

Applicability of Time-Modulated Arrays in Multi-layer PNT Scenarios

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Abstract—We propose an effective time-modulated array (TMA) architecture that enhances multi-layer positioning, navigation and timing (PNT) applications by enabling the generation and independent steering of four distinct beams. The proposed beamforming network achieves valuable capabilities, including precise multi-beam steering, Doppler shift compensation, and directional modulation, all while maintaining a simplified hardware design. These capabilities make the proposed TMA approach especially well-suited for strengthening PNT receivers against radio frequency interference and jamming threats.

I. INTRODUCTION

Traditional Positioning, Navigation and Timing (PNT) services are provided by Global Navigation Satellite System (GNSS) constellations, which are typically located in Medium Earth Orbit (MEO) transmitting L-band signals that, once reaching Earth's surface, are extremely weak, thus being inherently susceptible to interference, both intentional and unintentional. This vulnerability is increasingly critical as PNT addresses the demanding requirements of emerging applications such as robotics, smart cities, and the Industrial Internet of Things (IIoT).

Integrating MEO satellites with Low Earth Orbit (LEO) satellites leads to the multilayered PNT scenario shown in Fig. 1. Multilayered PNT enhances the resilience, availability, and continuity of PNT services. To fully leverage this approach, PNT users must be equipped with multibeam smart antennas featuring advanced Beamforming (BF) capabilities. These antennas enable dynamic self-alignment and the simultaneous tracking of multiple satellites. However, conventional BF methods—such as analog BF, which relies on costly and power-hungry Variable Phase Shifter (VPS), or digital BF, which requires as many Radio Frequency (RF) chains as antenna elements—present significant challenges in terms of complexity, cost, and power consumption, posing critical barriers to the efficient design of multilayer PNT user terminals.

In this work, we propose a simple, low-cost and energy-efficient solution for multi-layer PNT receivers: a multibeam Time-Modulated Array (TMA) that also enables advanced features such as Directional Modulation (DM) and Doppler compensation.

II. PROPOSED TMA FOR MULTI-LAYER GNSS RECEIVERS

Consider a uniformly excited receive planar TMA consisting of $M \times N$ isotropic elements arranged in the xy -plane, with a

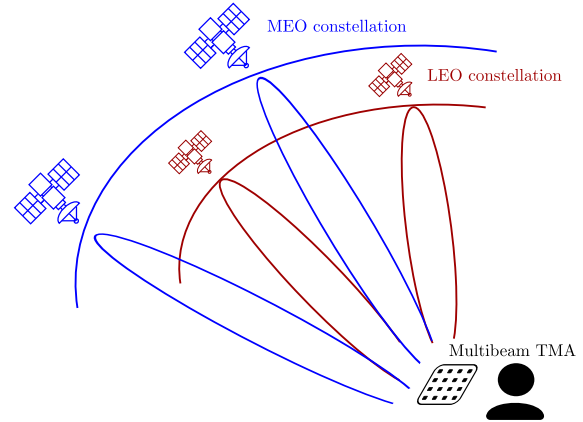


Fig. 1. Multi-layer PNT receiver supported by a TMA.

time-varying array factor given by

$$F(\theta, \phi, t) = e^{j\omega_c t} \sum_{m=1}^M \sum_{n=1}^N h_{nm}(t) e^{j\beta_c \Gamma_{mn}(\theta, \phi)} \quad (1)$$

where $\beta_c = 2\pi/\lambda_c$ represents the wavenumber for a carrier wavelength $\lambda_c = 2\pi c/\omega_c$; $\Gamma_{mn}(\theta, \phi) = x_m \sin \theta \cos \phi + y_n \sin \theta \sin \phi$, being (x_m, y_n) the positions of the individual antenna elements, with $m \in \mathcal{M} = \{1, \dots, M\}$ and $n \in \mathcal{N} = \{1, \dots, N\}$, and θ and ϕ the elevation and azimuth angles, respectively. $h_{nm}(t)$ refers to the TMA periodic modulating excitations shown in Fig. 2 and is given by

$$h_{mn}(t) = g_{mn}(t - D_{mn}^1)u_{mn}(t - D_{mn}^2) + g_{mn}(t - D_{mn}^1)v_{mn}(t - D_{mn}^3). \quad (2)$$

