# Demonstration of a Scalable Distributed Antenna System Using Real-Time Bit-Interleaved Sigma-Delta-over-Fiber Architectures

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***Abstract*** *We demonstrate a highly-scalable distributed antenna system enabled by real-time bit-interleaved sigma-delta-over-fiber links. By (time-)interleaving multiple sigma-delta modulated in-phase and quadrature pairs into one bitstream for each fiber, the optical bit-rate efficiency is improved while the remote radio unit complexity remains sufficiently low.*

## Introduction

Massive multiple-input multiple-output (MIMO) is considered as one of the key technologies for 5G mobile communications for its capability of improving the wireless spectral efficiency, energy efficiency, and processing complexity of the cellular systems[1]. Distributing the base station antennas can further improve the spectral efficiency[2],[3] and increase user fairness[4].

One of the main challenges of distributed antenna systems is the backhaul overhead[5]. In the 4G era, the centralized radio access network (RAN) architecture can ease such congestion by coordinating several remote radio units (RRUs) from a central unit (CU) via only the fronthaul network[6]. As the number of antennas increases, the RAN—especially the fronthaul network where the data traffic grows proportionally to the number of transmit antennas—must evolve substantially to accommodate the data. An extra layer, distributed unit (DU), has been introduced for 5G next-generation RAN (NG-RAN)[7].

The focus of our work is the next-generation fronthaul interface (NGFI) between a DU and the RRUs it serves. Radio-over-fiber (RoF) technologies are among the most convincing candidates for the fronthaul networks[8]. Sigma-delta modulated signal over fiber (SDoF) has been proposed as a solution leveraging the benefits of digitized radio-over-fiber (DRoF), which has relaxed linearity requirements on both optical and electrical components, and analog radio-over-fiber (ARoF), which features simple RRU architectures[9]–[11].

The SDoF-based 2×2 multi-user MIMO downlink demonstration at the 45th European Conference on Optical Communication (ECOC) has shown the high potential of SDoF-based networks[12],[13]. However, the optical bit-rate efficiency of the SDoF links is often challenged. To improve the bit-rate efficiency, this work introduces bit-interleaved SDoF links; the scalability in terms of the antenna number increases consequently. Furthermore, the uplink paths from the RRUs to the DU are included in the setup.

The objective of this demonstration is to show that SDoF-based networks can be a possible fronthaul network solution for the high-capacity hot-spot scenario of the 5G enhanced mobile broadband (eMBB) service.

## Demonstration Setup

The proposed demonstration setup consists of one distributed unit (DU) and two remote radio units (RRUs) as shown in Fig. 1. The DU includes a personal computer and a *Hitech Global* HTG-930 board; the HTG-930 comprises one *Xilinx UltraScale+* FPGA (VU13P) and connects to one four-port QSFP28 FMC (FPGA Mezzanine Card) module. Each RRU (Fig. 2) incorporates a *Xilinx Virtex Ultrascale* FPGA (VCU108) and an in-house developed active antenna unit (AAU), which consists of four wireless transceivers and connects to air-filled substrate-integrated-waveguide (AFSIW) cavity-backed slot antennas[14]. The downlink (DL) and uplink (UL)

**Tab. 1:** Signal Parameters

| | |
|---|---|
| Carrier frequency ($f_c$) | 3.6864 GHz |
| OFDM parameters: | |
| Data bandwidth | 40.96 MHz (128 subcarriers) |
| Subcarrier spacing | 320 KHz |
| Cyclic prefix (CP) size | 1/4 (0.78 us) |
| Data rate per user | 165 Mbps (64-QAM)<br>221 Mbps (256-QAM) |

