A Software-Defined mmWave Radio Architecture Comprised of Modular, Controllable Pixels to attain Near-Infinite Pattern, Polarization, and Beam Steering Angles IMS

Junho Park, Dongkwon Choi, and Wonbin Hong
Pohang University of Science and Technology, Pohang, Republic of Korea
whong@postech.ac.kr

Abstract—This paper presents a software-defined mmWave radio architecture using modular/controllable antenna pixels for 5G/B5G beamforming systems. The operating mechanism of the proposed phased array is conceptually analogous to that of a field programmable gate array (FPGA) board. The proposed concept not only supports almost infinite radiation modes, but is fully compatible with the currently existing mmWave beamforming architecture. The proposed concept can be modularly expanded into a two-dimensional structure exemplified in the 4 × 4 array using a low temperature co-fired ceramic process. The proof-of-concept model features multiple polarizations with different beamsteering angle selected from $5^{13}$ theoretically available modes.

Keywords— millimeter-wave antennas, 5G, software-defined radio, phased arrays, reconfigurable antenna.

I. INTRODUCTION

Millimeter-wave (mmWave) phased-array radios have been considered as a key enabling technology for next-generation wireless communication systems to fundamentally resolve high path loss issues and support directive wireless links [1]. The development of the phased array topology that can be universally applied across variety of platforms is highly required for massive adoption of mmWave technologies.

One way for implementing a universal phased array is to use a reconfigurable antenna (RA) which can simultaneously satisfy multiple design criteria using its versatile antenna modes [2]. RAs can alter their operation characteristics by rearranging the current distributions with the use of external passive and active components including PIN diodes, varactors and MEMS. Despite the great potential of multifunctional capabilities, the adoption of RAs to phased arrays (see Fig. 1 (a)) poses great challenges due to the following reasons: 1) The RF components and power supply circuitries added for the operation of the RA significantly increases the integration density of hardware. 2) In order to be compatible with an adaptive beamforming system, the operation of RAs should be synchronized with other circuitries and controlled by the baseband blocks. Due to these packaging and operational issues, RA topologies have not been adopted in mmWave phased array applications.

Recently, a software-defined phased array radio (SDPAR) operating at 28 GHz bands has been demonstrated to implement beam shaping and steering functions by using a large number of software-defined waveform in [3]. The proposed SDPAR solution enable extensive beam reconfigurable functions from the software interface. However, in such SDPAR implementations, reconfigurability is physically limited by the available radiation modes of the integrated antenna topology.

In this paper, we present a software defined modular/controllable mmWave radio architecture (SDMRA) for mmWave RF beamforming systems. Compared to the conventional architecture based on reconfigurable antenna arrays, the proposed concept (Fig. 1 (b)) only requires phase shifters and attenuators, which are essential components of mmWave RF beamforming systems [1]. Therefore, the proposed solution can be seamlessly adopted and integrated in the mmWave beamforming system without modification of other hardware configuration. Section II demonstrates the basic concept and operation mechanism of the antenna pixel concept. The two-dimensional 4×4 pixel array module with SDMRA is described in Section III. The measured and simulated results are discussed in Section IV. The paper is concluded in Section V.

II. WORKING MECHANISM OF UNIT ANTENNA PIXEL

In this Section, the unit antenna pixel concept is introduced and numerically analyzed using a current flow model. The unit antenna pixel (Fig. 2 (a)) consists of four connected half-wavelength loop antennas on the ground plane and includes
The radiation characteristics of the unit antenna pixel is determined by the current distribution on each branch. Each Greek letter (see Fig. 2 (b)) denotes a magnitude coefficient of the current flowing through each branch from input ports. In addition, the current distribution on each branch (A ~ E) of the unit antenna pixel can be equivalently expressed to the superposition of two simultaneously excited current sources, as illustrated in Fig. 2 (c). The current distributions in the case of n = 3 are exemplified and illustrated in Fig. 2 (d).

\[
I_1(z) = \cos(\beta z) + \cos(\beta z + \frac{n - 1}{2} \pi) \quad 0 \leq z \leq h
\]

\[
I_2(z, n) = \cos\left(\beta z + \frac{(n-1)^2}{2}\right) \quad (2)
\]

The radiation characteristics of the unit antenna pixel is determined by the current distribution on each branch. Each Greek letter (see Fig. 2 (b)) denotes a magnitude coefficient of the current flowing through each branch from input ports. In addition, the current distribution on each branch (A ~ E) of the unit antenna pixel can be equivalently expressed to the superposition of two simultaneously excited current sources, as illustrated in Fig. 2 (c). The current distributions in the case of n = 3 are exemplified and illustrated in Fig. 2 (d). The direction of the arrow is the same as the direction of the sinusoidal current source at a single time domain. In Fig. 2 (d), h denotes the height of the unit antenna pixel, s is the distance between the two vertical components, and z is the distance from the port. Based on the aforementioned definition, the current intensity in each branch is expressed in Table 1 when two ports are simultaneously excited. The well-known magnetic vector potential of the unit antenna pixel can be obtained and calculated by integrating the currents from the sources. The detailed calculation process is omitted for brevity. The calculated radiation pattern derived from the current flow model is plotted along with the 3-D full-wave simulation result, as illustrated in Fig. 3. The analytic radiation pattern is highly correlated to that of the full-wave simulation result, which confirms the possibility of the unit antenna pixel as a modularly expandable antenna element.

