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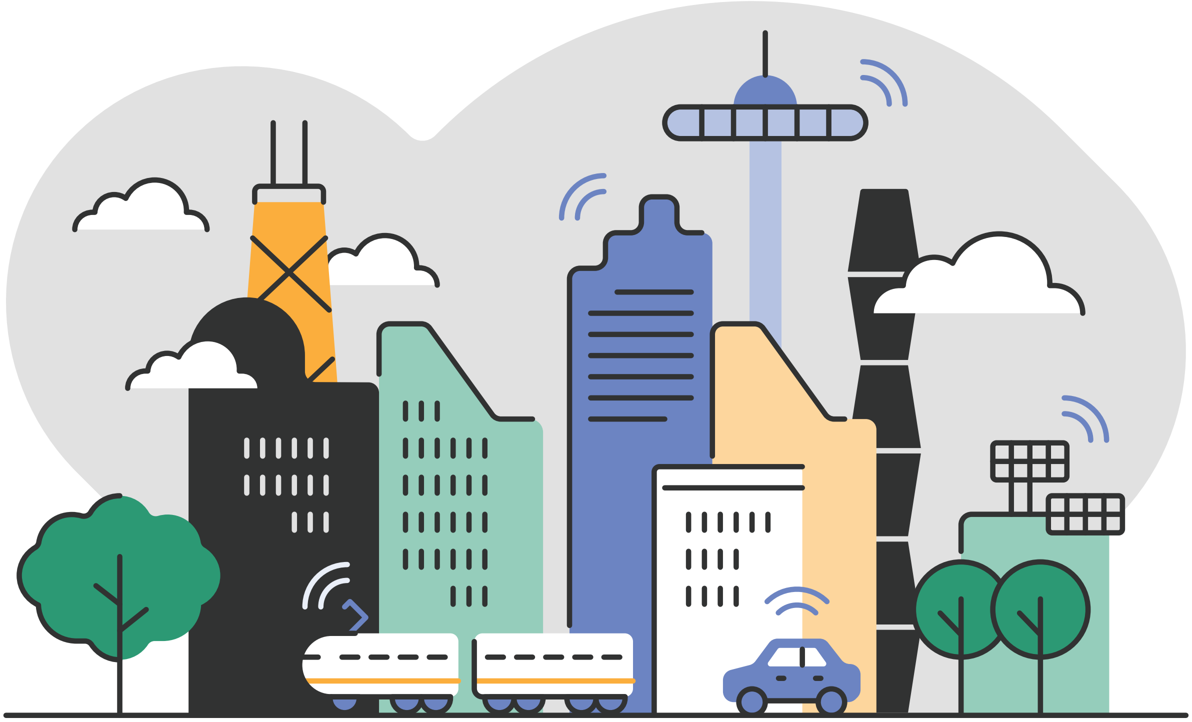

M-CUBE: A Millimeter-Wave Massive MIMO Software Radio

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Millimeter-wave (mmWave) technologies represent a cornerstone for emerging wireless network infrastructure, and for RF sensing systems in security, health, and automotive domains. However, the lack of an experimental platform has been impeding research in this field. In this article, we propose to fill the gap with *M*^{3} (*M-Cube*), the first mmWave massive MIMO software radio. 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. Case studies have demonstrated the usefulness of M^3 design for research in mmWave massive MIMO communication and sensing.

Millimeter-wave (mmWave) networking technologies are widely recognized as the most promising solution to confront the mobile data explosion. However, commercially viable use cases have been limited to short-range, static, point-to-point settings. The fundamental reason lies in the use of highly directional beams as the communication medium, which can be easily disturbed by obstacle blockage and device movement. These challenges become most severe when multiple phased arrays with a massive number of antenna elements are used, which leads to new requirements for an experimental research platform.

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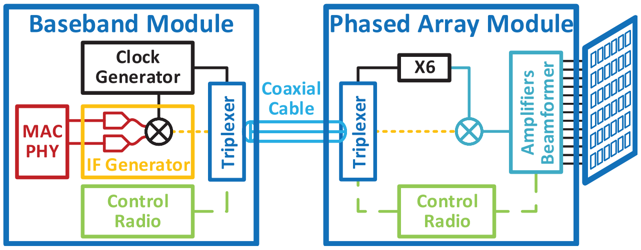


FIGURE 1. Schematic of the Tx RF chain on the commodity 802.11ad radio (Rx chain is similar).

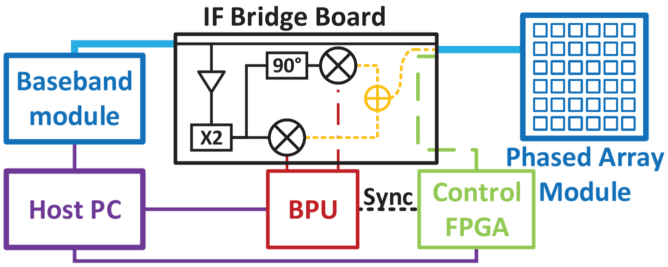


FIGURE 2. Schematic of a single Tx RF chain on the *M^3* mmWave MIMO software-radio (Rx chain is similar).

