DISTRIBUTED MU-MIMO DEMONSTRATION USING FPGA-BASED SIGMA-DELTA-OVER-FIBER

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Abstract

We will demonstrate a 2x2 distributed multi-user MIMO transmission using sigma-delta-over-fiber targeting 5G downlink. OFDM signals, sigma-delta modulated and digitally up-converted to 3.5 GHz on FPGA, are transmitted over 100-m multi-mode fibers at 850 nm using a commercial QSFP-100G-SR4 and wirelessly using in-house developed antennas.

1 Introduction

The fifth generation (5G) cellular network demands massive device connectivity, high data rate, and sustainable cost. The centralized/cloud radio access network (C-RAN) architecture in combination with the multiple-input multiple-output (MIMO) techniques is one of the key enablers to achieve the challenging goals.

In 5G C-RAN, a central office (CO), where the base-band units are aggregated, is expected to serve hundreds or even thousands of remote radio heads (RRHs) via the fronthaul network. The radio-over-fiber (RoF) technologies are the most convincing candidates for the fronthaul network because of their high capacity and low latency [1]. In our previous works [2]-[4], we have discussed the differences between three main RoF schemes: digitized radio-over-fiber (DRoF), analog radio-over-fiber (ARoF) and sigma-delta modulated signal over fiber (SDoF). SDoF combines the advantages of DRoF and ARoF. It has high scalability because of its simple thus low-cost RRH architecture. The relaxed requirement of linearity allows the use of non-linear direct-modulated laser sources. We have published the superior performance of transmitting single carrier data over SDoF links in real-time for the sub-6 GHz [4] and 22.75-27.5 GHz band [5].

The centralized processing allows resource-sharing at the CO. Furthermore, it provides the possibility of coordinating the RRHs to operate as a distributed MIMO system without overloading the backhaul network like LTE [6]. The inter-RRH interference can be cancelled, allowing an increase in the RRH density. By exploiting spatial diversity, the overall transmission data rate increases.

Several recently published papers have demonstrated the performance of MIMO ARoF systems [7]-[9]. In [10], MATLAB-generated sigma-delta modulated signals are used to demonstrate the performance of a single-carrier MIMO SDoF system.

In this demonstration, we present a 2×2 distributed multi-user (MU) MIMO orthogonal frequency division multiplexing (OFDM) SDoF system targeting 5G downlink. The proof-of-concept SDoF-based C-RAN fronthaul downlink architecture is fully implemented using commercial off-the-shelf and in-house developed components. The real-time sigma-delta modulators (SDMs) are implemented on the FPGA. The sigma-delta modulated OFDM signals centred around 3.5 GHz are transmitted over OM4 multi-mode fibers (MMFs) using a QSFP-100G-SR4 which has four 850 nm VCSELs (vertical-cavity surface-emitting lasers).

The objectives of this demonstration are to show the simplicity of SDoF links and provide a performance comparison. It will be shown in the live demonstration that the performance of the distributed MIMO system satisfies the 3GPP error vector magnitude (EVM) requirements: 12.5% for 16-QAM and 8% for 64-QAM [11]. The performance is also comparable to the single-input single-output (SISO) transmission, implying that the spectral efficiency doubles by exploiting spatial diversity.

2 Demonstration Setup

The detailed system architecture and the proposed demonstration setup are shown in Fig. 1. Two OFDM data sequences, one for each receiver, are transmitted. The OFDM signal parameters are summarized in Table 1. The parameters are similar to those of the IEEE 802.11ac 40 MHz bandwidth case [12]. However, the signal bandwidth is adjusted to fit the analog-to-digital converter sampling rate of the receivers.

