

Scalable Modular Beamformers for Energy-Efficient MIMO Applications Using Correlation Technologies

[§]eV-Technologies, France, ^{*}European Engineering & Consultancy UK, [†]UMS-RF, France

Abstract— A scalable Beamformer module built using unitary 1x8 sub-arrays integrating Antenna-in-Package (AiP) in a profile of 5mm pitch is introduced. The 1x8 module can be stacked either horizontally or vertically to create dynamic phased arrays of 8, 16, 32 or 64 elements horizontally or 8x8 or 16x16. The unit is USB controlled and is bidirectional. Beams can be calibrated and calibration stored in EEPROM for fast Look-Up-Table (LUT) access. The module offers 6-bit amplitude and 6-bit phase controls. The combined gain (assuming all elements sum up coherently) is 30dB for receive and 20dB for transmit. The module is capable of achieving +53dBm EIRP when used in an 8x8 configuration. The unit can switch seamlessly between TX and RX modes and has internal DCDC converters for maximum efficiency. Multiple-Input Multiple-Output (MIMO) Correlators are introduced for building scalable multi-beamforming front-end-modules (FEM) with embodied cognition. Unified mmWave and Baseband correlation technologies using energy density and EVM (Error Vector Magnitude) metrics are introduced for low complexity (leveraging sparsity of MIMO channels) cost-effective multi-beamforming systems. Combination of convolutional accelerators with analog signal processing for linking beam-selection algorithms to stochastic-wave-shaping (SWS) will foster new system architectures with critical functionalities including direction of arrival (DOA) estimation and secure communications.

Keywords— Scalable Beamformer, Phased-Arrays, Single and Multi-Beam systems, AiP, Correlation Technologies, Front-End-Modules, Thermal-Management, Energy Harvesting, EVM.

I. INTRODUCTION

Beamformer front-end-modules (FEM) enabling multi-user multiple-input multiple-output (MU-MIMO) operation for simultaneously connecting several user-equipment (UE) devices based on same time-frequency resources are known to achieve a higher capacity compared to single-user MIMO (SU-MIMO) [1-12]. However, in classical MIMO systems, fully digital beamforming requires that each antenna be driven by its dedicated radio frequency chain leading to impractical solutions as increasing the number of RF chains significantly impacts the hardware cost, system complexity and energy efficiency [12-28].

In this paper, we propose new *modular beamforming* solutions using *correlation* [10] *technologies* for building scalable MIMO systems. The proposed scalable modular-multi-beamforming architectures (Fig.1), in offering sparse properties in both time and angular dimensions, provide significantly reduced signal processing which result in a small set of correlation-based RF measurements for channel estimation of MIMO systems. Mosaic partitioning strategies, exploiting the sparsity of MIMO correlation matrix, open new possibilities for combining multiple arrays into a full array state (FAS) to form one single beam, or for using them to form separate beams in the sub-array state (SAS).

