High-Speed Millimeter-Wave Mobile Experimentation on Software-Defined Radios

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Millimeter-wave (mm-wave) communications have become an integral part of WLAN standards and 5G mobile networks and, as application data rate requirements increase, more and more traffic will move to these very high frequency bands. While for sub-6 GHz research there is an ample choice of powerful experimental platforms, building mm-wave systems is much more difficult due to the very high hardware requirements. To address the lack of suitable experimentation platforms, we propose *mm-FLEX*, a flexible and modular open platform with real-time signal processing capabilities that supports a bandwidth of 2 GHz and is compatible with current mm-wave standards. The platform is built around a fast FPGA processor and a 60 GHz phased antenna array front-end that can be reconfigured at nanosecond timescales. Together with its ease of use, this turns the platform into a unique tool for research on beam training in highly mobile scenarios and full-bandwidth mm-wave signal processing.

INTRODUCTION

The transition of wireless communications to mm-wave frequencies introduces new problems and challenges both at the hardware level as well as for the protocol design. Mm-wave hardware commonly integrates phased antenna arrays, which enable analog or hybrid beam forming mechanisms as well as advanced signal processing to steer the signal in a desired direction and thus overcome the high path loss at mm-wave frequencies. Since current mm-wave standards like IEEE 802.11ad only include simple beam training mechanisms, a significant amount of research over the past few years went into the design of more efficient beam training algorithms. Due to the lack of flexible experimentation platforms, such work either relied on off-the-shelf devices whose operation can only be modified within very narrow bounds, or was simulation-based.

While common software-defined radios (SDRs) such as USRPs have proven extremely useful for sub-6GHz experimentation, their sampling rates and processing capabilities are too limited for wideband mm-wave systems and only allow to roughly approximate real-world behavior through narrowband experiments [1,2]. Some commercial solutions [3] do offer the bandwidth required for standard-compliant operation, but due to their high cost and complexity they are far from ideal as general-purpose mm-wave experimentation platforms. Between those extremes are custom solutions that are more powerful than USRPs but still do not achieve standard compliance [4]. To advance practical mm-wave research, it is vital to have experimentation platforms that capture the unique characteristics of mm-wave systems and at the same time provide the flexibility and reconfigurability for researchers to easily use them for their experiments. Furthermore, a common missing feature of all the options listed above is fast antenna reconfigurability. This is a very important aspect for mm-wave experimentation to be able to design beam training algorithms for mobile scenarios as well as support more efficient in-packet training which requires antenna reconfiguration at symbol-level time scales, as specified in the next-generation IEEE 802.11ay mm-wave standard [5].

To this end, we design *mm-FLEX* as a flexible, modular and highly configurable platform that meets the bandwidth requirements of current mm-wave standards at only twice the cost of a high-end narrow-band SDR. Moreover, the platform provides real-time antenna reconfigurability at nanosecond time scales, making it ideal for next-generation mm-wave experimentation. The testbed is designed as a *hardware-in-the-loop* system, where part of the functionality can be modeled in software while time-critical functions are implemented in hardware, allowing the research community to easily develop and validate signal processing algorithms and extend the functionality.

HIGH-LEVEL ARCHITECTURE

To enable flexibility and reconfigurability, we chose a *memory-based* design with real-time processing capabilities. The user can send custom frames over the air, which are then captured at the receiver and stored in memory for offline processing, while at the same time, time-critical signal processing blocks can be implemented in hardware.

The system is modular, having a separate processing system (PS) and programmable logic (PL), both of which are linked by means of a fast communication interface. The processing system (PS) is responsible for controlling and managing the entire system using simple commands to configure each of the functional blocks. The interface offers enough bandwidth for fast data transfers from/to the PL, where the hardware processing blocks are implemented. For modularity of the PL itself, we choose AXI-streams to connect the different processing blocks of the transmitter and receiver data paths, as shown in Fig. 1. AXI interfaces are widely adopted for on-chip communication and facilitate synchronization, handshake signalling and block design by means of high-level synthesis tools. *mm-FLEX* has fully independent datapaths for the transmitter and receiver, which enable full-duplex and joint communication & radar systems. Moreover, the PL is equipped with AXI control buses for easy configuration of each hardware block from the PS.

