Radio over Fiber–driven Time Modulated Array Antennas for Efficient Beamforming within In-Building Environments

Andrea Giovannini(1,2), Jacopo Nanni(1), Giacomo Paolini(1), Federico Perini(3), Enrico Lenzi(4), Jean-Luc Polleux(2), Jean-Marc Laheurte(2), Diego Masotti(1), Giovanni Tartarini(1)

(1) DEI, Università di Bologna, Viale Risorgimento 2, 40136 Bologna (I) andrea.giovannini14@unibo.it
(2) ESYCOM, Université Gustave Eiffel, 6 Boulevard Newton, 77420 Champs-sur-Marne (F)
(3) IRA, Istituto Nazionale di Astrofisica, Via Fiorentina 3513, 40059 Medicina (I)
(4) Protech S.a.S, Via dei Pini 21, 31033 Castelfranco Veneto (I)

Abstract *A preliminary proof-of-concept of an innovative system combining the technologies of Radio over Fiber (RoF) and Time Modulated Array (TMA) Antennas is proposed. Through a theoretical and experimental analysis, the straightforward realization of steerable antenna arrays for capillary indoor wireless signal distribution is demonstrated.*

Introduction

In the context of the so-called *City of Tomorrow*[1], telecommunication systems must be able to face the ever-demanding challenges posed by the needs of increased wireless coverage, pervasivity, capacity and degree of flexibility.

This is particularly true for in-door environments, where the great majority of wireless traffic either originates or terminates, and where consequently the need of a satisfactory distribution of signals and services must go together with the need to keep at acceptable levels the global electromagnetic impact of the systems.

The Radio over Fiber (RoF) technology can give an important contribution in this context, since, exploiting the low attenuation and the high bandwidth of the optical fiber as a transmitting medium, it guarantees a capillary emission of the radiofrequency (RF) signals only in the areas where they are needed[2].

At the same time, the Time Modulated Array (TMA) Antennas technology can also be beneficially exploited within the aforementioned environment. Indeed, TMA features high flexibility due to its multi-frequency radiation ability and to the multitude of optimized modulating sequences. This allows to perform efficient beamforming operations, maximizing the final coverage and further minimizing the overall electromagnetic exposure[3,4].

In the present work, the matching of the two technologies is proposed and demonstrated, through the theoretical and experimental study of an initial "proof of concept" RoF-TMA system made by off-the-shelf optical and RF components. The confirmation of the realizability of the system which results from the study performed allows to consider RoF-TMA as a promising solution for the efficient wireless coverage of in-door environments.

Description of the System proposed

The overall system is schematized in Fig. 1.

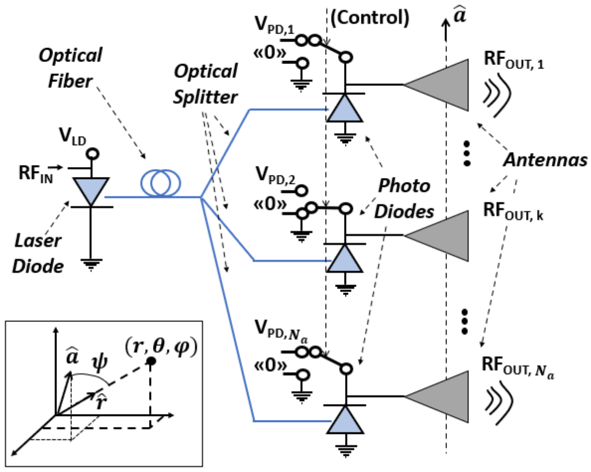

Fig. 1: General Scheme of the RoF-TMA System proposed. Inset: reference system utilized.

The RF signal to be transmitted, directly modulates a laser diode, and after having covered a distance through an optical fiber strand, is divided into N_a branches by an optical splitter, each terminating in a photodiode (PD). The RF outputs from the PDs feed corresponding antennas which form an array of N_a*elements*.

To realize a TMA, the input signal of each element is modulated by periodical rectangular pulses. The modulation is performed controlling the bias tension $V_k(t) = V_{PD,k}U_k(t), (k = 1, \ldots, N_a)$ of each PD, letting it switch between *On* $(U_k(t) = 1)$ and *Off* $(U_k(t) = 0)$ states.

Note that in general the modulating normalized *sequence* $U_k(t)$ exhibits a fixed period $T_M = 1/f_M$ (where f_M is the modulating frequency), while its duty cycle τ_k and starting time instant τ_{i_k} are characteristic of the $k-th$ PD.

The reason of performing the modulation of the elements through operation on optical-to-electrical conversion devices like the PDs, and not for example simply through RF switches placed immediately before each element, aims to leave the system flexible for future possible improvements, such as the introduction, instead of the PDs, of three-port Heterojunction Phototransistors (HPTs) controlled in their base tensions [5], to exploit their amplifying effect, as well as their integrability with CMOS-process-based components.

