters.

The receiving radiation pattern of the N-element TMA, also considering time-dependence, is given by

$$F(\theta, t) = e^{j2\pi f_c t} \sum_{n=0}^{N-1} p_n^{T_0}(t) \omega_n e^{j\hat{k}\cdot\vec{r_n}} \quad (1)$$

where the position vector corresponding to the n-th isotropic element of the array is $\vec{r_n}$. The array is assumed to be located in the plane XY, and the broadside is the z-axis. As stated in the figure, $p_n^{T_0}(t)$ is a periodic function with a fundamental period $T_0 = 1/f_0$, which governs the n-th array element, with $n = 0 \dots N-1$; $w_n = |w_n|e^{j\phi_n}$ represent the n-th antenna element complex static current excitation in its polar form; f_c is the carrier frequency of the incoming signal; and $k = 2\pi/\lambda$ is the wave number for a wavelength $\lambda = c/f_c$ with c being the speed of light.

Since $p_n^{T_0}(t)$ is a periodic signal, it can be represented by the following Fourier series:

$$p_n^{T_0}(t) = \sum_{q=-\infty}^{\infty} P_{nq} e^{jq2\pi f_0 t} \quad (2)$$

Considering τ_n the duration of the pulse and δ_n its delay, P_{nq} is given by:

$$P_{nq} = \xi_n \text{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n + 2\sigma_n)} \quad (3)$$

where $\text{sinc}(x) = \sin(x)/x$, $\xi_n = \tau_n/T_0 \in (0,1) \subset \mathbb{R}$ are the normalized pulse durations, and $\sigma_n = \delta_n/T_0 \in [0, 1-\xi_n] \subset \mathbb{R}$ are the normalized pulse delays. Note that for $q = 0$ we get $P_{n0} = \xi_n$. The resulting expression (1) can be rewritten as:

$$F(\theta, t) = \sum_{q=-\infty}^{\infty} e^{j2\pi(f_c + qf_0)t} \dots$$

$$\dots \sum_{n=0}^{N-1} I_n \xi_n \text{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n + 2o_n)} e^{j\hat{k}\cdot\vec{r_n}} \quad (4)$$

The overall expression shows that the resulting pattern is a sum of patterns at different frequencies separated qf_0 from the carrier f_c, with effective excitations $I_n \cdot P_{nq}$. The term $q = 0$ is usually called *fundamental mode*. Note that by a proper design of I_n, ξ_n and σ_n we can control in some degree the radiation pattern at each frequency.

III. Formulation for Near-Field Focusing problems.

Time-Modulated Arrays, as proposed in previous works, are formulated for FF reception problems only. When used in the receiver, propagation is not affected by the side frequencies as far as the received signal consists, according to the formulation, of a single frequency, f_c (the carrier frequency). The use of switches in the receiver results in the corresponding side-frequencies due to the Fourier series-representation of the rectangular pulses, but these frequencies are only present in the processed signal. However, when considering a transmitter based on TMAs, the side frequencies are present in the radiated signal, so this fact has to be accounted for when formulating the propagation. In particular, the wave-number depends on the wavelength and such dependency has to be included in the formulation.

A NF formulation for the radiation pattern suitable for transmission is:

$$F(\vec{r}, t) = e^{j2\pi f_c t} \sum_{n=0}^{N-1} g_n^{T_0}(t) I_n \frac{e^{j\hat{k}(\lambda_q)(\vec{r} - \vec{r_n})}}{|\vec{r} - \vec{r_n}|} \quad (5)$$

where the dependency of the wave number with the frequency has been included, being $\lambda_q = c/(f_c + qf_0)$ and $\vec{r}$ the position of the space where the field is evaluated. By expanding $g_n^{T_0}(t)$ using a Fourier series, the resulting expression accounting for the different frequencies is

$$F(\vec{r}, t) = \sum_{q=-\infty}^{\infty} e^{j2\pi(f_c + qf_0)t} \dots$$

$$\dots \sum_{n=0}^{N-1} I_n \xi_n \text{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n + 2o_n)} \frac{e^{j\hat{k}(\lambda_q)(\vec{r} - \vec{r_n})}}{|\vec{r} - \vec{r_n}|} \quad (6)$$

where the term for $q = 0$ corresponds to the carrier frequency. According to this expression, the resulting effective weights $I_n \xi_n \text{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n + 2o_n)} \in \mathbb{C}$, or their parameters $I_n \in \mathbb{C}$, $\xi_n, o_n \in \mathbb{R}$ may be calculated to achieve different behaviors at each frequency $f_c + qf_0$. Most previous works are devoted to side-frequencies suppression, neglecting their potential to achieve different behaviors that might be useful for multi-user scenarios. Through a proper synthesis scheme, the parameters that constitute the weights might be calculated so that different specifications are fulfilled for the different frequencies. It is true that the specific formulation of the weights applied to the TMA reduces drastically the number of degrees of freedom available for synthesis purposes with respect to a conventional array. However, some experiments have been carried out

