Proceedings Paper:

Ball, E.A. orcid.org/0000-0002-6283-5949 and Joseph, S.D. (2025) A 73 GHz time modulated array with beam steering and direct vector modulation of QPSK / 8PSK / 16QAM. In: 2025 IEEE International Mediterranean Conference on Communications and Networking (MeditCom). 2025 IEEE International Mediterranean Conference on Communications and Networking (MeditCom), 07-10 Jul 2025, Nice, France. Institute of Electrical and Electronics Engineers (IEEE), pp. 1-5. ISBN: 9798331529666.

https://doi.org/10.1109/MeditCom64437.2025.11104265

A 73 GHz Time Modulated Array with Beam Steering and Direct Vector Modulation of QPSK / 8PSK / 16QAM

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***Abstract*— We demonstrate the first use of a Time Modulated Array (TMA) steerable phased array at 73 GHz with data symbol vector modulation applied directly by the TMA. The concept removes the need for data modulation to be applied in earlier RF stages. Only TMA digital control waveforms are used, to both steer the beam and apply symbol modulation. Laboratory demonstration results using a custom 73 GHz hardware prototype show QPSK, 8PSK and 16QAM constellations are obtained as expected. Laboratory measured Error Vector Magnitude (EVM) ranges from 7.1% to 11%.**

Keywords—time modulated arrays, antennas, millimetre wave circuits, modulation

I. Introduction

Transmitting (TX) phased arrays are often conventionally constructed using analogue RF components, such as vector modulators or phase shifters. In such systems, the incoming RF signal is at a carrier frequency and already modulated with the required communications signal - the array is only used to form and steer the radiated beam. Techniques to simplify the RF modulation and beam steering process are valuable and relevant to future communications systems, such as 6G millimetre wave (mmWave). In this paper we present a new technique to apply data symbol vector modulation within a phased array directly. We use a bespoke 73 GHz TX TMA demonstration platform for this process.

The TMA is an underexplored technique to realize phased arrays. The TMA creates a phase steer through use of timing control waveforms applied to RF switches, or equivalent circuit functions [1] - [4]. Fourier analysis of these controlling waveforms shows that an equivalent resulting phase shift is applied to the RF signal.

The TMA, in general, has been used for TX arrays [5] and RX arrays [6]. Earlier work has also explored how the TMA could be a hardware efficient approach to steer an RX beam by incorporating subsampling [6].

There are very few practical works in TMAs published, and only one other mmWave TMA of which we are aware [7]. However, the system in [7] is intended for physical layer security rather than beam steering with direct data modulation. Other TMA works are focused on microwave systems, such as [8] considering circular polarization and [9] considering single sideband IQ circuitry for TMA beam steering hardware.

The TMA has also been applied to hybrid beamformer system designs [10] and radar systems [11], including contemporary systems providing radar functionality on the boresight beam and communications data transport on the other beams [12].

TMAs have been considered by very few researchers for direct antenna modulation (DAM) and related concepts. In [13] the TMA is used to directly modulate M-FSK, in addition to beam steering, and uses 6 switches per element. A multi-level amplitude and phase modulating TMA concept is presented in [14], requiring 2 bits per element for phase control and additional digitally controlled variable gain amplifiers for amplitude control. In [15] a TMA is used to TX a wanted QPSK signal, and also a noise signal, to provide direction-dependent modulation. In [16] a TMA metasurface concept is introduced, employing space-time coding in the array for modulation and beam steering. The metasurface is first illuminated with a radiated carrier. An approach for secure communications based on the TMA is introduced in [17], realising a 4-D antenna array with joint space-time modulation and 16QAM.

