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Advanced Reconfigurability of Frequency-diverse Radiators for both Localization and Powering

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***Abstract*— In this work an effective and feasible procedure for real-time focusing of Frequency Diverse Arrays (FDAs) is proposed, to be exploited for intentional far-field Wireless Power Transfer (WPT) applications. The array layout relies on a circular symmetric transmitting architecture where the frequency diversity is applied by rings. This solution represents one of the best in terms of focused area dimension and therefore able to support precise powering applications. Through a software control able to manage the multi-frequency excitation a preliminary localization phase for the collection of targets data position is performed, followed by a precise and energy-aware powering phase, enabling a real-time and capillary WPT system.**

***Index Terms*— Circular arrays, localization, ranging, wireless power transfer (WPT).**

I. Introduction

The recently proposed technique of frequency diversity applied to the radiating elements of arrays has gained importance within the scientific community for its properties: since each element radiates with a frequency slightly different from the one radiated by its neighbours, this allows to exploit the ranging capability, i.e., the ability to dynamically provide energy not only in prescribed directions, but also at prescribed distances from the transmitting source. In this way, the possibility to concentrate the power at desired spots and to drastically reduce it in undesired ones is achieved, with the twofold advantage, not possible with traditional beaming techniques, of increasing energy efficiency where it is needed and of minimizing where it is not needed, at the same time.

Most of the literature is devoted to linear (1-D) architecture [1]. With the choice of exploiting bi-dimensional architecture the frequency diverse arrays (FDAs) can result eligible for precise powering applications. A first attempt has been introduced in [2], replacing the 1-D linear array with 2-D matrix array where the frequency diversity is applied by columns.

The most promising layout seems to be the concentric circular frequency diverse array (CCFDA), proposed in [3] from a mere analytical point of view, where the circular symmetry is exploited for the first time by FDA architectures and the frequency diversity is applied to the different concentric rings of the array.

A realistic, multilayer implementation of such a topology is provided in [4], highlighting the great advantage that circular symmetric transmitting architectures provide in terms of precise focusing.

In this work the exploitation of this architecture is presented, for the first time, as a smart radiator able to localize the targets and, after collecting their positions, to power them in a very precise and energy-saving way. A deep study of the best waveform to be adopted to control the time-dependency of the radiation phenomenon is also presented.

II. Circular Concentric Frequency Diverse Array Properties

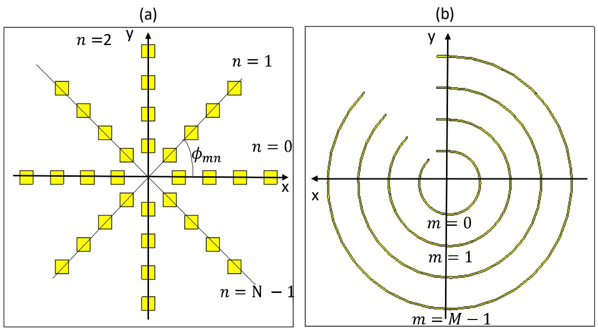

Fig. 1. Topology of a planar multilayer circular FDA with M = 4 rings and N = 8 elements per ring (a) upper radiating layer and (b) bottom feeding layer [4].

Let us consider a planar array with the radiating elements arranged with circular symmetry in the XY plane, as shown in Fig. 1, whose multilayer realization, operating at 24 GHz, is detailed in [4]. The structure is composed by elements laying on M concentric rings of radius md_0 (with m=0,..., M-1 and $d_0 = \lambda/2$), each ring has N elements, and the frequency diversity is applied by rings (therefore all the elements belonging to the same ring radiate the same frequency) and a linear increasing frequency offset Df is adopted ($f_{mn} = f_0 + m\Delta f$, with n=0,…,N-1).

Each radiating element in the XY-plane can be identified by a radius $r_{mn} = md_0$ and an angle φ_{mn}.

The signal radiated by the mn-th element (hence, by an element of the n-th spoke) can be expressed as:

$$x_{mn}(t) = \mathrm{Re}[b_{mn}\exp(j2\pi f_{mn}t)] \quad (1)$$

where b_{mn} is a generic complex coefficient representing the excitation of the mn-th element.

