Multi-spot Adaptive Near-Field Focusing through Transmitting Time-Modulated Arrays

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***Abstract*—A novel approach for Near-Field Focusing is studied, which is based on the Time-Modulated Arrays concept. The latter exploits the adaptation of digital signals to control the radiating properties of an antenna array, hence simplifying the implementation of adaptive arrays with respect to more complex architectures based on high-frequency amplifiers and phase shifters. The price to pay is a strong reduction in the number of degrees of freedom available for synthesis purposes, and whose potential impact is here evaluated. It is especially intended for scenarios where multiple users are present and different frequency channels may be used, with devices to be wirelessly fed and requiring a fast adaptation of the radiating system, for example in applications such as Wireless Power Transfer, IoT or 5G scenarios. Some preliminary tests and results are presented to evaluate the potential of the proposed approach.**

***Index Terms*—Wireless Power Transfer, Near Field Focusing, Antenna Arrays, Time-Modulated Arrays, Multi-spot focusing.**

I. Introduction

Wireless Power Transfer (WPT) [1], [2] is becoming a relevant state-of-the-art research topic as far as new results allow its implementation using different technologies. It consists on concentrating energy onto a position where a device to be fed is located so that it may capture and use such energy. Different technologies have been proposed into the WPT frame, but one of the most promising ones is Near-Field Focusing (NFF) [3], [4], [5], [6] using antenna arrays, which allows concentrating radiated field power on certain pre-assigned spots in the antenna near-field (NF) region.

The most popular approach to NFF is the Conjugate-Phase (CP) approach [4], [5], a robust technique with a clear physical meaning that can operate fast enough for real-time applications, but that is intended for one focal point, i.e., one target or device to be fed. Near-Field Multi-Focusing (NFMF) [7], [8] has been proposed as an efficient technique able to create simultaneous multiple focal spots in different positions of the antenna near-field region. It has been formulated as an optimization problem whose inputs are the assigned locations for the devices to be fed, and whose outputs are the complex weights to be applied to the array elements. Although NFMF has been shown to provide excellent results, one of the drawbacks of this approach (or any other based on synthesizing weights) is the complicated implementation of an adaptive system able to change the current weights of the array elements in such a way that the focal spot can continuously track the device to be fed even when the latter is moving. Implementation technologies at the frequencies involved in usual WPT applications are based on radio- or high-frequency amplifiers and phase shifters, resulting in a complicated hardware architecture.

In this paper we study a novel approach to NFMF based on a simpler implementation allowing for a digital control over the radiation properties of the array. This approach is based on Time-Modulated Arrays (TMAs) [9], [10], [11], [12], 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 using switches in the feeding line of each array element, resulting in different radiated frequencies each one with a different radiated field distribution depending on some parameters associated to the control signals. A proper choice of the parameters defining these control signals may allow a certain control on the radiation properties of the array at each frequency. Modifying these digital control signal is much easier than using high-frequency hardware for a direct control over the weights at each array element, resulting in a potential simplified implementation. The price to pay is a strong reduction in the number of available degrees of freedom, and hence in the focusing capabilities of the radiating system. One of the objectives of this work is evaluating if TMAs may be suitable for NFF applications despite the reduced focusing performance with respect to conventional NFF array architectures [13].

Moreover, TMAs have only been formulated for far-field (FF) coupling, and the previously proposed formulation has only been developed for their use as receivers or for a very narrow bandwidth, not accounting for propagation effects at different frequencies separated from the carrier. In this paper we extend previous formulation so that it may be used in NFF using transmitting arrays, hence widening the range of potential applications.

II. Time-Modulated Arrays: background

TMAs are antenna arrays whose radiation properties are controlled using switches in the feeding line of each array element. In Fig. 1, the block diagram of a TMA with N elements implemented with switches is reresented, where I_n is a static weight (for example, related to the feeding line length) applied to the n-th element of the array. The periodic (T_0) pulse train $p_n^{T_0}(t)$ that is used to control the n-th switch is plotted in Fig. 2 along with its properties: the pulse duration and switch-on instant, both normalized to the fundamental

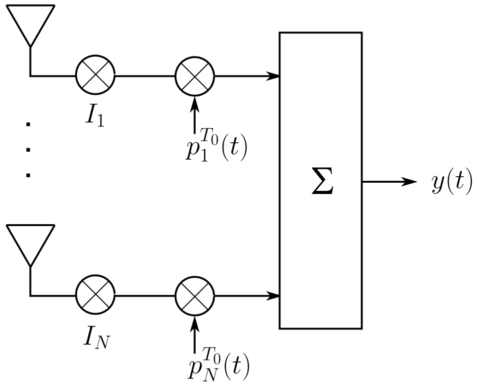

Fig. 1. Time-Modulated Array: receiving scheme.