The first 73 GHz steerable TX TMA demonstrator system, using custom GaAs integrated circuits, was introduced by our team in [18], and is the platform now used in this paper. In this new work, we extend the mmWave TX TMA concept of [18] to allow it to apply vector modulation (phase and amplitude) to a carrier signal, thus creating a single system that forms and steers a beam and also directly digitally modulates the signal, requiring only 2 bits per element. Only a CW carrier is applied to the input of the array. FPGA digital timing control waveforms to the RF circuitry perform both the beam steering and modulation function. To the best of our knowledge, this is the first work to demonstrate a mmWave TMA system that is also applying symbol modulation directly in the array.

II. The TMA as a Vector Modulator

The TMA and the modulation strategy are now introduced.

A. Introduction to TMA

The array factor (AF) (1) of the TMA allows us to calculate the steered beam magnitude as a function of TMA harmonic n and inspected angle θ [18]. In (1) ω_c is the RF carrier frequency in rad/s, k is the phased array element number [1..*N*], Tp is the TMA frame period and $\omega_p = 2\pi/Tp$. Parameter φ_k is an element-specific shift in phase due to array geometry with element spacing d and with wavelength λ, found using (2) [18].

$$AF(\theta,n,t) = e^{j[\omega_c + n\omega_p]t} \sum_{k=1}^{N} e^{j\varphi_k} \frac{sin\left(n\pi\frac{T_k}{T_p}\right)}{n\pi} e^{-jn\pi\left(2\frac{T_{0k}}{T_p}+\frac{T_k}{T_p}\right)} \quad (1)$$

$$\varphi_k = (k-1)\frac{2\pi}{\lambda} d sin(\theta) \quad (2)$$

This work was supported by the U.K. Research and Innovation (UKRI) Future Leaders Fellowship under Grant MR/T043164/1.

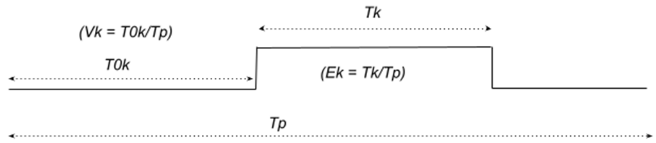


Fig. 1. A TMA RF switch timing cycle showing key features.

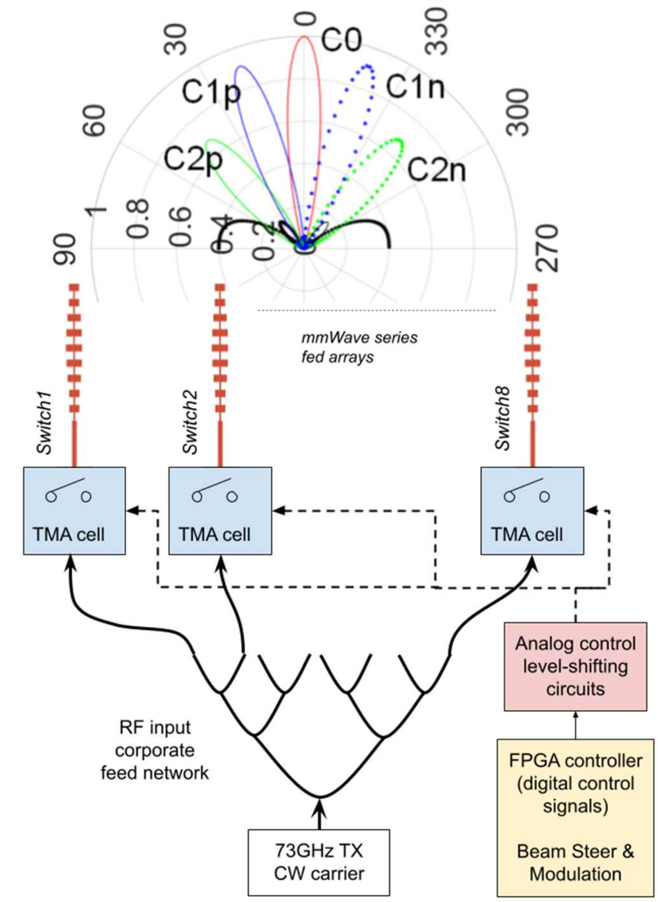


Fig. 2. Concept mmWave TMA transmitter, showing emitted steerable modulatable harmonic beams (*C0*, *C1p*, *C1n*, etc.).