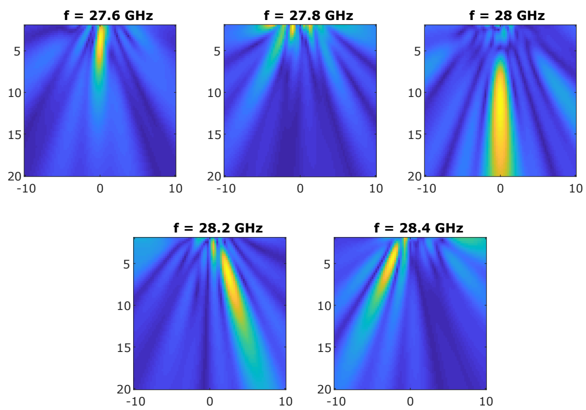

Fig. 2: Experiment #1.

to verify if the suitable control over the arrays weights is enough to allow some control on the resulting patterns, taking advantage of the simpler implementation of this kind of array that allows the use of adaptive weights through the modification of the pulse signals, which may be generated using a digital system.

IV. Results

In experiment #1, an 8×8 element array, with interelement distance $d = 0.7\lambda$ operating at 28GHz has been considered. The fundamental frequency for the pulse signal is 200MHz. Four focal points have been specified, according to the following frequency distribution where all the distances are referred to $\lambda = c/f_c$:

q	Freq	Focal point
-2	27,6 GHz	$(0, 0, 5)\lambda$
0	28 GHz	$(0, 0, 10)\lambda$
1	28,2 GHz	$(3, 0, 8)\lambda$
2	28,4 GHz	$(-3, 0, 6)\lambda$

TABLE I: Experiment #1. Frequency distribution for each focal point.

After a direct optimization (in a very basic approach), the results are plotted in Fig. 2.

In experiment #2, a 16×16 element array, with interelement distance $d = 0.7\lambda$ operating at 28GHz has been considered. The fundamental frequency for the pulse signal is 200MHz. Five focal points have been specified, according to the following frequency distribution where all the distances are referred to $\lambda = c/f_c$:

In this experiment, the required weights for each frequency have been calculated using the CP method. The parameters of the weights $I_n G_{nq}$ have been optimized to make them as close to the CP-obtained weights as possible. The results are plotted in Fig. 3.

q	Freq	Focal point
-2	27,6 GHz	$(5, 0, 12)\lambda$
-1	27,8 GHz	$(0, 0, 12)\lambda$
0	28 GHz	$(-3, 0, 12)\lambda$
1	28,2 GHz	$(3, 0, 12)\lambda$
2	28,4 GHz	$(5, 0, 12)\lambda$

TABLE II: Experiment #2. Frequency distribution for each focal point.

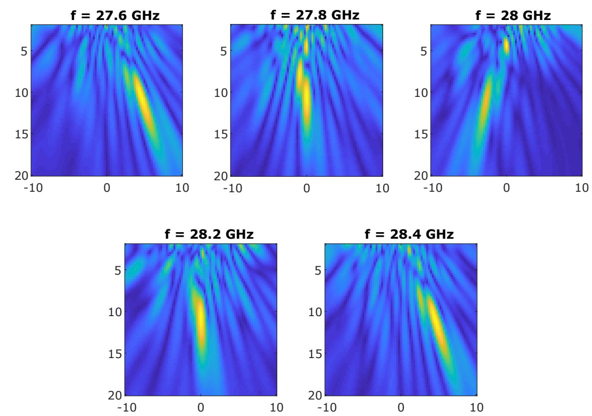

Fig. 3: Experiment #2.

V. Conclusion

A promising method for NFF able to concentrate field on multiple targets has been presented. Its number of degrees of freedom is reduced with respect to conventional NFF methods, but the presented results let us think that they may be enough for proper multiple-user focusing in WPT applications. The control parameters that determine the resulting radiation pattern at each frequency are part of the digital control signals, and not of the radio-frecuency system itself, so fast and simple adaptation may be possible by modifying those parameters and simplifying the implementation of real adaptive systems.

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