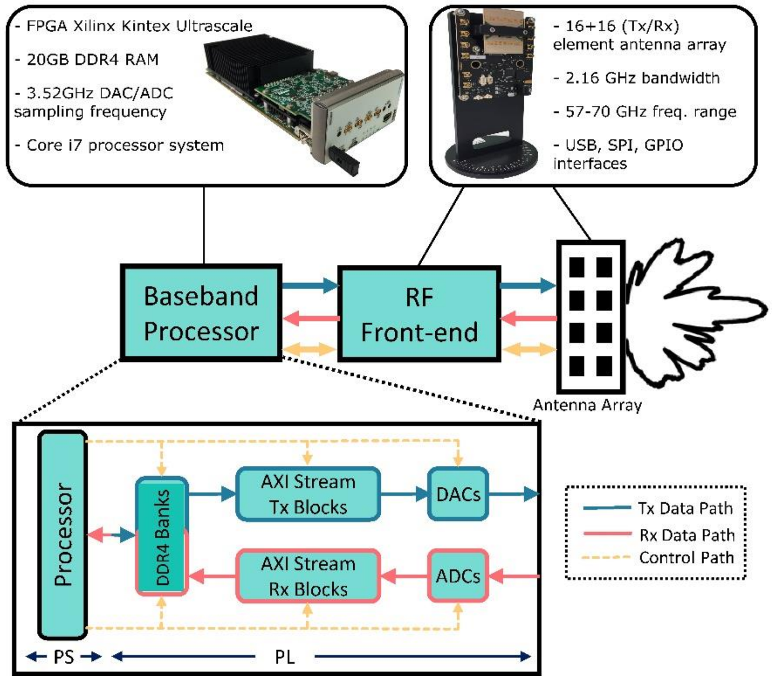

Figure 1: High-level architecture of the platform

To implement the platform, we combine a fast baseband processing system and a mm-wave RF front-end, as shown in Fig. 1. The baseband processor is implemented on a modular Vadatech system comprising an AMC599 slot card with a powerful FPGA (PL), multi-Giga-sample AD/DA converters, 64 GB of DDR memory, and another AMC726 slot card providing a high-end microprocessor (PS), with another 8 GB of DDR memory and 32 GB SSD storage. The cards communicate with each other through a PCIe backplane and together form a high-end programmable embedded system. The supported sampling rates meet the bandwidth requirements of current mm-wave standards. We process the data on the FPGA using super-sampling-rate (SSR) datapaths that process multiple I/Q samples in a single clock cycle in parallel. This SSR can be configured depending on the specific design requirements, to trade off area size and timing constraints. To meet the requirements of the IEEE 802.11ad standard, here we select an SSR factor of 16 and a clock frequency of 220MHz, giving a sampling frequency of 3.52GHz. The system can capture I/Q samples using custom-designed DDR read/write hardware blocks in two different modes: i) *simple writing*, where the user directly triggers a configurable number of I/Q samples to be stored in memory in a single capture and ii) *burst saving*, where the user can integrate an external trigger (e.g., a signal coming from a packet detector) to capture a configurable number of packets for further offline processing. Note that for both modes, the received signals can be packets sent from another *mm-FLEX* device or from standard-compliant off-the-shelf devices.

For the mm-wave front-end, we use a Sivers IMA EVK06002 development kit with 60GHz up/down converters supporting the frequencies and the bandwidth of IEEE 802.11ad channels. It integrates 16+16 (Tx/Rx) element phased arrays with phase shifters for each antenna element for analog beamforming. The kit can be controlled from the PS and PL using three different interfaces: USB, SPI and GPIO pulses. The testbed can also be used with other front-ends, e.g., 28GHz kits for 5G-NR applications.

From the user point of view, a C/C++ application is used to control the system through simple commands that initialize the system, send and receive samples to/from memory, and configure PL blocks. To start the system, an "init" function configures the PLLs for the converters, sets up the transmitter and receiver data paths, and configures the system peripherals. The RF front-end is controlled by the processor by means of a USB interface and Python functions to set the antenna configuration, power amplifier gains, and carrier frequency, and switch between transmitter and receiver operation at runtime, among other features.

REAL-TIME FUNCTIONALITY

To combine real-time signal processing functions with the memory-based approach described above, time critical functions are hardware implemented. Here, we discuss two examples in more detail. 1) Analyzing beam training packets from off-the-shelf IEEE 802.11ad compatible devices, requires capturing sequences of training frames that are sent every 100 ms and last for approximately 1 ms. To capture only the frames of interest rather than mostly noise requires real time preamble detection of valid frames. 2) IEEE 802.11ay introduces the concept of *in-packet* training, where multiple antenna configurations are tested within a single training packet to rapidly select the best antenna configuration and properly align the antenna beams [5]. Again, such reconfiguration has to happen in real-time over the course of packet transmission/reception.