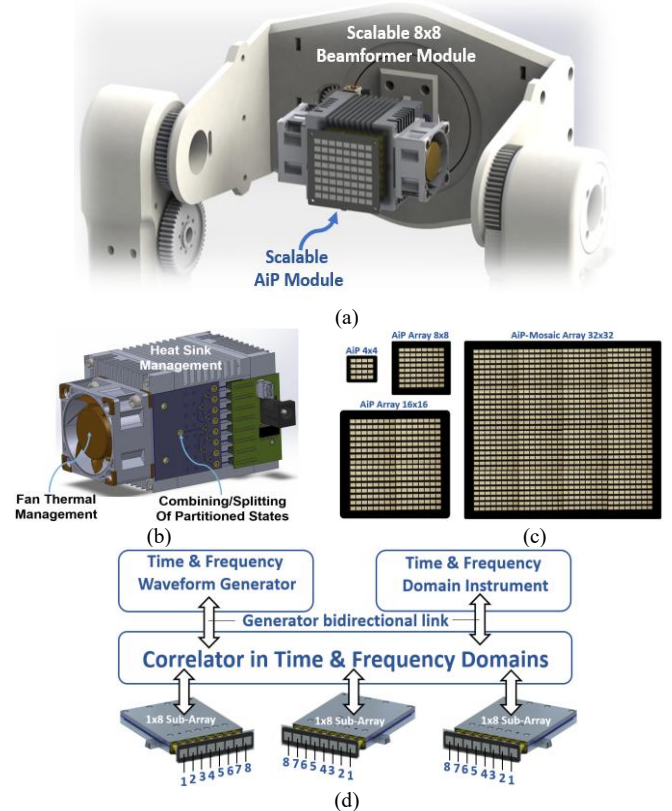


Fig. 1: Scalable 8x8 beamformer module (a) built using 8 partitions of 1x8 sub-arrays mounted on 3D rotary system for beam-search testing. System assembly including thermal management solution (b). 4x4, 8x8, 16x16 and 32x32 scalable beamformer modules with connectable AiP elements (c). Time and frequency domains correlation technologies (d) for stochastic fields signal processing.

Space-time pulse shaping strategies will foster new energy-efficient modulated amplitude (AM) and phase (PM) waveforms that can be accurately and separately engineered to meet critical OTA performances. The AM and PM waveforms may be dynamically modulated in a predefined manner by properly mapping pulse train sequences to desired beamforming characteristics. The optimization of desired beamforming characteristics covering the carrier signal and its harmonic components can benefit from built-in convolutional accelerators for RF embodied cognitive signal processing.

II. MAIN RESULTS, ANALYSIS AND DISCUSSION

A. Design Scalability and System Integration

The module is controlled from the computer using simple terminal commands. Each unit can be easily controlled for maximum versatility. All parameters can be altered as follows: Channel Enable 1-8, TX/RX modes, Gain control, Phase

control, temperature read, read EEPROM, write EEPROM, trigger and beam sequence commands.

- The Beamformer 015-1x8 is a 1x8 module with a profile of 5mm pitch array.
- The module can be stacked either horizontally or vertically to create dynamic phased arrays of 8, 16, 32 or 64 elements horizontally or 8x8 or 16x16.
- The unit is USB controlled and is bidirectional. Beams can be calibrated, and calibration stored in EEPROM for fast access. The module offers amplitude and phase control of 6 bits.
- The combined gain (assuming all elements sum up coherently) is 30dB for receive and 20dB for transmit.
- The unit can switch seamlessly between TX and RX modes and has internal DCDC converters for maximum efficiency.
- Power Supply: 5V to 20V, per module in TX mode, 30dBm RX mode
- Phase Step Range: 0 – 63 (5 degrees per step)
- Gain Control Range : 0-32 in 0.5dB steps
- TX Gain: 20dB, PSAT 18dBm per channel (assuming full coherence)
- RX Gain: 30dB (assuming full coherence)

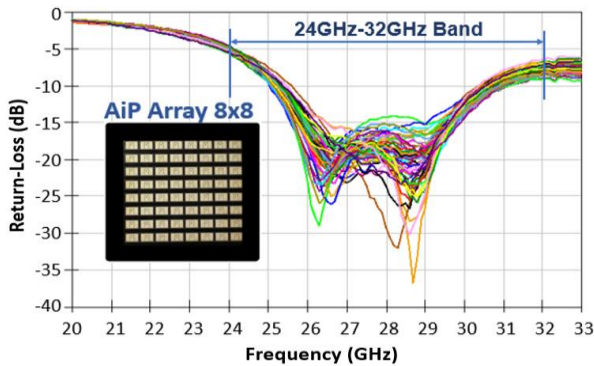


Fig. 2: Measured Return-Loss of all 64-Channels of designed and fabricated broadband Antenna-in-Package through calibrated 2-to-64 correlator module.