Each of the N RF switches (or equivalent circuit function) in a TMA will have a unique timing control pattern, with terms T_{0k}, T_k, T_p as represented in Fig. 1 for the kth switch.

Our TMA TX system is constructed conceptually as shown in Fig. 2. The concept of harmonic beams is central to the TMA and is also illustrated in Fig. 2.

TMAs produce a set of harmonically related beams, due to frame period Tp. These result in a radiated beam being produced at a frequency offset from the carrier. For example, from (1), a first harmonic beam (n = 1) results in the wanted beam emitting on $(\omega_c + 1\omega_p)$ and we refer to this as beam C1p. Beam C0 is always boresight to the TMA and is on the carrier frequency ω_c.

The timing control patterns to phase steer a desired beam conventionally can be derived [5], using (3) and (4).

$$E_k = \left[\frac{arcsin(G(k))}{n\pi}\right] \tag{3}$$

$$V_k = \left[\frac{(k-1)dsin(\theta_t)}{n\lambda} - \frac{E_k}{2}\right] \tag{4}$$

Parameters E_k and V_k represent the normalised timings for element k, as illustrated in Fig. 1. *G(k)* is an amplitude weight applied to the array elements for sidelobe control, such as a Dolph-Chebyshev taper. The desired beam pointing direction is θ_t. E_k and V_k are related to TMA frame timing and period Tp by (5) and (6).

$$E_k = \frac{T_k}{T_p} \tag{5}$$

$$V_k = \frac{T0_k}{T_p} \tag{6}$$

B. Vector Modulation using the TMA

By inspection of (1), it is seen that the term controlling AF amplitude from element k on TMA harmonic n is (7).

$$A(k) = \frac{sin\left(n\pi\frac{T_k}{T_p}\right)}{n\pi} \tag{7}$$

Similarly, by inspection of (1), the phase controlling term for element k can be seen to be (8).

$$P(k) = e^{-jn\pi\left(2\frac{T_{0k}}{T_p}+\frac{T_k}{T_p}\right)} \tag{8}$$

This suggests that it should be possible to also apply arbitrary amplitude and phase modulation using the TMA timings. For a TX symbol modulation, this will be the same applied to each element and so will not affect the beam steering operation (within the timing limits imposed by Tp).

From (7) and (8) it is possible to calculate the TMA timing *modification* required to implement an additional amplitude and phase shift to perform arbitrary vector modulation for a symbol. Our newly developed approach for this combined steering and modulation will now be presented. Let the required modulation magnitude scaling of the RF carrier for a particular symbol be R, and the additional carrier phase shift required for the modulation be δ. It is expected that this symbol modulation will be applied to all array elements. It can then be shown that the adapted timings for each TMA element (k = 1..N) are found using the following steps :-

1) Calculate Ek using (3).

2) Apply the required magnitude scaling R [0..1], corresponding to the required symbol magnitude, producing (9).

$$E'_k = R.E_k \tag{9}$$

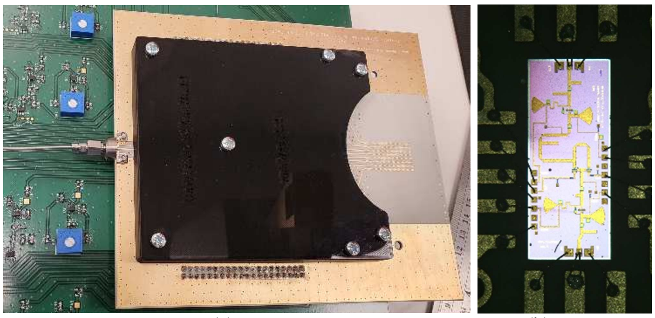
3) Find the required initial Vk to steer the beam, using (4) and now E'_k.