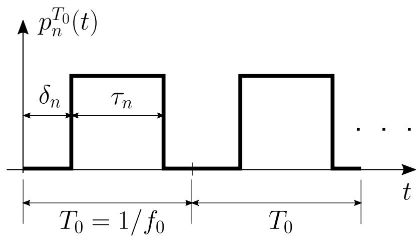

Fig. 2. Time-Modulated Array: control signal for the n-element of the array.

period T_0, are denoted by $\xi_n = \tau_n/T_0$ and $\sigma_n = \delta_n/T_0$, respectively. In the existing literature (see [9], [10], [11], [12] and the references therein) it is shown that the use of the aforementioned pulses results in side frequencies whose associated radiation patterns depend on the pulse parameters.

The FF receiving pattern of a TMA with N ideal isotropic elements, also considering time-dependence, is given by

$$F(\theta,t) = e^{j2\pi f_c t}\sum_{n=0}^{N-1} p_n^{T_0}(t) I_n e^{j\hat{k}\cdot\vec{r}_n'} \qquad (1)$$

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, the broadside ddirection coincides with the z-axis, and the radiation angle θ is determined by the direction of the unitary propagation vector $\hat{k}$. As shown in Fig. 2, $p_n^{T_0}(t)$ is a periodic function with a fundamental period $T_0 = 1/f_0$, which governs the n-th array element, with $n = 0 \ldots N-1$; $w_n = |w_n|e^{j\phi_n}$ represent the n-th antenna element complex static current excitation; f_c is the carrier frequency of the incoming signal.

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

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

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

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

where $\mathrm{sinc}(x) = \sin(x)/x$, $\xi_n = \tau_n/T_0 \in (0,1) \subset \mathbb{R}$ 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:

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

$$\ldots \sum_{n=0}^{N-1} I_n \xi_n \mathrm{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n+2\sigma_n)} e^{j\hat{k}\cdot\vec{r}_n'} \qquad (4)$$

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 given by the product $I_n \cdot \xi_n \mathrm{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n+2\sigma_n)}$. 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 [9], [10].

III. Formulation for Near-Field Focusing problems.

Time-Modulated Arrays, as formulated in the previous section, are intended for FF receivers only. When using TMAs in a receiver, phase delay of the propagation terms does not affect the pulse signal since it is introduced at the receiver (see Fig. 2). The use of switches at the receiver side 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 pulse signals are also affected by the propagation delay, so this fact has to be accounted for when formulating the propagation phenomenon. Considering this fact, the formulation for the NF electric field distribution, suitable for transmission, is:

$$E_{NF}(\vec{r},t) = e^{j2\pi f_c t} \ldots$$

$$\ldots \sum_{n=0}^{N-1} p_n^{T_0}\left(t - |\vec{r}-\vec{r}_n'|/v\right) I_n \frac{e^{-jk_c|\vec{r}-\vec{r}_n'|}}{|\vec{r}-\vec{r}_n'|} \qquad (5)$$

where the propagation delay between $\vec{r}_n'$ and $\vec{r}$ has been included in the pulse signal, $\vec{r}$ is the position of the space where the field is evaluated, k_c is the wavenumber at f_c, and v is the propagation velocity. By expanding $p_n^{T_0}(t)$ using a Fourier series, the resulting expression accounting for the different frequencies is

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

$$\ldots \sum_{n=0}^{N-1} I_n \xi_n \mathrm{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n+2\sigma_n)} \frac{e^{j(k_c+qk_0)|\vec{r}-\vec{r}_n'|}}{|\vec{r}-\vec{r}_n'|} \qquad (6)$$

where the term for $q = 0$ corresponds to the carrier frequency, and k_0 is the wavenumber at f_0. According to this expression, the resulting effective weights $I_n \xi_n \mathrm{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n+2\sigma_n)} \in \mathbb{C}$, or their parameters $I_n \in \mathbb{C}$, $\xi_n, \sigma_n \in \mathbb{R}$ may be calculated to achieve different behaviors at each frequency $f_c + qf_0$. Most previous works are devoted

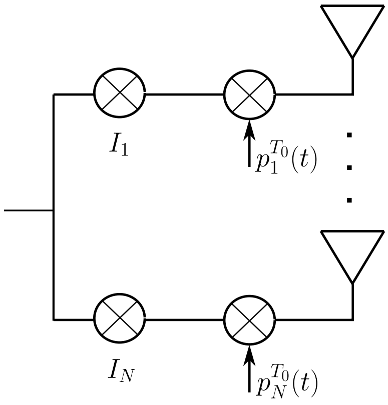

Fig. 3. Time-Modulated Array: transmitting diagram.