A 26-30 GHz phased-array AiP module with 64 dual-polarized elements has been designed, fabricated and characterized. The module can achieve +53 dBm EIRP when used in an 8x8 configuration. Measurement results on an assembled phased array module including the package and the transceivers are shown in Fig.3 in TX mode and ± 40 degrees scanning range (Fig.2). The AiP module is a mechanically optimized Rogers and is reinforced with an aluminum base plate machined with a mechanism to overcome the high engage and disengage force. The top of the antenna has radiation absorber material. The AiP technology offers industrialized "Mosaic Partitioning" solution for building MIMO and Massive-MIMO modules: Full modularity for combining multiple arrays into a full array state (FAS) to form one single beam, or for using them to form separate beams in the subarray state (SAS) in combination with Front-End-Modules.

The MIMO link measurement of the 8x8 beamformer module uses a GaN-based transceiver FEM, operational in the frequency band 24-30GHz, as shown in Fig.4.

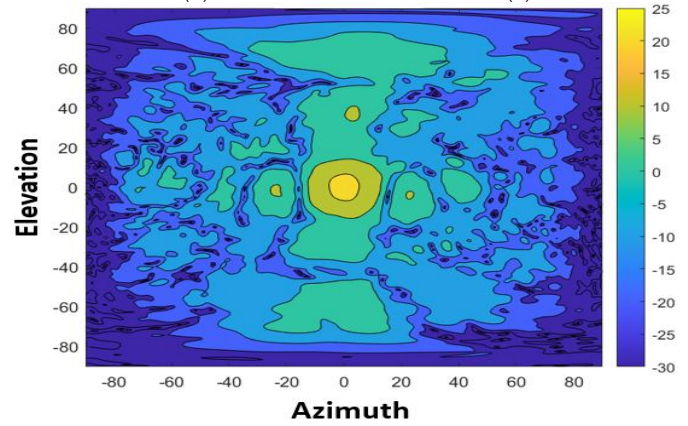
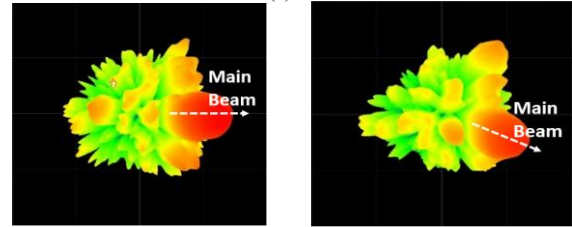
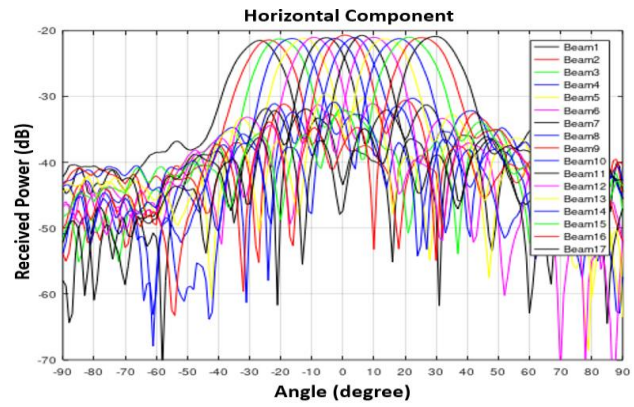


Fig. 3: Measured beamforming at 28GHz in ± 90 degrees angle scan (a), measured 3D radiation patterns (b),(c), (d) using mechanical positioner system with controllable step motors.

