Demo: M-Cube: An Open-Source Millimeter-Wave MIMO Software Radio for Wireless Communication and Sensing

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ABSTRACT

Millimeter-wave (mmWave) technologies represent a cornerstone for emerging wireless network infrastructure, and for RF sensing systems in security, health, and automotive domains. Through a MIMO array of phased arrays with hundreds of antenna elements, mmWave can boost wireless bit-rates to 100+ Gbps, and potentially achieve near-vision sensing resolution. However, the lack of an experimental platform has been impeding research in this field. We propose to fill the gap with M^3 (M-Cube), the first mmWave massive MIMO software radio [1]. M^3 features a fully reconfigurable array of phased arrays, with up to 8 RF chains and 256 antenna elements. Despite the orders of magnitude larger antenna arrays, its cost is orders of magnitude lower, even when compared with state-of-the-art single RF chain mmWave software radios. In this demo, we will show M^3's hardware modules, and demonstrate its usage in mmWave MIMO communication and sensing.

CCS CONCEPTS

• **Networks** → **Programming interfaces**; • **Hardware** → **Wireless devices**; *Signal processing systems.*

KEYWORDS

60 GHz, Millimeter-wave, MIMO, Testbed, Experimental platform

ACM Reference Format:
Renjie Zhao, Timothy Woodford, Teng Wei, Kun Qian, and Xinyu Zhang. 2022. Demo: M-Cube: An Open-Source Millimeter-Wave MIMO Software Radio for Wireless Communication and Sensing. In *The 20th Annual International Conference on Mobile Systems, Applications and Services (MobiSys '22), June 25–July 1, 2022, Portland, OR, USA.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3498361.3538659

1 INTRODUCTION

To fully explore the challenges and opportunities in mmWave technologies, it is critical to have a programmable experimental platform with the following capabilities: *(i)* Equipped with low-cost and large-scale phased arrays which allow real-time beam switching, to accommodate high mobility vehicular networking/sensing scenarios; *(ii)* Supporting the mmWave MIMO architectures to be used in 5G NR and 802.11ay radios [2, 3]; *(iii)* Allowing reconfiguration of beam patterns, communication/sensing algorithms and network stack. Existing mmWave experimental platforms are either too costly (around $200K per link [4]), or lack a reconfigurable phased array antenna with reasonable size [5, 6]. Moreover, such devices are often bulky and can barely support mobile experiments.

To meet the aforementioned requirements, we developed M^3, the first mmWave massive MIMO experimental platform which is low cost and comprised of up to 256 antenna elements and up to 8 RF chains. The key research thrust in M^3 is to repurpose a commodity 802.11ad phased array as a programmable one, and to interface it with an existing baseband processing unit (BPU), such as an FPGA with data converters, or a low-frequency software radio. M^3's design cuts the per-node cost significantly, *e.g.*, the cost of our prototype is down to $3.8K for a narrowband (56 MHz) 2 RF-chain 72-antenna mmWave MIMO, and below $15K for a wideband (4 GHz) 4 RF-chain 128-antenna version.

We made M^3 available to the wireless research community, through open-source hardware and paid fabrication/assembly services. More than 10 groups are using M-Cube in their mmWave sensing, communication, and networking projects. Further information can be found on the project website, http://m3.ucsd.edu/sdr/.

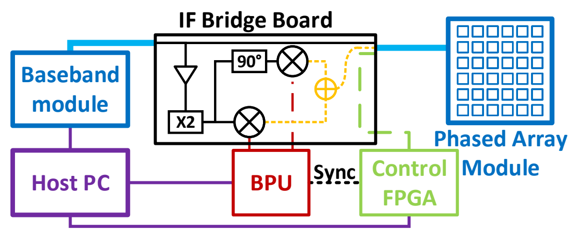

Figure 1: Schematic of a single Tx RF chain on the M^3 mmWave MIMO software-radio (Rx chain is similar).

2 COMMODITY 802.11AD RADIO

The main idea of M^3 is turning low-cost commodity 802.11ad radio into a software radio. Therefore, we first deeply analyzed and reverse engineered the commodity 802.11ad radio. We found that the most popular 802.11ad radio is in a split-IF architecture, which contains a baseband module (BM) and a phased array module (PM).

Baseband module: The BM we choose is chip QCA6335, which has a single RF chain but 8 IF ports connecting to 8 phased array

*Teng Wei contributed to this work when he was a visiting student in UC San Diego.