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 tests have been carried out 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. Synthesis of Time-Modulated Arrays Using Direct Optimization

In order to perform different tests and simulations to evaluate the potential of TMAs for multi-user NFF applications, a simple synthesis technique based on an optimization method has been tested. It is based on the minimization of a cost function accounting for the distance between the *target* NF distribution and the synthesized one for each frequency. The target distribution is built as an artificial (and unreachable) distribution consisting on unitary values in the samples corresponding to the assigned focal points, and zero values at any other position, according to:

$$T(\vec{r}_m, q) = \begin{cases} 1, & \text{if } \vec{r}_m \text{ is a focal point in } f_c + qf_0 \\ 0, & \text{if } \vec{r}_m \text{ is not a focal point in } f_c + qf_0 \end{cases} \tag{7}$$

The optimization problem is formulated as:

$$\underset{I_n,\xi_n,\sigma_n}{\text{minimize}} \sum_q \sum_{m=1}^{M} \left(T(\vec{r}_m, q) - D(\vec{r}_m, q)\right)^2 \tag{8}$$

with

$$D(\vec{r}_m, q) = \sum_{n=0}^{N-1} I_n \xi_n \operatorname{sinc}(q\pi\xi_n) e^{-jq\pi(\xi_n+2\sigma_n)} \frac{e^{j(k_c+qk_0)|\vec{r}-\vec{r}_n'|}}{|\vec{r}-\vec{r}_n'|}$$

and subject to

$$\xi_n \in (0,1) \subset \mathbb{R}$$
$$\sigma_n \in [0,1] \subset \mathbb{R}$$
$$I_n \in \mathbb{C}$$

where M is the number of positions $\vec{r}_m$ considered in the NF region.

V. Results

In simulation #1, an 8×8 element array, with interelement distance $d = 0.7\lambda$ operating at $f_c = 28$ GHz has been considered. The fundamental frequency for the pulse signal is $f_0 = 200$ MHz. Four focal points have been specified, according to the frequency distribution presented in Table I 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

Simulation #1. Frequency distribution for each focal point.

After a direct optimization using (8), a set of parameters corresponding to the NF distributions in Fig. 4 are obtained. All the focal points have been specified in the plane $y = 0$ in order to simplify the representation. It can be observed how the focal points lay into -3 dB spots for all the four frequencies of interest, and no focal spot may be observed in the frequency 27.8 GHz for which there were no requirements.

In simulation #2, a 32×32 element array, with interelement distance $d = 0.7\lambda$ operating at 28 GHz has been considered. The fundamental frequency for the pulse signal is now 20 MHz. Five 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	27.96 GHz	$(5, 0, 12)\lambda$
-1	27.98 GHz	$(0, 0, 12)\lambda$
0	28 GHz	$(-3, 0, 12)\lambda$
1	28.02 GHz	$(3, 0, 12)\lambda$
2	28.04 GHz	$(5, 0, 12)\lambda$

TABLE II

Simulation #2. Frequency distribution for each focal point.

In this simulation, the required weights for each frequency have been calculated again using the direct optimization (8). The results are plotted in Fig. 5.

It may be observed that the obtained maximum points are much closer to the focal points than in simulation #1 due to the increased degrees of freedom of the larger array, and the synthesized spots are much smaller, hence concentrating the radiated power at the assigned positions. However, an interesting effect to point out is related to the power density itself, at is is reduced as the frequencies are more separated from the carrier. It may be noticed that for f_c there is a -3 dB focal spot where both the focal and maximum points are contained, but such spot does not exist for the other frequencies and the resulting spots are -6 dB with respect to the maximum power density in the NF region, or even -9 dB as it is observed in $f_c + 2f_0 = 28.04$ GHz. This effect is due to the frequency response of the system, determined by the *sinc* function in (5), that enforces a reduction of the field level according to the main lobe of the sinc. It may be potentially reduced if certain constraints are introduced in the optimization so that the parameters of the control signals are limited to values corresponding to a wider sinc function. This simulation has been carried out with a direct optimization without any constraints, so the resulting parameters might lead to this level-reduction effect. Further developments regarding the synthesis of TMAs with control of the resulting patters at each frequency should include these aforementioned constraints.