The total signal transmitted by the whole CCFDA in the generic far-field position can be computed as the superposition of the $x_{mn}(t)$:

$$x(t) = \sum_n \sum_m x_{mn}(t - R_{mn}/c) \quad (2)$$

where c is the speed of light and R_{mn} represents the distance between the mn-th element and the far-field observation point $(R_0, \theta_0, \varphi_0)$.

Simulations of the layout of Fig. 1, hence considering M = 4 rings a N = 8, with f_0 = 24 GHz and Δf = 5 MHz are provided in Figs. 2. As can be evinced from Figs. 2(a,b) representing a snapshot at t = 100 ns in two different cutting planes, the use of this circular topology with the aforementioned frequency diversity scheme, allows to create a well-defined and confined spot of power, thus enabling the focusing of the power at a selected distance from the source. This allows to overcome the problem of the very well-known 'S-shape' [1], unavoidable for 1-D or 2-D architectures (without circular symmetry involvement) exploiting the linear increasing frequency offset.

From Fig. 2(c) one can evince how the frequency diversity is the cause of the movement of the main beam with time: this property can profitably be exploited for radar applications, but can result an issue for WPT purposes since it is not possible to fix the power at a certain distance from the source if ad-hoc time-based countermeasures are not involved, as the time-controlled frequency diversity TCFDA technique [5].

In the next sections, an advantageous exploitation of the movement of the main beam for the CCFDA is presented for the first time in a two-step smart radiating procedure for WPT applications in indoor scenarios: first the CCFDA is used for the localization of energy-hungry targets and then it precisely powers them thanks to an innovative time-controlling technique.

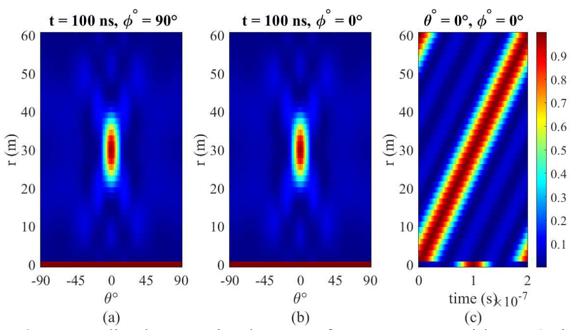

Fig. 2. Normalized transmitted power for a CCFDA with M=4 rings working at different frequency, with N=8 antennas per ring: (a) in the plane (r, θ, φ = 90°), (b) in the plane (r, θ, φ = 0°) (both at t = 100 ns), and (c) as a function of time for (θ = 0°, φ = 0°).

III. Localization Phase

For localization purposes, the received signal formulation must be provided considering a target in the far-field position $(R_t, \theta_t, \varphi_t)$. Without loss of generality, we consider targets that lay in xz plane (φ = 0).

The transmitted signal presents a space and time periodicity equal to $c/\Delta f$ and $1/\Delta f$, respectively, because a linear increasing frequency offset is involved. To avoid replicas of the same targets the first value is set as maximum relevance distance R_{tmax}, whereas the second one is set as scanning period T_s.

This choice implies the use of a *bi-static radar* since the envisaged application involves a restricted area, hence very small flight times: therefore, the FDA array would have no time to switch from transmitting to receiving mode ($2R_t/c < T_s$). The signal transmitted is scattered by the targets and received by an omni-directional antenna located in the same region of the transmitting array.

Since the CCFDA offers a confined spot where the signal is concentrated, a steering technique is required to cover the entire half-space in front of the transmitting antenna. To obtain this, suitable values of the complex coefficients b_{mn} must be computed as in [6] to steer the maximum in (R_{max}, θ_{max}) for the initial time instant.

To cover the entire xz-half-space θ∈[-90°,90°] the dimension of the spot in θ must be known in order to understand how many scanning periods are required. The beamwidth is computed as the first null beam width (FNBW), i.e. the angular sector covered by the transmitted signal fixing the range and time in one cutting plane (xz plane), as highlighted in Fig. 3 referring to the CCFDA with M = 4 and N = 8.