Table 1 OFDM Signal Parameters

Parameters	Values
Carrier frequency	3.44064 GHz
Bandwidth	40.96 MHz
Number of subcarriers	128 (index: -64 to 63)
Null subcarrier indices	-1 to 1 (DC), -64 to -59, 59 to 63
Number of Pilots	6 (index: ±11, ±25, ±53)
Cyclic prefix (CP) size	1/4
Modulation scheme	16-QAM (116 Mbps per user), 64-QAM (175 Mbps per user)

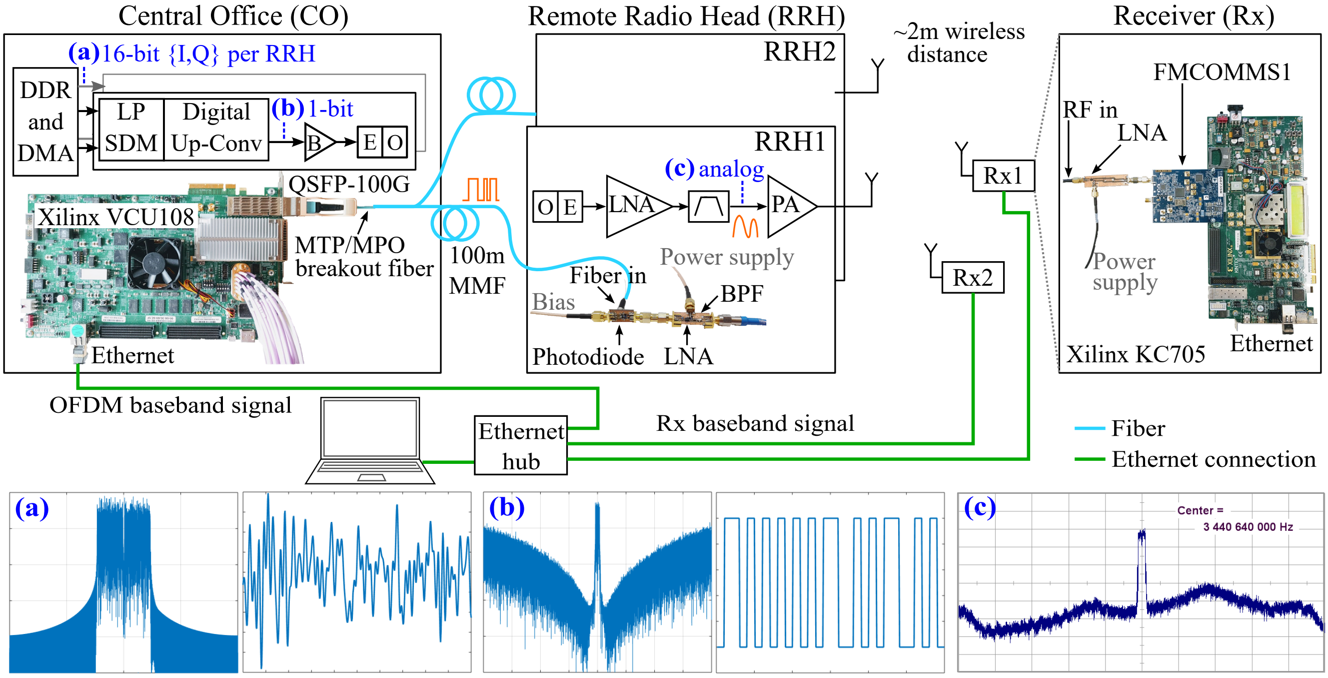

Fig. 1 Demonstration setup. (a) Spectrum and waveform of the OFDM baseband signal; (b) simulated spectrum and waveform of the digital up-conversion output; (c) measured spectrum of the band-pass filter (BPF) output. (DMA: direct memory access; LP SDM: low-pass sigma-delta modulator; B: binary driver; E-O: electrical-to-optical; O-E: optical-to-electrical; LNA: low-noise amplifier; BPF: band-pass filter; PA: power amplifier.)

2.1 *Central Office (CO)*

The OFDM baseband signals are generated by MATLAB; Fig. 1(a) shows the spectrum and waveform of the generated signal. The in-phase (I) and quadrature (Q) signal are 16-bit. The CO, including the SDMs and digital up-conversion, is implemented on a *Xilinx Virtex Ultrascale* FPGA (VCU108). The data is loaded to the onboard memory of the CO via the Ethernet connection and then streamed to the low-pass SDMs (LP SDMs) by a *Xilinx* AXI direct memory access (DMA) IP.

The 2x2 (one I-Q pair per RRH) LP SDMs modulate the baseband signal at 7GSps (sample per second). To have a high signal-to-noise and distortion ratio, second-order LP SDMs are chosen for this architecture. A parallel multi-stage scheme is employed to achieve the desired sample rate. The quantization noise is shaped by the LP SDMs to higher frequencies. The detailed hardware implementation of the SDM can be found in [13]. Digital up-conversion [14] translates the modulated I and Q signal (both 1-bit) to one binary signal with a centre frequency around 3.5 GHz for each RRH. Fig. 1(b) shows the simulated spectrum and waveform using fixed-point representation.