4) Apply the required symbol modulation phase shift δ to Vk using (10).

$$V'_k = V_k + \frac{\delta}{2\pi n} \tag{10}$$

5) Use (5) and (6) to obtain the resulting TMA element switch timings using the obtained E'_k and V'_k. These timings thus now incorporate both the required beam steering and vector modulation for an applied symbol.

We now go on to show laboratory results from using the above approach at mmWave 73 GHz in our hardware system.



(a) (b)

Fig. 3. 73 GHz TX TMA system: (a) RF PCB (ICs under the black plastic cover) with antenna arrays on right, partially visible green PCB is a control interface board, (b) 1 of 8 TMA RF switching ICs mounted to the RF PCB.

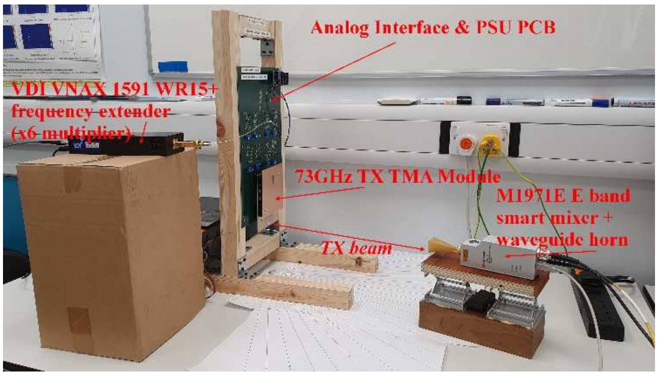


Fig. 4. 73 GHz TX TMA test system (TX is the vertical PCB on wooden frame on left / RX front end system is seen on right). RX can be manually scanned horizontally to capture the radiated TX signal at an angle of interest.

III. Laboratory Prototype

We tested the joint beam steering and direct vector modulation concept using our 8 element 73 GHz TX TMA platform [18], that also incorporates a C0 beam reduction technique. Fig. 3a shows the 73 GHz TMA module (all RF circuitry is under the black cover). Fig. 3b shows one of the 8 GaAs integrated circuits (ICs) mounted and wire bonded to the RF PCB. The radiating antenna elements controlled by the TMA are series fed arrays, seen on the right of Fig. 3a. In the prototype there are 8 GaAs ICs performing the mmWave switching function, with each switch controlled by just 2 digital lines [18]. This means the full 8 element phased array can be fully controlled (steering and symbol modulation) using just 16 digital binary lines. This simple digital control is a key advantage of the TMA.

Fig. 4 shows the laboratory test set-up used to capture the radiated beam. The TX CW signal source used a Rohde & Schwarz SMM100A signal generator at 12.1667 GHz and VDI VNAX 1591 WR15+ frequency extender as a x6 frequency multiplier, producing a carrier at 73 GHz to apply conducted to the TMA. The radiated TX TMA signal was then captured using a Keysight M1971E E band smart mixer with Eravant waveguide horn (SAZ 2410-12-S1, 24 dBi), and Keysight N9030B PXA spectrum analyser.

IV. Laboratory Measured Results

We tested the prototype TMA's ability to modulate random data in QPSK, 8PSK and 16QAM on a steered beam. In each case, 2000 symbols were used. The symbol rate was 500 K symbols/s (a limitation imposed by the FPGA interface platform and not the RF hardware. The N9030B PXA IQ capture sampling rate was 2.5 M samp/sec.