where D_{mn}^l , $l \in \Xi = \{1, 2, 3\}$ are instrumental time-delays that can be independently adjusted to steer the main lobes of four beams towards desired independent directions. The periodic signals $g_{mn}(t)$, $u_{mn}(t)$, and $v_{mn}(t)$ (see Fig. 2) have fundamental frequencies $\omega_l = 2\pi/T_l$, $l \in \Xi$, and Fourier coefficients G_{mn}^q , U_{mn}^i , and V_{mn}^k , respectively, allowing (2) to be expressed as

$$\begin{aligned} h_{mn}(t) = & \sum_{q \in \Psi_g} G_{mn}^q e^{-jq\omega_1 D_{mn}^1} e^{jq\omega_1 t} \sum_{i \in \Psi_u} U_{mn}^i e^{-ji\omega_2 D_{mn}^2} e^{ji\omega_2 t} + \\ & + \sum_{q \in \Psi_g} G_{mn}^q e^{-jq\omega_1 D_{mn}^1} e^{jq\omega_1 t} \sum_{k \in \Psi_v} V_{mn}^k e^{-jk\omega_3 D_{mn}^3} e^{jk\omega_3 t} \end{aligned} \quad (3)$$

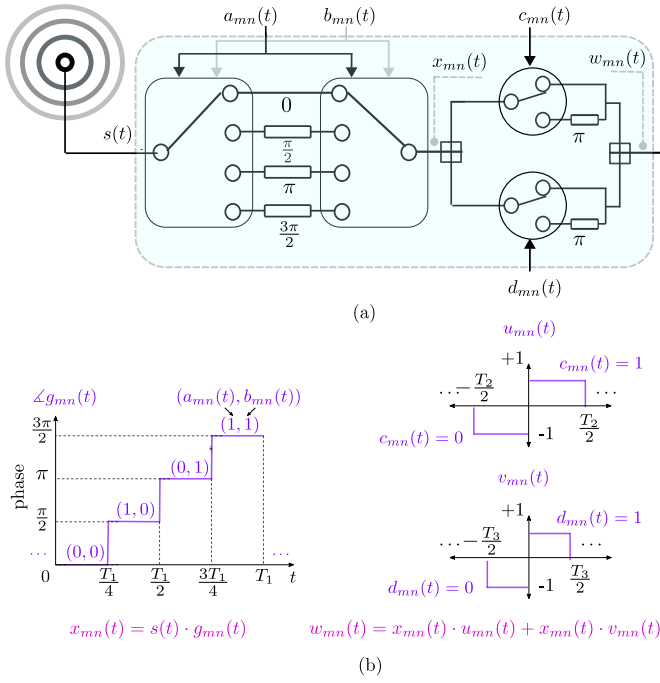


Fig. 2. (a) Switched BFN for the $(m\text{-th}, n\text{-th})$ element of the proposed TMA, designed to synthesize four independently steerable beams; (b) TMA periodic modulating pulses and their relationship with the corresponding switching control signals.

with Ψ_q , Ψ_u , and Ψ_v being the respective index sets of the nonzero harmonics. By identifying the dynamic excitations

$$\begin{aligned} q I_{mn} &= G_{mn}^q U_{mn}^i e^{-j(q\omega_1 D_{mn}^1 + i\omega_2 D_{mn}^2)} \\ k I'_{mn} &= G_{mn}^k V_{mn}^k e^{-j(q\omega_1 D_{mn}^1 + k\omega_3 D_{mn}^3)} \end{aligned} \quad (4)$$

we can restate equation (1) as

$$\begin{aligned} F(\theta, \phi, t) &= \\ &= \sum_{q \in \Psi_g} \sum_{i \in \Psi_u} \sum_{m=1}^M \sum_{n=1}^N q I_{mn} e^{j\beta_c \Gamma_{mn}(\theta, \phi)} e^{j(\omega_c + q\omega_1 + i\omega_2)t} + \\ &+ \sum_{q \in \Psi_g} \sum_{k \in \Psi_v} \sum_{m=1}^M \sum_{n=1}^N k I'_{mn} e^{j\beta_c \Gamma_{mn}(\theta, \phi)} e^{j(\omega_c + q\omega_1 + k\omega_3)t} = \\ &= \sum_{q \in \Psi_g} \sum_{i \in \Psi_u} q F(\theta, \phi) e^{j\omega_i t} + \sum_{q \in \Psi_g} \sum_{k \in \Psi_v} k F'(\theta, \phi) e^{j\omega_k' t} \end{aligned} \quad (5)$$