VI. Conclusion

A promising method for NFF able to concentrate field on multiple targets, but using a technology allowing a much simpler and affordable implementation, has been presented. It is based on the Time Modulated Arrays concept, which provides different radiating configuration by modifying the parameters of a digital control signal, and not using high-frequency hardware such as variable amplifiers or phase shifters. It has been proven useful to perform multi-user NFF by assigning a frequency (or channel) to each user. Its number of degrees of freedom is drastically 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 applications such as Wireless Power Transfer. Fast and simple adaptation of the system may be possible by modifying the digital signal parameters, hence simplifying the implementation of real adaptive systems suitable for applications where moving devices are involved.

Further developments must be carried out to address certain pending issues: a proper synthesis method, a way to deal with the field level reduction of the side frequencies due to the frequency response of the system, or a study of the limitations due to the reduced degrees of freedom in the synthesis of radiated field distributions. However, the presented preliminary results indicate that after these developments, a reasonable approach to multi-user NFF might compensate its drawbacks with its simpler implementation.

Acknowledgment

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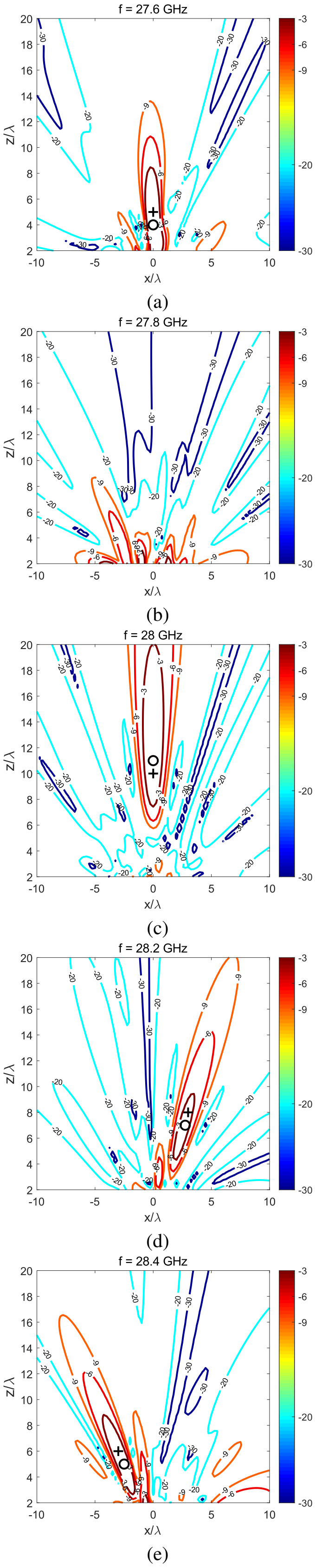

Fig. 4. Simulation #1. Normalized NF power density distribution in the plane $y = 0$ for the frequencies $f_c + qf_0$ with $q \in [-2, 2]$. The symbols + and $\circ$ represent the focal and synthesized maximum points respectively.

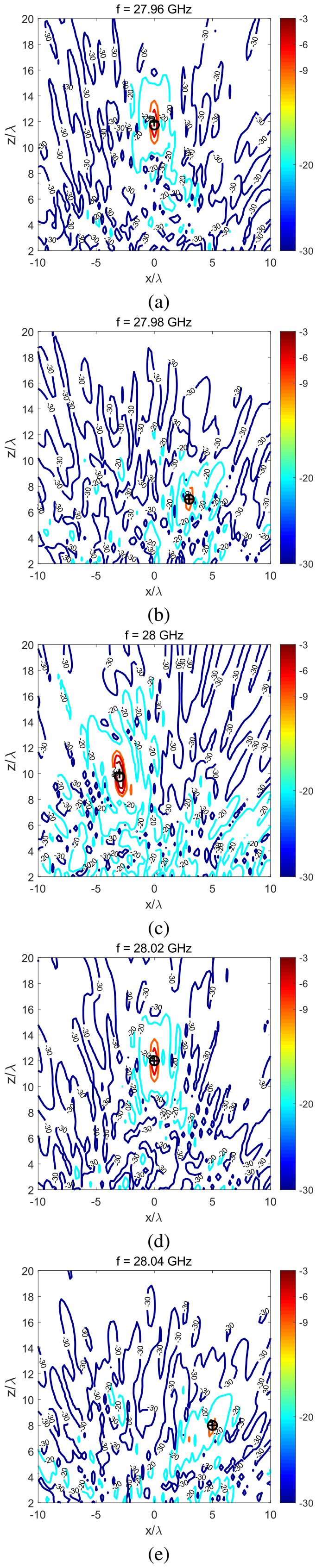

Fig. 5. Simulation #2. Normalized NF power density distribution in the plane $y = 0$ for the frequencies $f_c + qf_0$ with $q \in [-2, 2]$. The symbols + and $\circ$ represent the focal and synthesized maximum points respectively.