KEEP CAPABILITIES NEEDED ON A mmWAVE MIMO PLATFORM

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 networking/sensing scenarios [1, 2]; (ii) Supporting the mmWave MIMO architectures to be used in 5G NR and 802.11ay radios [3, 4]; (iii) Allowing reconfiguration of beam patterns, communication/sensing algorithms and network stack.

Commercial mmWave devices such as 802.11ad radios satisfy the requirements (i) but since the 802.11ad standard only adopts single RF chain with fixed modulation, they cannot meet requirements (ii) and (iii). Most importantly, the lack of programmability renders commercial devices unsuitable for exploring future techniques.

Existing programmable mmWave platforms are either too costly (around $200K per link [5]), or lack a reconfigurable phased array antenna with reasonable size [6, 7]. Moreover, such devices are often bulky and can barely support mobile experiments. None of the existing platforms include support for both multiple RF chains and reconfigurable phased arrays, which are critical for research into mmWave MIMO–a key feature in the forthcoming 5G NR and 802.11ay radios.

M-CUBE

To meet all of the aforementioned requirements, we have designed M^3, the first mmWave massive MIMO experimental platform, which is based on commodity 802.11ad radio. M^3 is a low-cost software-defined radio/radar 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 phased array, 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 software radio/radar 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 will follow WARP project model [8] to make M^3 available to the wireless research community, through open-source hardware and paid fabrication/assembly services. The source code, hardware schematics, and other documentation have been released through the project website, http://m3.ucsd.edu/sdr/ More technical details of M^3 are available in [9].

ANATOMY OF COMMODITY 802.11AD RADIOS

The main idea of M^3 is to convert commodity 802.11ad radio into a software radio so that we can make use of the low cost of commodity devices. Therefore, we first deeply analyzed and reverse engineered the commodity 802.11ad radio to fully understand the architecture and control mechanism.

Mainstream mmWave radios follow a modular split-IF architecture as illustrated in Figure 1. The radio comprises two modules connected via a coaxial cable: a baseband module (BM), which converts between baseband signals and IF signals, provides reference clock and control signals to the phased array; and a phased array module (PM), comprised of the phased array antenna for beamforming and RF front-end for converting between the IF signals and 60 GHz RF signals.

DESIGN OVERVIEW

Based on the above architectural anatomy, we design M^3 by transforming the commodity 802.11ad radio into an SDR. We reuse the baseband module (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 to as a bridge board), and regenerate the control signal using an FPGA-based digital controller. The architecture of a single RF-chain is illustrated in Fig. 2. M^3 separates the data path (BPU, IF Bridge board, PM) and control path (Control FPGA, IF Bridge board, PM) and makes both reconfigurable.

DATA PATH

A data path between BPU and PM is needed so that the signal transmitted through PMs can be generated or captured by the BPU.

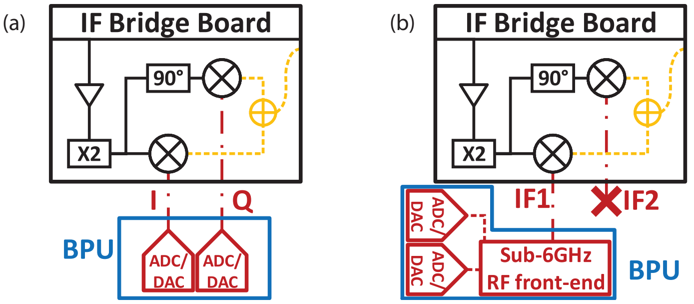
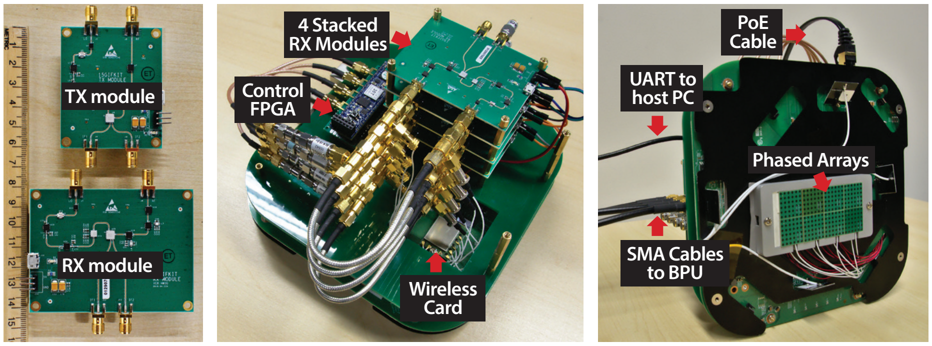


FIGURE 3. Bridging path architecture: (a) homodyne and (b) heterodyne.