A closed formulation for the beamwidth for this topology is not available, but it can be computed numerically, as reported in Tab. 1: here, the beamwidth is given as a function of the number of rings.

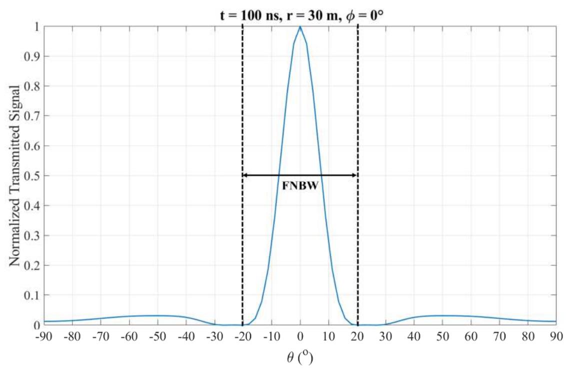

Fig. 3. FNBW of the proposed CCFDA

Table 1

Number of rings (M)	FNBW
2	49°
3	40°
4	31.5°
5	27°

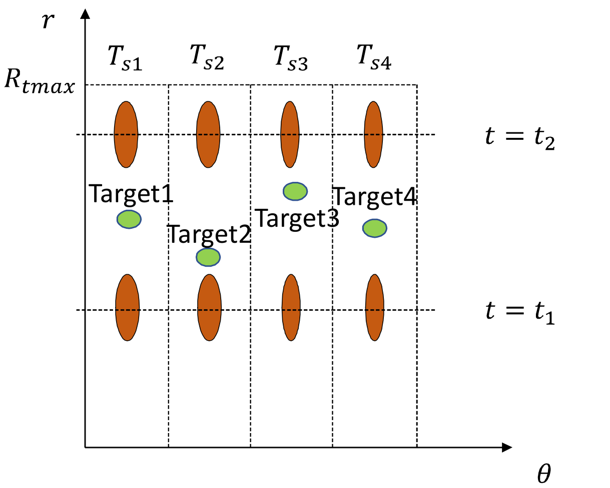

Fig. 4. Scheme of the localization process of 4 targets ($Target_1$, …, $Target_4$) in 4 consecutive scanning period (T_{s1}, …, T_{s4})

It must be stated that, even if by increasing the number of rings the directivity obviously increases, this choice can be dangerous, especially if millimeter-waves are involved, because adding rings with longer radii leads to a radiation efficiency loss of the higher order rings, since the length of the line connecting all the ring elements in the multilayer layout of Fig. 1 would increase, thus increasing the losses, as explained in [4].

Once the layout has been established, by pointing in a precise θ-direction in the xz-plane, the target position can be easily derived obviously using the time of arrival ($T_{arrival} = 2R_t/\Delta f$).

A scheme for a visual explanation of the localization process is presented in Fig. 4.

After kT_s, where $k = 180°/(FNBW)$, all the target positions are retrieved and the second phase of the WPT procedure can start.

IV. Powering Phase

As previously mentioned, the adopted frequency diversity is responsible for the main beam movement with time, not allowing to fix the power where desired. While this property is profitably exploited for localization purposes, as explained in the previous section, suitable countermeasures must be considered when the powering phase is of interest. Among all the solutions proposed in the literature, the most promising one in terms of ease of realization is the time-controlled frequency diverse array (TCFDA), firstly introduced in [5]. The original idea is to introduce a square wave pulse modulating the RF input signals. The macroscopic effect should be to control the intermodulation of the different modulated tones such that the constructive interference appears in user-defined regions, 'intercepting' the power at certain distances, only.

With a software control of the pulsed input signals, in particular of the key parameters pulse duration (t_{rect}) and delay with respect to the FDA period (T_{prect}), a dynamically and ad-hoc powering application can be exploited.

A first implementation and experimental validation of the operating principle of TCFDA is given in [5].

Unfortunately, since the pulsed signal width is not infinitesimal in time, the area invested by the maximum of power is not tied only to the target position, but also to the region around it, wasting energy where it is not needed.