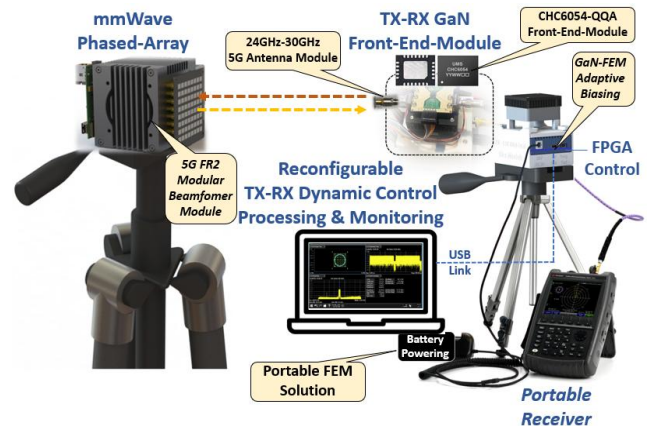


Fig. 4: OTA setup with MIMO link using combined 8x8 Beamformer and GaN-based Front-End-Module.

The GaN-based transceiver module (Fig. 5) module is controlled from the computer using simple terminal commands. Each drain

and gate can be individually controlled. The unit can display the drain current for a given gate voltage.

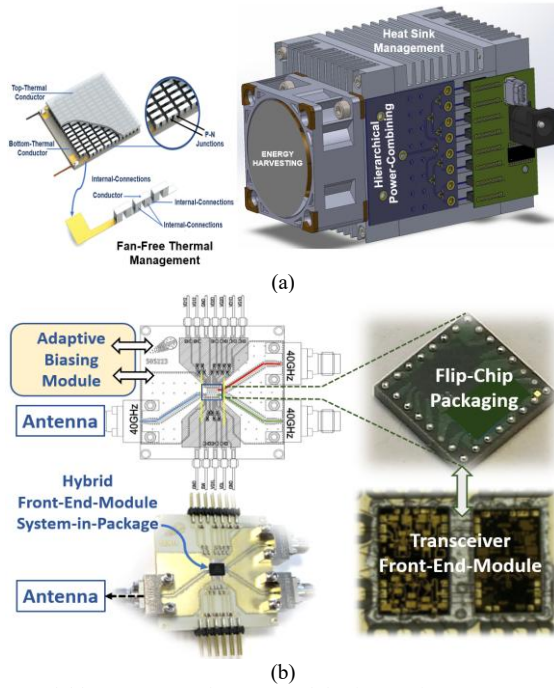


Fig. 5: Scalable 8x8 Beamformer module integrating Energy-Harvesting functionality (a) GaN-based Front-End-Module for OTA testing of beamforming (b).

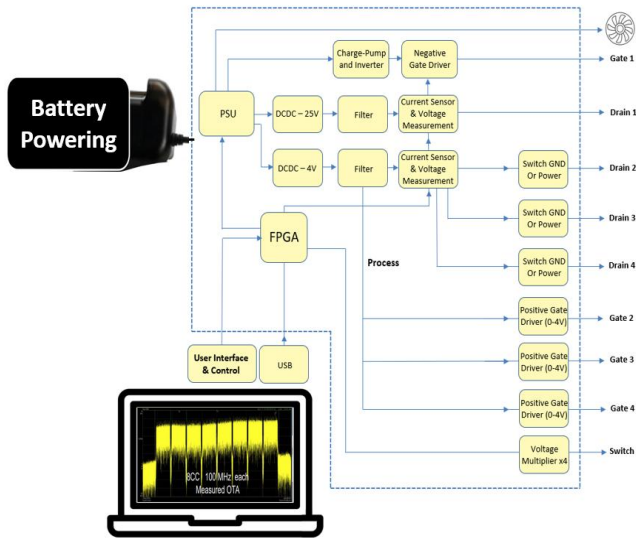


Fig. 6: Synoptic view of Adaptive-biasing module for GaN-based Front-End-Module including configurable Power-Supply-Modulation functionality.

A smart self-biasing mode can be invoked to automatically adjust the gate voltage to achieve a desired drain bias current. The module will constantly monitor the current and turn off should the drain current go too high, thus preventing damage. The unit can switch seamlessly between TX and RX modes. Fig. 6 presents a synoptic view of the smart self-biasing module which includes a programmable FPGA for automatically driving the GaN-based transceiver module. Measurement of RF performances of the transceiver module including EVM are presented in Fig. 7.