To address such use cases, we integrate in the *mm-FLEX* platform signal processing blocks for packet detection, antenna reconfiguration and received signal strength (RSS) computation. The packet detector implements a normalized autocorrelation algorithm to detect the periodic sequences of the preambles of IEEE 802.11ad and 802.11ay frames. The block meets the tight timing constraints of these mm-wave standards and has an AXI interface for flexible integration into the architecture. It generates a flag once the correlation result is higher than a user configurable threshold, which can be used as a trigger for the DMA block to save only valid packets to the memory. For real-time antenna reconfiguration, we use the GPIO interface of the 60GHz front-end which allows it to rapidly change through different phase shifter configurations by means of fast pulses sent from an external device. We implement an FPGA state-machine which is able to send a set of pulses, separated by a configurable number of clock cycles once the block receives an external trigger. This way, the device can sweep through a configurable number of antenna configurations before returning to a predefined beam pattern. The RSS computation block is designed to work synchronously with the antenna reconfiguration block, to compute one RSS value per antenna configuration. Using the packet detector output to trigger the antenna reconfiguration and RRS computation blocks, the system is able to quickly change through multiple antenna configurations within a single frame, allowing the user to implement fast training mechanisms such as the one defined in the IEEE 802.11ay standards. The system is able to change the antenna configuration each ~50ns which far exceeds the requirements of IEEE

802.11ay systems. Further details about the designed blocks can be found in [6] and all the project files are available from the project webpage [7].

EXPERIMENTAL RESULTS

To showcase the transmit and receive features of *mm-FLEX*, we setup a 10 m Line-of-Sight (LOS) link and use mm-FLEX to transmit IEEE 802.11ad compliant frames (generated offline) for the different single-carrier Modulation and Coding Schemes (MCSs) of the IEEE 802.11ad standard, from MCS 1 to 12. The receiver captures the frames using its packet detection capabilities, while the actual frame decoding is done offline in software. Fig. 2 shows an example of the results with the received I/Q samples for the different MCS frames, correlation output of the packet detector (performed in hardware) and channel impulse response and constellation points for an MCS 9 frame.

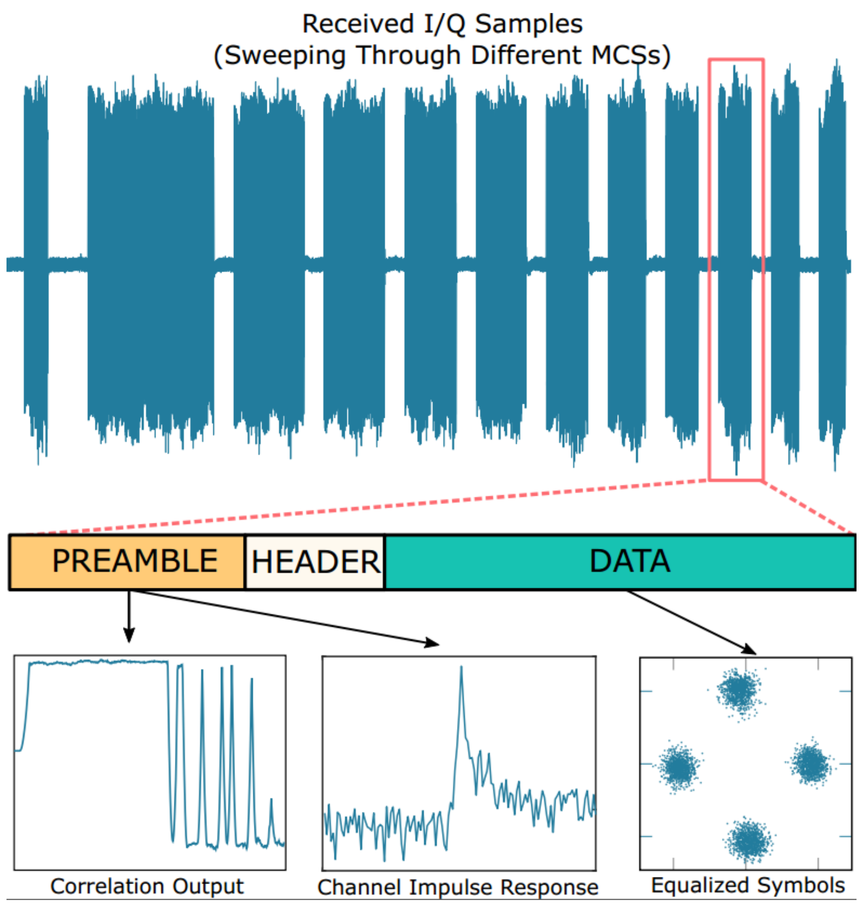

Figure 2: Example of multiple frames with different MCSs captured using *mm-FLEX* (top) and details of different parts of the decoding process (bottom).