For the electrical-optical conversion, we use a commercial QSFP-100G-SR4 (850 nm) module to transmit over OM4 MMFs. It consists of four parallel transmitters; each transmitter has a clock and data recovery (CDR) block, a laser driver and a VCSEL. An MTP/MPO breakout fiber carries the four light streams into four individual fibers for different RRHs; in this demonstration, we use two such RRHs connected by fibers. The optical signals are transmitted over 100 m MMFs.

2.2 *Remote Radio Head (RRH)*

At each RRH, the photodiode is impedance-matched to the low-noise amplifier (LNA) to maximize the power transfer at 3.5 GHz [15]; the LNA amplifies the electrical signal coming from the photodiode. Then, the out-of-band quantization

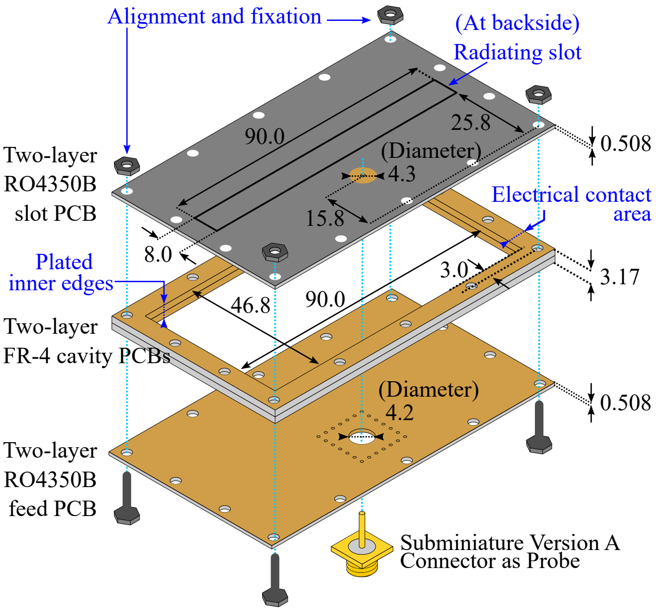

Fig. 2 Topology of the AFSIW cavity-backed slot antenna. (Dimension unit: mm.)

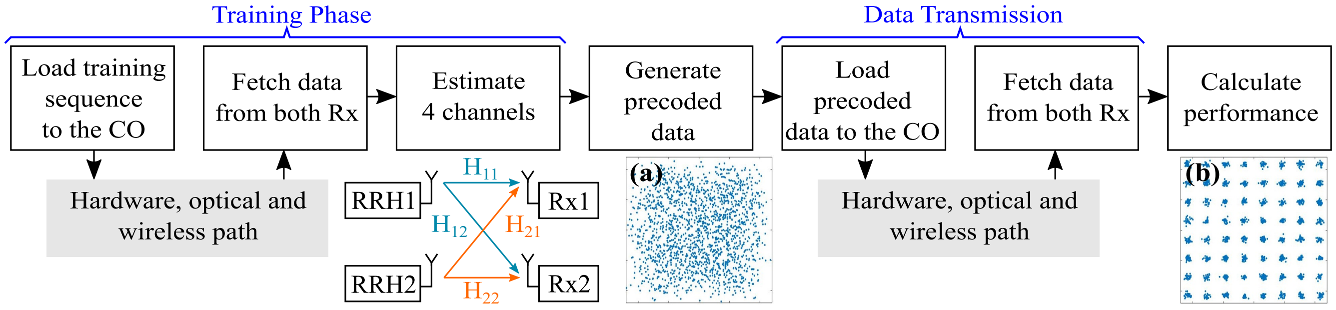

Fig. 3. Demonstration workflow. (a) Constellation diagram of precoded data; (b) constellation diagram of received data.

noise is filtered by a band-pass filter (BPF) as shown in the measured spectrum Fig. 1(c). *Mini-Circuits* amplifiers ZX60-83LN-S+ are used as the last-stage amplifiers. Two in-house developed air-filled substrate-integrated-waveguide (AFSIW) cavity-backed slot antennas (Fig. 2) are used to transmit the radio-frequency (RF) signals. The highly efficient antennas are matched to a 50 Ω impedance over a wide frequency band ranging from 2.95 GHz to 3.90 GHz.