(a) (b) (c)

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

Due to the fact that PM only accepts signal in the IF band, which cannot be provided by most of BPU, we designed an IF bridge board to perform frequency converting. The bridge board is designed to be compatible with various kinds of BPUs. As shown in Figure 3, it can fit into two different architectures along the data path:

i) Homodyne architecture: the baseband I/Q signals are directly upconverted to IF with a quadrature LO, which is generated using the reference from BM. With this 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) Heterodyne architecture: a low-frequency software-defined radio (SDR), e.g., USRP or WARP, first generates a carrier-modulated first-stage sub-6 GHz IF signal, then the bridge board acts as a second stage IF mixer to upconvert the signal into the desired IF data signal.

CONTROL PATH

Real-time beam sweeping and flexible control of codebook are needed for real-time beam selection algorithm and codebook design verification. In M^3, the control path is separated by two parts to meet the two requirements:

i) Through BM: The set of beam patterns is stored on the PM as a codebook matrix during initialization and can be updated using wireless module interface (WMI) commands. Therefore, to flexibly reconfigure the beam pattern, we reverse engineered the codebook architecture and determine the index mapping between antenna elements and codebook entries. The codebook entry corresponding to a specific beam width and direction can be computed through well-known theoretical models [10]. Then the beam patterns can be reconfigured by loading different codebook using WMI driver commands.

ii) Through control FPGA: Beam selection commands can be sent through the BM in order to control the phased array beams. Beam selection can be done by generating control commands from BM. But it will need to run corresponding driver commands on the host PC, which leads to large delay introduced by the operating system. 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.

MIMO mmWAVE ARCHITECTURE

The BM on the commodity 802.11ad radio is based on Qualcomm's QCA6335 chipset. It has a single RF chain but 8 IF ports connecting to 8 PMs while sharing the same reference clock. The shared clock 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 SDR. More specifically, by connecting several bridge boards to the IF 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 for many mmWave applications, e.g., mmWave MIMO TX/RX communication, monostatic software-defined mmWave MIMO radar, etc. The final multi-RF-chain system is shown in Figure 4.

CASE STUDY – mmWAVE MU-MIMO

Here we use one case study on mmWave MU-MIMO to show the functionality of M^3. Unlike the prior research in mmWave MIMO, which either used statistical channel models [11, 12] or synthesized MIMO by moving a single phased array to different locations [13, 14], we conduct the real time mmWave MU-MIMO link measurement using M^3.

We created a 2×2 MU-MIMO setup by using one 2-RF-chain Tx and two 1-RF-chain Rx in a multipath-rich conference room and a multipath-poor outdoor environment. The channel data is collected by using two codebooks, corresponding to narrow and wide beams. With the channel data, we determined the total capacity of the channel for three beamforming strategies: (i) analog beamforming alone, using the best capacity among all beam

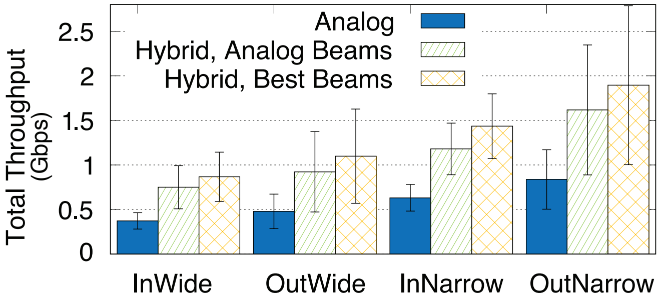


FIGURE 5. MU-MIMO capacity in different scenarios: In/Out: Indoor/Outdoor; Wide/Narrow: different beamwidths.

selections, (ii) mmWave MIMO using zero-forcing with the globally optimal beam selections, (iii) mmWave MIMO as in (ii), but using the beams selected in (i). We evaluated 50 random sets of Rx locations for each test scenario.

From the results (Figure 5), we observe that MU-MIMO achieves higher capacity in the outdoor environment because multipath introduces additional interference for widely spaced Rx. Zero-forcing increases the achievable indoor capacity by 2.2× and outdoor capacity by 2.3×, which suggests that there are large performance gains available from hybrid beamforming in MU-MIMO scenarios, rather than analog beamforming alone. These capacity gains are approximately equal for both codebooks (narrow and wide), which suggests that interference significantly impairs capacity even with a more directional codebook. Moreover, we note that using MU-MIMO with the optimal beams from analog beamforming achieves 1.9× improvement over analog beamforming alone, which means that we can harvest MU-MIMO capacity gains by simply using zero-forcing along with a beam selection algorithm such as [13, 15], without requiring multiple measurement rounds as proposed in existing approaches [14].

CONCLUSION

We have demonstrated the feasibility of reengineering a commodity 802.11ad mmWave radio into a low-cost massive MIMO software radio, i.e., M^3. Our design choices in M^3 focus on optimizing the radio performance, while keeping its architecture simple and scalable. Our experiments have verified the effectiveness of the M^3 design. Considering its flexibility, performance, and affordability, we expect M^3 to change the landscape of research in mmWave networking and sensing. Since commodity mmWave radios tend to share similar architectures, our design can potentially be applied to create mmWave software radios on other frequency bands (e.g., 5G NR radios). ■

Acknowledgment

The work reported in this paper is supported in part by the NSF under Grant CNS-1952942 and CNS-1925767.

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