### III. SOFTWARE-DEFINED MMWAVE RADIO ARCHITECTURE

#### A. Unit Pixel Structure

The unit antenna pixel concept (Fig. 4) is exemplified and designed using low-temperature co-fired ceramic (LTCC) process. The LTCC packages consist of 10 stacked dielectric layers featuring a thickness of 100 μm and a permittivity of 5.9, and a loss tangent of 0.002 at 28 GHz. The conductor layers are implement using silver with thickness of 10 μm. The diameters of the via holes and the capture pads are
configured to be 100 μm and 150 μm, respectively. The dimensions of each branch (s) and vertical component (t) is optimized and determined to achieve a half-wavelength resonance mode, and the diameter of the clearance \( r_p \) is adjusted to match an input impedance to 50 Ohms. All other parameters are summarized in Table 2.

### B. Multi-dimensional Pixel Array Structure

The previously designed unit pixel is extended to the 1 × N structure to increase the directivity of the antenna, as illustrated in Fig. 5. It can be seen that when the phase difference between two adjacent ports is 180° (n=3), the effective current is linearly arranged in the expanded direction while the currents on other branches cancel each other. The directivity and gain of the antenna is studied as a function of the number of unit pixel at 28 GHz.

![Simulated surface current distribution](image)

The two-dimensional structure of pixels can maximize the achievable radiation modes since a wide variety of effective currents can be obtained depending on the weighting vector matrix. The 4×4 pixel array module is designed to verify the reconfigurability including pattern, polarization, and beam steering agility, as illustrated in Fig. 7. The mush-room type EBG structure is added to suppress the undesired surface current and improve impedance matching of each antenna. The 4×4 pixel array module contains 13 input ports and the other vertical components are connected to the ground plane. Therefore, if a RFIC featuring m-bit phase control and n-state magnitude control is available, the number of theoretically achievable modes of the 4×4 pixel array module is \((1 + (n - 1) \times 2^m)^3\) modes. For this demonstration, the parameters are configured as follows: m = 2, n = 1 and a total of 9 antenna modes are selected from 513 theoretically available modes. Fig. 8 illustrates the simulated 3-D far-field radiation patterns of the 4×4 pixel array module. The x-axis and y-axis polarized broadside beams with different steering angle are demonstrated in Fig. 8 (a) ~ (c) and Fig. 8 (d) ~ (f), respectively. Additional \( \phi = 135° \) and 45°-polarized broadside beams are achieved in Fig. 8 (g) and Fig. 8 (h), respectively. An omni-directional beam is also obtained in Fig. 8 (i).

### C. System Architecture

In order to operate the proposed SDMRA, a mmWave beamformer board, a FPGA board for digital control, and a mmWave waveform generator are configured together, as illustrated in Fig. 9. The weighting matrix can be predominantly determined by the wireless link quality metrics (EVM, BER) and the channel matrix. The calculated input weighting matrix is assigned to the beamformer board by using the FPGA board which also provides the required bias voltages to the RFIC. The modular pixels with the beamformer board can energy-efficiently transmit/receive mmWave wireless signals by utilizing near-infinite radiation modes.

![Geometry of the 4×4 pixel array structure](image)
The reflection coefficients of the fabricated 4×4 pixel array module are measured using Keysight PNA-X, as illustrated in Fig. 10. Considering the symmetry of the 4×4 pixel array module, the characteristics of PORT 1 is only discussed. The measured and simulated reflection coefficients feature an impedance bandwidth of 5.1 GHz (26.9 – 32 GHz) and 2.8 GHz (27.8 – 30.6 GHz), respectively. The discrepancy between two results is dominantly attributed to the deviation of the electrical properties of the substrate material at the frequency design. Nevertheless, an acceptable tendency is observed between the simulated and measured results.

The system configuration (described in Section III B) is constructed to access pattern, polarization, and beam-steering agility of the 4×4 pixel array module. A representative 6 beams selected from the 513 available modes are demonstrated at 28 GHz according to the assigned weighting vector matrix, as illustrated in Fig. 11. It is noted that good correlation is achieved between simulated and measured normalized far-field radiation patterns in all cases. Directional and bi-directional modes are implemented in Fig. 11 (a). In Fig. 11 (b) and Fig. 11 (c), the dual-polarized beams are simultaneously achieved in two orthogonal planes (xz and yz plane).

V. CONCLUSION

We have demonstrated a software-defined mmWave radio architecture (SDMRA) based on the modular/reconfigurable pixels. The proposed concept is fully compatible with mmWave RF beamforming schemes since the proposed SDMRA only requires phase shifters and attenuators. Numerical calculations and simulation results demonstrate the modular scalability and reconfigurability of the proposed concept. The proposed concept is exemplified in the 4 × 4 pixel array structure with 13 RF ports and 28 GHz RF beamforming modules. The fabricated 4×4 pixel array module with the proposed SDMRA proves the reconfigurability featuring a distinctive combination of polarizations and beamsteering angles selected from 513 theoretically available modes. Future works will focus on the development of a machine learning-driven optimization algorithm for mmWave 5G and sub-terahertz 6G phased-array architectures.

ACKNOWLEDGMENT

This work was partially supported by the Institute of Information & communications Technology Promotion (IITP) grant funded by the Korean government (MSIT) (No. 2018-0-00733). In addition, the authors thank Dr. Sinhyung Jeon, Dr. Jeongnam Cheon of Samsung Electronics Global Technology Center for their invaluable support.

REFERENCES