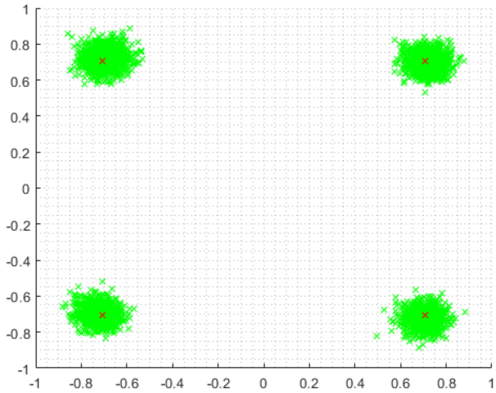


Fig. 5. Measured QPSK constellation at C2p beam centre (15 degrees). In all cases the red crosses are the expected ideal symbol locations, the green marks are each individual measured RX symbol (2000 used).

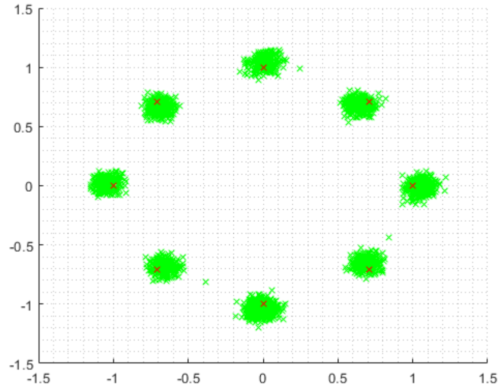


Fig. 6. Measured 8PSK constellation at C2p beam centre (15 degrees). In all cases the red crosses are the expected ideal symbol locations, the green marks are each individual measured RX symbol (2000 used).

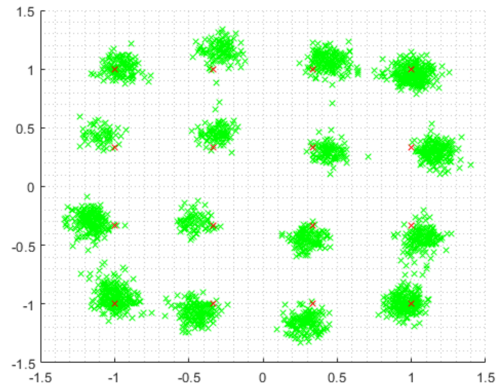


Fig. 7. Measured 16QAM constellation at C2p beam centre (15 degrees). In all cases the red crosses are the expected ideal symbol locations, the green marks are each individual measured RX symbol (2000 used).

The RF hardware can be controlled faster. A 20MHz *Fp* was demonstrated in [18] ($Fp = 1/Tp$), but switching speed is ultimately limited by the IC phase changeover delay of 391ps [18]).

The TMA was configured to use the second harmonic beam ($n = 2$, i.e. the *C2p* beam shown in Fig. 2) resulting in the wanted radiated beam emitting at $(\omega_c + 2\omega_p)$. The TMA phased array timings were first chosen to steer the *C2p* beam to +15 degrees.

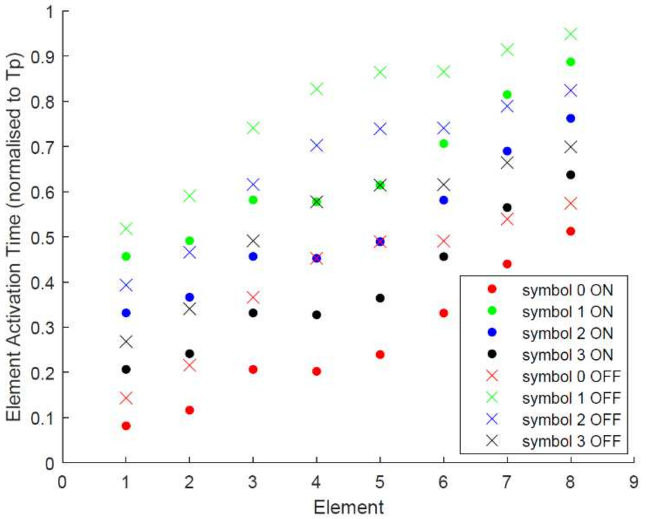


Fig. 8. TMA antenna timing control patterns for the QPSK modulated beam. Note the 4 different element turn-on and turn-off states- representing the phase shift for the symbol and additional to the beam steering timings.