The biasing features the following attributes:

- Efficiently power-up and power-down.
- Reduced complexity and improved reliability for end-users.
- Allowing intuitive tuning, and robust RF design for end-users.
- Unified single input Power-Supply through USB.
- Possible current-mode control with synchronization to external clock for advanced PA-based applications.

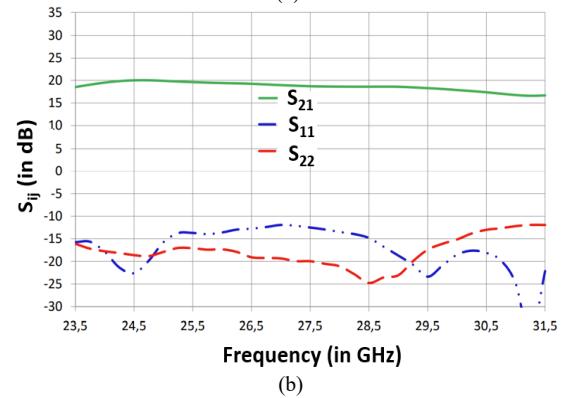
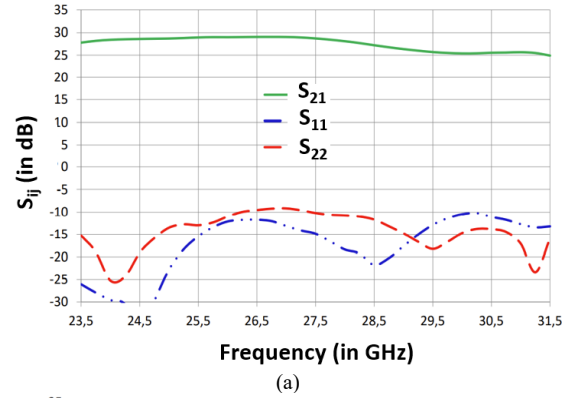


Fig.6: Gain and Return-Loss against frequency in TX (a) and RX (b) modes.

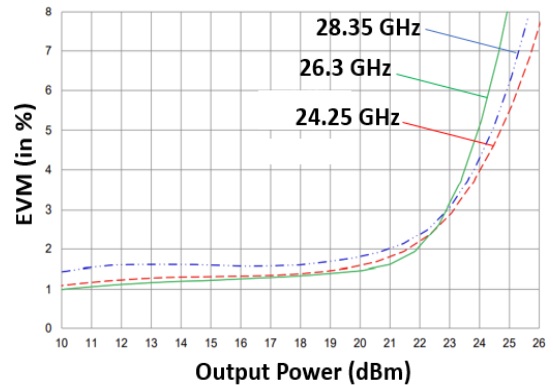


Fig. 7: Error Vector Magnitude versus output power at 24.25GHz, 26.3GHz and 28.35GHz without DPD for 256 QAM modulation.

B. Correlation Technologies for Single-Beam and Multi-Beamforming

The proposed scalable beamforming solutions drive correlation-based EVM measurement enabling industrial-testing of RF/mmWave Front-End-Modules and Beamformers:

The optimum gain is computed by using autocorrelation and cross-correlation of ideal and received symbols. A combination of convolutional accelerators with analog signal processing (compliant with ASIC and FPGA implementations) is used for single-beam and multi-beam applications. The resulting solutions can benefit from adaptive linearization techniques accomplished based on sub-partitioned separate feedback (FB) paths, each of which considers the combined outputs of the multiple transmit units (e.g., Power Amplifiers) in one sub-array. Using multiport correlators, the feedback paths are either considered individually, are all combined, or are partially combined (i.e. grouped or clustered) in accordance with how the sub-arrays may be merged to form beams.