A significant improvement can be achieved through the novel introduction of a triangular pulse, replacing the square wave, to reach the maximum of power only at the target position (mainly selected through the t_{rect} value), and significantly reducing the energy wasted in the surrounding regions.

The triangular pulse can be obtained by the original square wave pulse through the convolution method. Basically, modifying the parameters of duration and delay of the square wave pulse the desired triangular pulse can be provided. It is considered a square wave pulse periodic of period $T = 1/\Delta f$:

$$x_{rect}(t - \tau_{rect}) = \sum_h a_h \cos(h2\pi/T(t - \tau_{rect})) \quad (3)$$

with $a_h = (2A/h\pi)\sin(h\pi T_{prect}/T)$, τ_{rect} is the key parameter to be chosen to delay the pulse within the FDA , thus "fixing" the beam at the desired distance, T_{prect} represents the on-duration of the pulse, thus defining the power spot width in time, A is the pulse amplitude, the integer $h = 0, \dots, n_h$, and n_h is the number of harmonics of interest.

The triangular pulse is obtained from the rectangular one by selecting a proper value of T_{prect} and τ_{rect} remembering

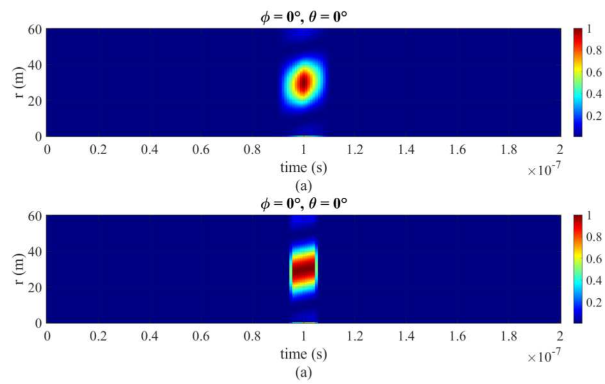

Fig. 5. Normalized transmitted power vs. time for (a) triangular pulse and (b) rectangular pulse.

that, due to the convolution, its duration will be $2T_{prect}$ and its delay will be $2\tau_{rect}$.

After the convolution of (3) with itself, the desired triangular pulse that reaches its maximum only for $t = \tau_{rect}$ is obtained.

The comparison between the two methods involving the triangular pulse and the square wave pulse, in terms of power focusing at the desired distance, is provided in Fig. 5, considering two pulses with duration T_{prect}=20 nsec, delay τ_{rect}=100 ns and unitary amplitude, such that the maximum of power is at 30 m of distance, for the present use case.

From figure inspection, it can be easily evinced how the region of space where the power is concentrated results more confined, and therefore the powering more selective, for the TCFDA involving triangular pulse. The area of the region invested by power is 50% less with the introduction of the triangular pulse if compared to the rectangular one; whereas, if we refer to the region invested by at least half of the maximum of the available power, the coverage improvement reaches the 75%, thus confirming the energy-awareness of the new proposed time-based methodology.

The possibility to easily shape the input waveform signals by means of modern software defined radios, makes the TCFDA with triangular pulse modulation the most promising solution, to the authors' knowledge, for ad hoc, and real-time focusing for indoor WPT applications.

V. Conclusion

The idea of CCFDA is proposed again to enhance the focusing capability of the radiation mechanism of transmitting architecture based on frequency diversity. The simulations performed at 24 GHz highlight the advantages of this arrangement with respect to traditional FDA architectures in terms of beam shape.

The exploitation of such a topology as an intelligent and ad-hoc WPT radiator has been analyzed for the first time. The results highlight that it can be used for localization purposes with the aim of collecting the position data of the targets exploiting the natural displacement in time of the main beam in few scanning periods: the standard tuning of the complex coefficients phase allows also to steer in space the maximum of the beam to cover the whole half-space in front of the transmitting antenna.

After this, the powering phase can be exploited with a very precise and confined spot where the energy can be fixed with the introduction of a new version of the time-based technique (TCFDA), where triangular pulses modulate the RF signals at the antenna ports instead of the standard square wave pulses: simulations demonstrate important energy savings, thus paving the way for an ad-hoc, real-time, and efficient wireless power transmission.

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