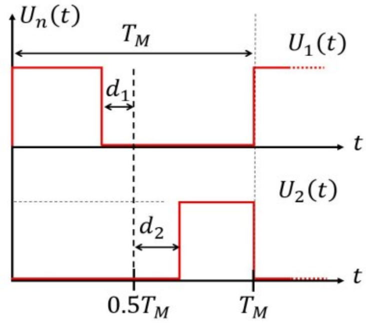

Fig. 2: Example of TMA sequences for $N_a = 2$. The duty cycle of are $\tau_1 = 0.5 - d_1/T_M$ and $\tau_2 = 0.5 - d_2/T_M$,while the starting time instants are $\tau_{i_1} = 0$ and $\tau_{i_2} = 0.5T_M + d_2$. See text for details

Fig.2 shows an example of modulating *sequences* for the case $N_a = 2$.

The modulation of the single element can be expressed as the product of two terms: a constant excitation term A_k (in which $V_{PD,k}$ is included) and $U_k(t)$.

Considering equally spaced antennas, aligned over a direction $\hat{a}$, such that $\hat{a} \cdot \hat{r} = \cos\psi$ (see inset in Fig. 1), the far field radiated by the array, evaluated in the generic point (r, θ, φ) is then:

$$\boldsymbol{E}(r,\theta,\varphi,t) = \boldsymbol{E_0}(r,\theta,\varphi) \sum_{k=1}^{N_a} A_k U_k(t) e^{j\beta kL\cos\psi} \tag{1}$$

with $\boldsymbol{E_0}(r,\theta,\varphi)$ being the far field radiated by the basis element of the array at the carrier frequency (which can be evaluated through full-wave analysis under normalized excitation conditions[6]), L being the array spacing and β being the free space propagation constant.

Focusing on the whole term multiplying $\boldsymbol{E_0}(r,\theta,\varphi)$, which constitutes the time-dependent Array Factor $AF(\theta,\varphi,t)$ of the TMA, it can be observed that the periodicity of $U_k(t)$ allows to Fourier-transform it, resulting in the expansion:

$$AF(\theta,\varphi,t) = \sum_{h=-\infty}^{+\infty} AF_h(\theta,\varphi,t) = \\ = \sum_{h=-\infty}^{+\infty} \sum_{k=1}^{N_a} A_n u_{hk} e^{j\beta kL\cos\psi} e^{j2\pi(f_0 + hf_M)t} \tag{2}$$

where u_{hk} is the h –th Fourier coefficient of $U_k(t)$. As can be evinced by the multi-harmonic AF representation (2), a fundamental consequence of the modulation in the TMA is the variety of simultaneous radiation patterns at harmonic frequencies close to the carrier frequency. Indeed, given the fact that the modulating frequency $f_M = 1/T_M$ is usually much lower than the RF carrier frequency f_0, the first N_h harmonic frequencies around the carrier of the resulting quasi-periodic regime, ranging from $f_0 - (N_h/2)f_M$ to $f_0 + (N_h/2)f_M$, are still frequencies where the antennas resonate. Therefore, the array efficiently radiates at carrier frequency f_0, but also at frequencies $f_0 \pm hf_M$. The radiation patterns at carrier and side bands frequencies depend on the coefficients u_{hn}, thus relatively close frequencies can radiate in a different way. The proper choice of these coefficients is the key for shaping the desired radiation patterns [7,8].

Through straightforward derivation, it can be shown that the coefficients u_{hk} depend mainly on the two parameters τ_k and τ_{i_k} introduced above.

Experimental results

The proof-of-concept experimental set-up exploits a 2-element TMA, and is shown in Fig. 3.

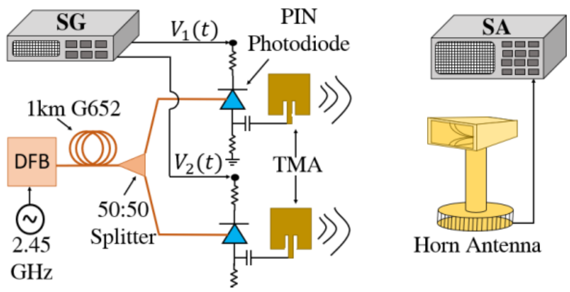

Fig. 3: Experimental set-up utilized. See text for details.

A DFB laser operating at 1550nm is modulated with a sinusoidal tone with frequency $f_0 = 2.45\ GHz$. After propagation inside 1 km of G652 fiber the optical signal is received by two PDs of PIN type, to which the signal generator SG provides the sequences $V_1(t)$ and $V_2(t)$. In the TMA, the two elements are circularly polarized patch antennas, resonant at 2.45 GHz and separated by a distance $\lambda/2$ (~61 mm). The far field is then evaluated by a rotating horn antenna positioned 1.20 m away from the array and connected to a spectrum analyzer (SA).

Note that the use of a DFB laser as optical transmitter is not mandatory for the system proposed. In particular, if optical detectors based on the *SiGe* technology were to be utilized, like the HPT mentioned above, lasers of VCSEL type emitting at 850 nm should be appropriate, which would mean also to take advantage of their low cost and low power consumption [9].