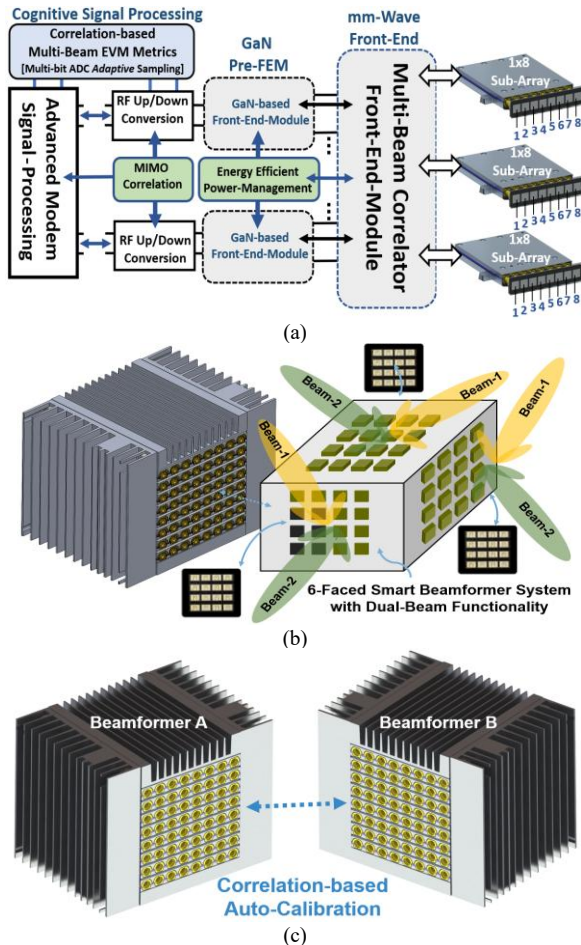


Fig. 8: Time and frequency domains distributed correlator architecture correlation (a) combining scalable Beamforming sub-array modules with GaN-based Front-End-Modules for Multi-Beamforming applications. Single-face (b) and multi-face (c) Cubic implementations of Multi-Beam systems.

The proposed EVM testing platform will exploit the metrics of Correlation-Functions as criteria for assessing the quality of high-throughput video-streaming using multi-beam configurations. Error Vector Magnitude (EVM) is used in modern communication standards to measure the overall degradation of the signal due to linear or nonlinear distortions, and to noise, interference, and multipath impairments. The classical method for EVM (Error Vector Magnitude) computation is to compute vector errors between received (y_n)

and ideal (x_n) symbols and then to compute a root-mean-square of the magnitude of these vectors for all symbols in a frame. All these computations can be done in the following steps by replacing the optimum gain by its value and using the covariance between the ideal \mathbf{x} and received \mathbf{y} symbols vectors.

$$e_n = y_n - \gamma x_n \quad (1)$$

$$\sigma = \sqrt{\frac{1}{N} \sum_{n=1}^N |e_n|^2} = \sqrt{\frac{1}{N} \sum_{n=1}^N |y_n - \gamma x_n|^2} \quad (2)$$

$$\gamma = \frac{\sum_{n=1}^N y_n x_n^*}{\sum_{n=1}^N x_n x_n^*} \quad (3)$$

The optimum gain is computed by using autocorrelation and cross-correlation of ideal and received symbols. All these computations can be done in the following steps by replacing the optimum gain by its value and using the covariance between ideal \mathbf{x} and received \mathbf{y} symbols vectors.