To highlight the fast antenna reconfiguration, we set up the system to capture IEEE 802.11ay packets including the necessary training sub-fields (TRN units) for *in-packet* training [5]. To this end, we configure the testbed to perform 10 antenna reconfigurations after the system detects a valid packet using the packet detection feature. We perform antenna reconfiguration each 436 ns to match the length of a TRN field. In Fig. 3 we show the details of a received packet along with a timing diagram which shows how the amplitude of the signal changes multiple times due to the different antenna configurations and how RSS values are computed for each one of the TRN fields. Our system can even perform antenna reconfiguration an order of magnitude faster (~50ns), providing ample margin to design more efficient beam alignment algorithms [6].

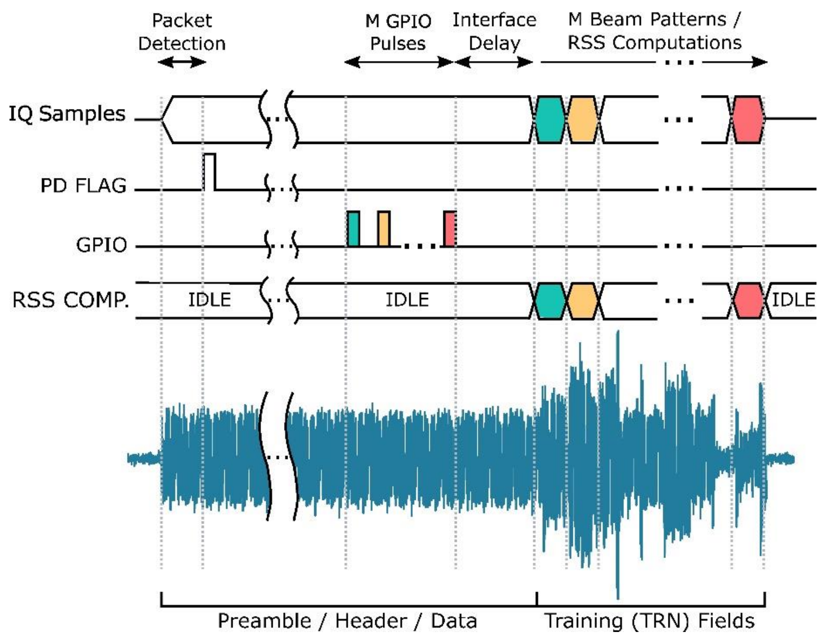

Figure 3: Example of the multiple antenna reconfiguration capabilities of the testbed to implement IEEE 802.11ay *in-packet* training.

CONCLUDING REMARKS

mm-FLEX is a flexible, modular and reconfigurable testbed suitable for mm-wave experimentation in ultra-wideband channels. The system is powerful enough to accommodate real-time complex signal processing blocks and at the same time serves as a simple ready-to-use platform for researchers that want to focus on the higher layer functionality while using the physical layer implementation as is. The project is provided as open-source [7], making it an ideal platform for the research community to modify and extend the functionality as needed.

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REFERENCES

[1] O. Abari, H. Hassanieh, M. Rodriguez, and D. Katabi. 2016. Poster: A Millimeter Wave Software Defined Radio Platform with Phased Arrays. In Proceedings ACM MobiCom '16, New York, NY, USA

[2] A. Moreno, J. Lacruz, and J. Widmer. 2020. Open Source RFNoC Based Testbed for Millimeter-Wave Experimentation Using USRP Software Defined Radios. In Proceedings ISCAS-2020

[3] S. Kumar, et al. 2019. X60: A programmable testbed for wideband 60 GHz WLANs with phased arrays. Computer Communications 133 (2019), 77–88.

[4] J. Zhang, X. Zhang, P. Kulkarni, and P. Ramanathan. 2016. OpenMili: A 60 GHz Software Radio Platform with a Reconfigurable Phased array Antenna. In Proceedings ACM MobiCom ’16, New York, NY, USA

[5] Y. Ghasempour, C. R. C. M. da Silva, C. Cordeiro, and E. W. Knightly. IEEE 802.11ay: Next - Generation 60 GHz Communication for 100 Gb/s Wi-Fi. IEEE Communications Magazine, 55(12):186–192, 2017

[6] J. Lacruz, D. Garcia, P. Jiménez, J. Palacios, and J. Widmer. 2020. Mm-FLEX: an open platform for millimeter-wave mobile full-bandwidth experimentation. In Proceedings ACM MobiSys '20, New York, NY, USA

[7] J. Lacruz and J. Widmer. mm-FLEX: Millimeter Wave Mobile Full-Bandwidth Experimentation Platform. http://wireless.networks.imdea.org/mmflex