In the presented application we take f_M = 10 kHz and we consider symmetric sequences, corresponding to the ones represented in Fig. 2, taking $d_1 = d_2 = d$. In this way, it is possible to simultaneously have an in-phase excitation of the two antennas at the carrier frequency (providing a broadside *Sum* pattern) and an out-of-phase excitation at the first two sideband harmonics (providing a *Difference* pattern)[10].

The RF signal modulating the laser source exhibits a power of 3 dBm, and while a uniform static excitation ($A_1 = A_2$) is guaranteed at the two antenna ports, save possible asymmetries of the optical splitter. The aim is to test the TMA with different sequences in order to demonstrate that the hybrid RoF-TMA system can support beamforming just like an only-RF-driven TMA system would do[10].

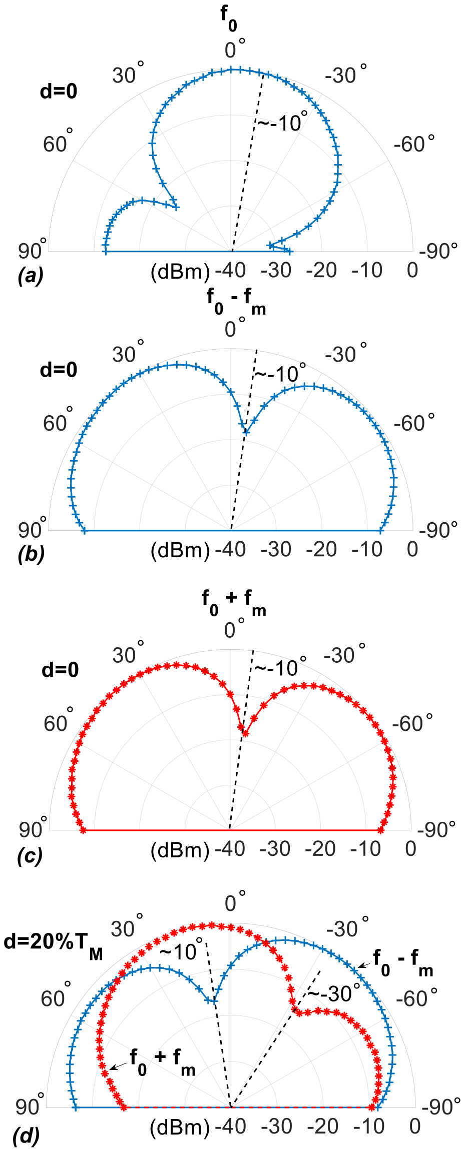

Fig. 4: Measured radiation patterns. Above each figure is stated the frequency and the duty cycle of the sequences. See text for details.

As the reference case, the adopted sequences have 50% duty cycle ($d = 0$ in Fig. 2). The far field is evaluated at frequencies f_0 and $f_0 \pm f_M$. The expectation for this sequence is to see a broadside maximum at carrier frequency and an identical zero located in broadside direction at $f_0 \pm f_M$[10]. Looking at the resulting radiation patterns, it can be confirmed the presence of maximum radiation at the carrier frequency (*Sum* behavior, Fig 4(a)) and the presence of a common zero direction at frequencies $f_0 \pm f_M$ (*Difference* behavior, Fig.'s 4(b) and 4(c)). However, these maximum and zero directions result tilted with respect to their ideal theoretically expected angular position (0°).

The reason of this fact lies in an undesired phase-unbalance which is present between the signals separately received by the two antennas.

Numerical simulations which were performed inserting the measured value of this phase mismatch (around 30 degrees), showed indeed that the considered directions of maximum and zero should be located at an angle $\sim -10°$, which is in agreement with the measured ones. The introduction of appropriate components at the optical and/or RF level to reduce this phase difference to acceptable levels is currently under evaluation.

As a further TMA capability exploitation, a beam steering measurement is then carried out. When changing the duty cycle of the sequences of Fig. 2 by increasing d, the zeros at $f_0 \pm f_M$ are expected to move in opposite directions with respect to their common direction of the case $d = 0$, thus changing also the main beam direction. Instead, the radiation pattern at f_0 is not supposed to change[10].

Fig. 4(d) allows to appreciate the measured behaviors referred to the case $d = 20\% \cdot T_M$. Indeed, it can be seen that the zero direction has shifted to $\sim 10°$ for $f_0 - f_M$, while it has shifted to $\sim 33°$ for $f_0 + f_M$. Both zeros appear neat and sharp, and confirm that angular shifts of $\sim \pm 20°$ have taken place with respect to the common zero direction of $\sim -10°$ which corresponded to $d = 0$. At f_0 (not reported) there is no difference for $d = 20\% \cdot T_M$ with the reference case $d = 0$, and the radiation pattern practically coincides with the one of Fig. 4(a), as expected.

Conclusions

The possibility to combine RoF and TMA technologies, allowing to take advantage both of the wireless coverage capillarity of the former and the beamforming capabilities of the latter has been successfully demonstrated. Practical system realizations can be envisaged e.g. using VCSEL sources and HPT detectors, which are expected to add cost-effectiveness and energy-efficiency to the technical attractive features of the proposed solution.

Acknowledgements

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