MobiSys '22, June 25–July 1, 2022, Portland, OR, USA

ACM ISBN 978-1-4503-9185-6/22/06.
https://doi.org/10.1145/3498361.3538659

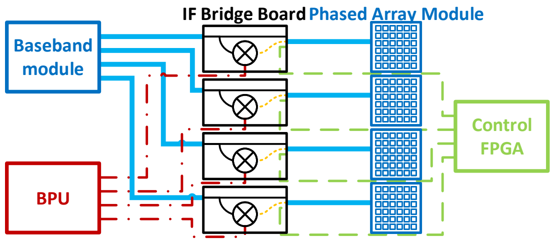

Figure 2: Integrating multiple RF chains to form the MIMO mmWave RF front-end.

modules. The BM is usually mounted on a host PC which runs driver, loads firmware and controls the PM through driver level wireless module interface (WMI) commands. We extensively studied the control and architecture of BM and then proposed the design shown in Fig. 1. M^3 replaces the waveform generation and beam sweeping control by external bridge board, BPU and control FPGA, so that we can implement the flexible software defined radio (SDR) function.

Phased array module: In M^3, we use a 6×6 uniform planar array (UPA), which accepted in 802.11ad outdoor backhaul radios or indoor access points [7]. The array can be more easily calibrated to generate desired beam patterns. But the other modules build on Qualcomm QCA6310 RFIC will also work for M^3. We analyzed and reverse engineered the codebook function and finally realized flexible beam pattern reconfigurability by loading different codebook using WMI commands.

3 M^3 SINGLE CHAIN ARCHITECTURE

In order to transform the commodity 802.11ad radio into an SDR, our basic idea is to *reuse the BM as a clock/power generator and boot loader, but create a customized data path by using a programmable BPU plus a baseband-to-IF converter (referred as bridge board), and regenerate the control signal using an FPGA-based digital controller for real-time beam control*. As illustrated in Fig. 1, M^3 separates the data path (BPU, Bridge board, PM) and control path (Control FPGA, Bridge board, PM) and makes both reconfigurable.

Data path design: The bridge board design can fit into two different architectures along the data path: homodyne and heterodyne.(i) In the homodyne architecture, the BPU can be several gigahertz sampling rate ADC/DAC module with an FPGA so that it can cover the several gigahertz bandwidth. (ii) For the heterodyne architecture, a low-frequency software-defined radio (SDR), e.g., USRP or WARP, can be reused for lower cost.

Control path design: Beam selection can be done by generating control commands from BM. But it will needs to run corresponding driver commands on the host PC and introduce large system level delay. Therefore, to implement real time beam sweeping, we reverse engineer the control path waveform, and regenerate the control commands using a low-profile *control FPGA*.

4 MIMO MMWAVE ARCHITECTURE

As we mentioned in Sec. 2, QCA6335 BM has 8 RF ports sharing the same clock which can guarantee the carrier phase coherency between the 8 PMs. Therefore, the single RF-chain design can be easily extended to a multi-RF-chain MIMO mmWave architecture as illustrated in Fig. 2. More specifically, by connecting several bridge boards to the RF ports of the same QCA6335 BM, and attaching one PM to each bridge board, we can realize a multi-RF-chain, multi-phased-array, mmWave MIMO RF front-end. Then, each RF-chain has a separate control path and data path, generated by the control FPGA and a multi-channel BPU, respectively. This will provide flexible configuration of phased arrays, e.g., mmWave MIMO TX/RX communication, monostatic software-defined mmWave MIMO radar etc.

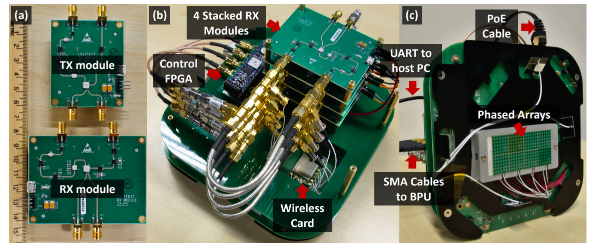

Figure 3: (a) TX and RX bridge boards. (b) Rear view of the 4 RF-chains node. (c) Front view of fully assembled M^3 node with 8 6×6 phased arrays on the same plane.

5 DEMO SETUP

We will set up a pair of M^3 TX node and RX node for the demo. Similar to the diagram in Fig. 3, each node comprises one baseband module, two TX/RX bridge boards, one control FPGA and two active phased-array modules. A host PC will be used to facilitate the BPU and configure M^3 nodes. We will demonstrate (i) BPU choice flexibility – the RFSoC based BPU and USRP N310 [8], corresponding to homodyne and heterodyne architecture respectively, will be used to run single RF-chain OFDM communication. (ii) channel estimation while doing fast beam sweeping – the channel state information (CSI) of each TX/RX beam combination will be collected. (iii) MIMO setup configuration, channel estimation and data communication – an open loop MIMO code will be used as a simple example to show the CSI and BER. (iv) range detection – a one TX one RX M^3 node will be used to set up a monostatic software-defined radar with Frequency-Modulated Continuous-Wave (FMCW) waveform generated in baseband by RFSoC.

ACKNOWLEDGMENTS

The work reported in this paper is supported by the NSF under Grant CNS-1901048, CNS-1925767 and CNS-2128588. We also acknowledge the gracious equipment donations and loans from Samsung Research America and National Instruments.

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