These initial TMA timing patterns were then modified to incorporate the required symbol modulation test patterns, using the approach described earlier.

The measured symbol constellations as captured from the PXA at 73 GHz are shown in Figs. 5-7. Received signal SNRs were circa 18 dB. To help illustrate operation, in Fig. 8 the TMA timing control sequences are shown for the QPSK signal, showing how each of the antenna element turn-on and turn-off times shift with each of the four symbols, thus implementing the required phase shift at the carrier. The modulation is present on all the harmonic beams. However, in practice only the first and second harmonic beams have sufficient energy to be useful. If necessary, unwanted harmonic beams could be removed by band-pass filtering before the antenna element. From our measured results, the recovery of usable symbol constellations on the steered beam are shown in all cases.

There is some variation and distortion on constellation points, leading to observed error vector magnitude (EVM) of between 7.1% to 11%. We suspect the phase-noise like disturbance is due to timing jitter from the FPGA clock, or could be an issue in the lab mmWave RX hardware. If problematic, TX constellation distortion could possibly be reduced by using predistortion techniques on the symbol TX timings. Jitter could also be reduced by using high quality, low phase-noise, clock sources for the FPGA.

Table 1 provides a brief comparison to other recent works in direct TX modulation and DAM, with and without beam steering. The spectral efficiency (SA) metric is defined as tested baseband bit rate / beam RF signal 3 dB bandwidth. Square symbol pulses, with no symbol shaping, were used in our tests. Table 1 shows that our proposed system has the lowest complexity of input control interface (just 2 digital lines per element) for complex modulation types. Table 1 also shows our system has the best EVM, and highest number of controllable radiating elements of reported direct modulation systems at high mmWave and upwards.

V. Conclusion

We present a new technique, using the TMA, that can simplify mmWave systems for transmitting modulated signals on steerable RF beams.

TABLE I. Recently Published Works with TX Digital Modulation Interfaces (EIRP = Effective Isotropic Radiated Power, P_{SAT} = Saturated TX RF power, NA = Not Available).

Ref.	**Carrier (GHz) / SA (bits/s/Hz)**	**Modulation Type / EVM (%)**	**Control Interface**	**Implementation**	**RF Power (dBm) / DC power (mW)**
This work	73 / 2.3 73 / 3.4 73 / 4.5	QPSK / 7.1 8PSK / 8.4 16QAM / 11	2 bits per element, for beam steering & modulation	8 element steerable TMA	15.9 (*C2p* P_{SAT} EIRP) / 490 [18]
[13]	2.5 / NA	4-FSK	6 switches per element	4 element TMA (simulation)	N/A (no hardware)
[19]	2.4 / NA	64QAM / 4.6	10-bit modulator	4 element phased array	27 (conducted, peak) / 1350
[20]	6 / 4.5	16QAM / 3.3	10-bit digital IQ (1 bit sigma-delta RF DAC)	8 element beamformer	13.7 peak (conducted) / 47.5
[21]	170 / 1.5	8PSK / 18.2	3 bits, (direct digital modulator)	2 elements, fixed beam	4 (EIRP) / 560
[22]	210 / NA	On Off Keying (OOK) / NA	1-bit, (direct digital modulator)	4 elements, fixed beam	5.1 (EIRP) / 480

The concept incorporates vector modulation via the TMA digital timings, removing the need for traditional modulators in the early TX RF stages. We demonstrate the concept on prototype hardware using QPSK, 8PSK and 16QAM, with good radiated EVM seen. To the best of our knowledge, we believe this is the first demonstration of a TMA applying direct modulation to a steerable beam at 73 GHz.

Acknowledgment

The authors thank Ms. Sideqe Askre at the *UKRI National mmWave Measurement Laboratory* [23] for laboratory test support.

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