where

$$\begin{aligned} q F(\theta, \phi) &= \sum_{m=1}^M \sum_{n=1}^N q I_{mn} e^{j\beta_c \Gamma_{mn}(\theta, \phi)} \text{ and} \\ k F'(\theta, \phi) &= \sum_{m=1}^M \sum_{n=1}^N k I'_{mn} e^{j\beta_c \Gamma_{mn}(\theta, \phi)} \end{aligned} \quad (6)$$

are the spatial array factors at frequencies $q\omega = \omega_c + q\omega_1 + i\omega_2$ and $k\omega' = \omega_c + q\omega_1 + k\omega_3$, respectively. The characteristics of the modulating signals in Fig. 2b (see [1], [2]), imply that the dominant harmonic patterns in (5) are those corresponding to the indices $q=1$, $i=\pm 1$, and $k=\pm 1$ because their beam patterns

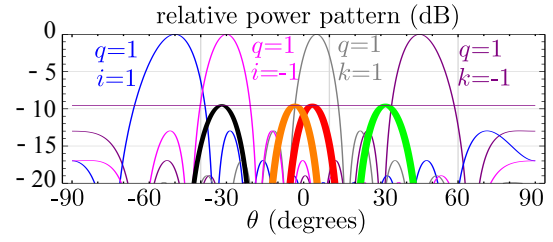


Fig. 3. We consider a configuration with $M=10$, $N=1$, $\omega_1=\omega_2=\omega_3$, and a scenario with four satellites in the $\phi=0^\circ$ plane cut. The useful beam patterns for the TMA shown in Fig. 2, namely ${}^1_1 F(\theta)$, ${}^1_{-1} F(\theta)$, ${}^1_1 F'(\theta)$, and ${}^1_{-1} F'(\theta)$ are steered to $\theta_1 = -50^\circ$, $\theta_2 = -30^\circ$, $\theta_3 = 5^\circ$, and $\theta_4 = 45^\circ$, respectively, by properly adjusting the delays D_{mn}^l , $l \in \Xi$, $m \in \mathcal{M}$, and $n \in \mathcal{N}$, in accordance with (7). Unexploited harmonics remain below -9.54 dB, regardless of the selected pointing directions.

${}^1_1 F(\theta, \phi)$, ${}^1_{-1} F(\theta, \phi)$, ${}^1_1 F'(\theta, \phi)$, and ${}^1_{-1} F'(\theta, \phi)$ have a peak level of 9.54 dB above the remaining ones. Accordingly, these four patterns are used to perform independent beam-steering. Furthermore, in view of (4) and (6), to point each beam to the corresponding satellite positions, (θ_1, ϕ_1) , (θ_2, ϕ_2) , (θ_3, ϕ_3) , and (θ_4, ϕ_4) , the time delays must meet the conditions:

$$\begin{aligned} e^{-j(\omega_1 D_{mn}^1 + \omega_2 D_{mn}^2)} &= e^{j\beta_c \Gamma_{mn}(\theta_1, \phi_1)} \\ e^{-j(\omega_1 D_{mn}^1 - \omega_2 D_{mn}^2)} &= e^{j\beta_c \Gamma_{mn}(\theta_2, \phi_2)} \\ e^{-j(\omega_1 D_{mn}^1 + \omega_3 D_{mn}^3)} &= e^{j\beta_c \Gamma_{mn}(\theta_3, \phi_3)} \\ e^{-j(\omega_1 D_{mn}^1 - \omega_3 D_{mn}^3)} &= e^{j\beta_c \Gamma_{mn}(\theta_4, \phi_4)} \end{aligned} \quad (7)$$

Fig. 3 shows the multibeam ability of a basic configuration of the TMA in a simplified scenario (albeit without loss of generality) representing a PNT user terminal tracking 4 satellites. The proposed TMA approach provides the following additional advantages in the PNT domain: 1) Doppler compensation by adjusting TMA frequencies, such that $\Delta\omega_1 + \Delta\omega_2 = \omega_{D1}$, $\Delta\omega_1 - \Delta\omega_2 = \omega_{D2}$, $\Delta\omega_1 + \Delta\omega_3 = \omega_{D3}$, and $\Delta\omega_1 - \Delta\omega_3 = \omega_{D4}$, being $p \in \{1, \dots, 4\}$ and ω_{Dp} the corresponding Doppler shifts of the signals received by each beam. 2) DM by exploiting the unwanted harmonics, the same hardware can be used to perform intentional spectral aliasing in all spatial directions except in the desired one, leveraging optimized control techniques [3].

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