$$\cos \theta = \frac{|\sum_{n=1}^N y_n x_n^*|}{\sqrt{\sum_{n=1}^N y_n y_n^*} \sqrt{\sum_{n=1}^N x_n x_n^*}} = \frac{|\langle y, x \rangle|}{\|y\| \|x\|} \quad (4)$$

$$EVM = \sqrt{\frac{1}{\cos^2 \theta} - 1} = \tan(\theta) \quad (5)$$

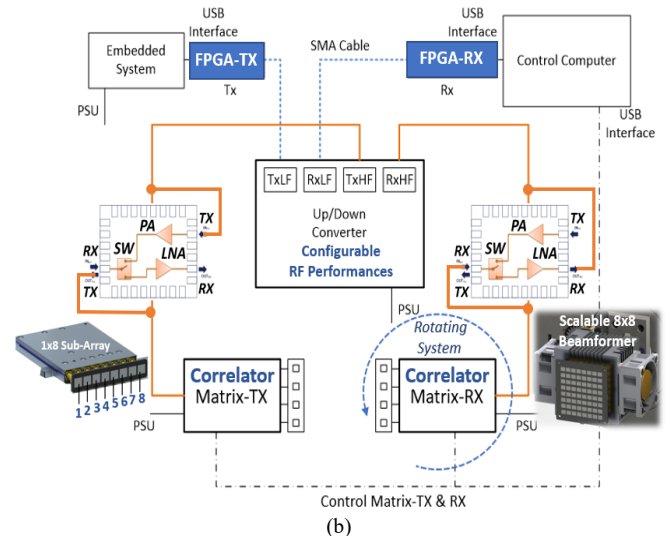


Fig. 9: Auto-Calibration solution for Scalable Beamformer modules based on Correlation technologies (a). EVM-based TX-RX MIMO link (b).

EVM can be applied over the air (OTA) to each beam of a multibeam antenna and to each channel or the combination of channels of a MIMO transmission. FPGA-based reconfigurable platform is proposed for OTA testing of multi-beamforming systems using correlation-based EVM metrics. The flexibility offered by FPGA platforms enables versatile control and monitoring of the radiation properties, the radiation pattern, the polarizations, the frequency band, the Direction of Arrival (DoA). The resulting platforms call for unification of modeling and measurement into a coherent framework. The benefits of coherent measurement (instrumentation) and modeling (EDA tooling) solutions go beyond the simple need for productivity enhancement, and they open new possibilities for transforming apparent antagonisms between theory and experiment into necessary complementarities driving Digital-Twin requirements (security, distributed information redundancy, Deep-Learning, AI inferences, etc.). These multiphysics

platforms will benefit from unified Thermal-EM testing solutions [29].

III. CONCLUSION

In this work, we have successfully demonstrated low cost and energy-efficient modular beamformers in the realization of scalable MIMO systems. The 1x8 modules can be stacked either horizontally or vertically to create dynamic phased arrays of 8, 16, 32 or 64 elements horizontally or 8x8 or 16x16. The unit is USB controlled and is bidirectional. Beams can be calibrated, and calibration stored in EEPROM for fast Look-Up-Table (LUT) access. The module offers amplitude and phase control of 6 bits. The combined gain (assuming all elements sum up coherently) is 30 dB for receive and 20 dB for transmit. The module can achieve +53dBm EIRP when used in an 8x8 configuration. The unit can switch seamlessly between TX and RX modes and has internal DCDC converters for maximum efficiency. Multiple-Input Multiple-Output (MIMO) Correlators are introduced for building scalable multi-beamforming front-end-modules (FEM) with embodied cognition. The proposed scalable modular-multi-beamforming architectures, in offering sparse properties in both time and angular dimensions, provide significantly reduced signal processing which result in a small set of correlation-based RF measurements for channel estimation of MIMO systems. Mosaic partitioning strategies, exploiting the sparsity of MIMO correlation matrix, open new possibilities for combining multiple arrays into a full array state (FAS) to form one single beam, or for using them to form separate beams in the sub-array state (SAS). Unified mmWave and Baseband correlation technologies using energy density and EVM (Error Vector Magnitude) metrics are introduced for low complexity (leveraging sparsity of MIMO channels) cost-effective multi-beamforming systems. Combination of convolutional accelerators with analog signal processing for linking beam-selection algorithms to stochastic-wave-shaping (SWS) will foster new system architectures with critical functionalities including direction of arrival (DOA) estimation and secure communications.

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