2.3 *Receiver (Rx)*

The two receivers, each with an architecture identical to a SISO receiver, operate independently. They use the same antennas as the RRHs. For each receiver, the antenna is first connected to an LNA with a fixed gain of 20 dB. The amplified received signal is down-converted and sampled by an analog front-end evaluation kit (*Analog Device FMCOMMS1-EBZ*) at 163.84 MHz (4×40.96 MHz). A *Xilinx Kintex 7* FPGA (KC705) collects the data to the onboard memory. The data is loaded to a laptop via the Ethernet connection for offline signal processing using MATLAB. The signal processing includes OFDM frame boundary detection, carrier frequency offset (CFO) correction, fast Fourier transform (FFT) and channel estimation. The performance is presented with the constellation diagrams and the error vector magnitude (EVM) values.

3 Demonstration Workflow

The demonstration workflow illustrated in Fig. 3 is fully realised in MATLAB. The workflow includes two parts: the training phase and data transmission.

The training phase starts with loading the frequency-interleaved training sequence for channel estimation to the CO. As illustrated in Fig. 4, in the first time slot, RRH 1 only sends QPSK data on the subcarriers with even index while RRH 2 sends data on the odd subcarriers only; in the second time slot, they switch. Using the received data from each receiver respectively, the channel frequency response between the receiver and each transmitter can be estimated. A MATLAB function calculates the precoding matrix for each data subcarrier based on the estimated channel frequency response using the zero-forcing algorithm. Then, the data transmission starts with loading the precoded data (Fig. 3(a)) (one data sequence per receiver) to the CO, responsible for the transmission. After cancelling the effect of the channel and the CFO, the received data is demodulated. The constellation diagrams (Fig. 3(b)) and the EVM values of both receivers are displayed to show the performance.

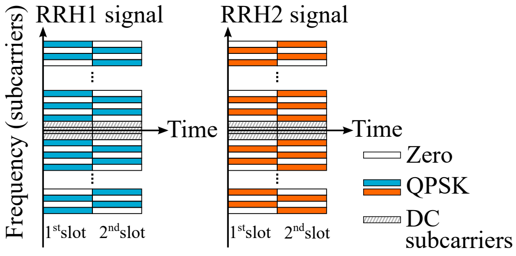

Fig. 4. Frequency-interleaved training sequence.

The precoding minimizes the interference between the signals for different users. It will be demonstrated that the performance difference between the MU-MIMO setup and a SISO-link is negligible in terms of EVM.

4 Conclusion

In this demonstration, we will present a fully implemented 2×2 distributed multi-user MIMO OFDM sigma-delta modulated signal over fiber (SDoF) system targeting 5G downlink including both the optical and wireless paths. This proof-of-concept SDoF-based C-RAN fronthaul downlink architecture is realised using low-cost commercial off-the-shelf and in-house developed components. On the FPGA functioning as the central office, two OFDM baseband signals, generated by MATLAB, are modulated by the real-time high-speed sigma-delta modulators, digitally up-converted to a carrier frequency around 3.5 GHz and transmitted over 100 m OM4 multi-mode fibers using a commercial QSFP module.

It will be shown that the performance satisfies the 3GPP EVM requirements while exploiting spatial diversity to increase the (wireless) spectral efficiency. Moreover, the demonstration will prove that combining SDoF and MIMO techniques is definitely a feasible and cost-efficient solution to meet the 5G challenges.

5 Acknowledgements

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Demo 05

Dynamic synthesis of disaggregated hardware platforms via cache coherent interconnect optical bridge

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Demo 06

Distributed MU-MIMO demonstartion using FPGA based sigma-delta-over-fiber

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Demo 07

Demonstartion of fault localisation and recovery of optical connectivity supporting 5G vRAN

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Demo 08

First demonstration of real-time DSP-free 4-mode 10-km MDM transmission

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Demo 09

Demonstartion of 100 gbit/s active measurements in dynamically provisioned optical paths

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Demo 10

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