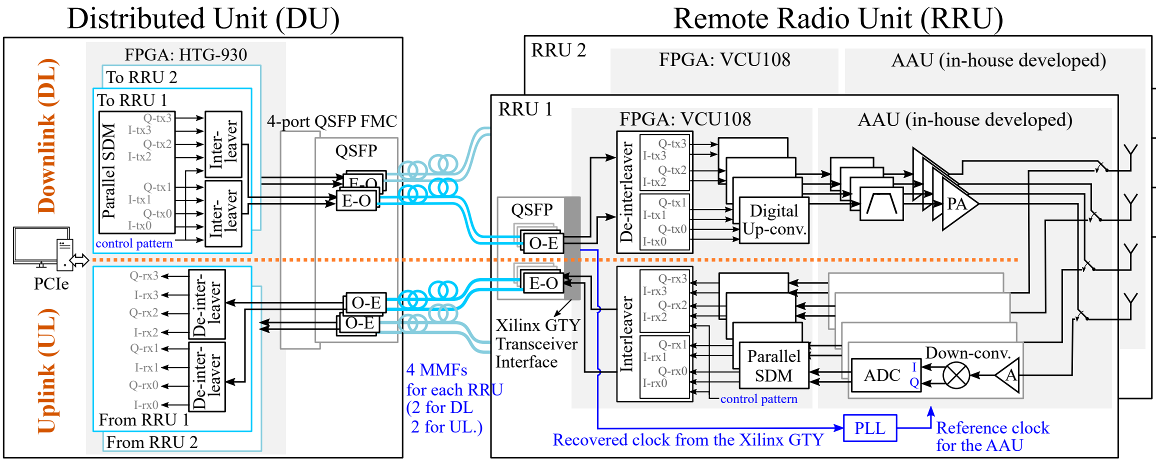


**Fig. 1:** Demonstration setup. (AAU: active antenna unit; SDM: sigma-delta modulator; E-O: electrical-to-optical; O-E: optical-to-electrical; MMF: multi-mode fiber; Up-/Down-conv.: up-/down-conversion; PA: power amplifier; A: low-noise amplifier; ADC: analog-to-digital converter; PLL: phase lock loop.)

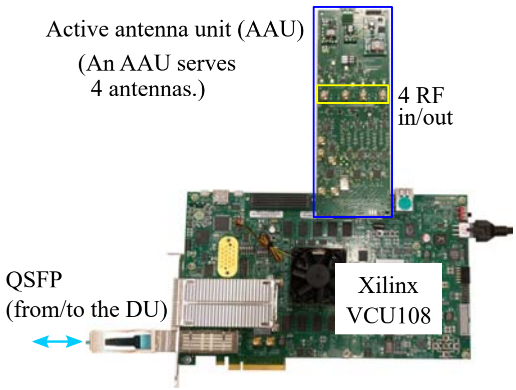


**Fig. 2:** Remote radio unit.

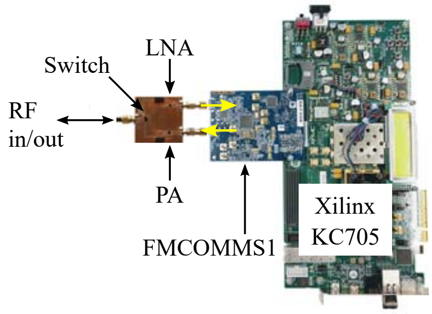


**Fig. 3:** Mobile user.

data paths are separated via time division duplexing (TDD).

Between the DU and an RRU, two multi-mode fibers (MMFs) are used for the DL transmission and two others for the UL. One QSFP port at the DU can serve two RRUs. Therefore, the DU can serve up to eight RRUs, i.e. 32 wireless transceivers in total. This setup uses three QSFP-100G-SR4 modules, which has four 850nm VCSELs (vertical-cavity surface-emitting lasers): one for the DU and one for each RRU.

The mobile user (Fig. 3) has one antenna for both transmission and reception. When receiving DL signals, the antenna is first connected to a low-noise amplifier (LNA). The amplified received signal is down-converted using a zero intermediate frequency (zero-IF) receiver and sampled by an analog front-end evaluation kit (*Analog Device* FMCOMMS1-EBZ). A *Xilinx Kintex* 7 FPGA (KC705) collects the data for offline signal processing. When transmitting UL signals, the KC705 streams the data to the FMCOMMS1-EBZ. The up-converted analog signal is amplified by a power amplifier (PA) and transmitted by the antenna.

Python-generated orthogonal frequency division multiplexing (OFDM) baseband signals are used for both the DL and UL transmission. Tab. 1 summarizes the signal parameters. To provide the signals for transmission and collect the received signals for offline processing, the DU FPGA is connected to the computer via the PCIe (Peripheral Component Interconnect Express) interface and the Ethernet connection is used for the mobile user interface.

### Downlink (DL) Transmission

As illustrated in the upper half of Fig. 1, the DL data goes from the DU to RRUs via the optical links and is then transmitted by RRUs wirelessly.

1. Distributed Unit (DU)
   On the VU13P, sixteen parallel low-pass sigma-delta modulators (SDMs)—2 (RRUs) $\times$ 4 (in-phase-and-quadrature (I-Q) pairs per RRU) $\times$ 2 (I and Q)—modulate the baseband signals at 3.6864 GSps (sample per second). The detailed hardware implementation of the real-time high-speed SDMs can be found in

our previous work[15]. Every four bi-level sigma-delta modulated signals and one bi-level control sequence are time-interleaved into one bitstream and transmitted over one fiber; the bit-rate over fiber is 18.432 Gbps.

2. Remote Radio Unit (RRU)
   At each RRU, after converted to the electrical domain by a QSFP, the received 18.432 Gbps bitstreams are de-interleaved. The 3.6864 Gbps sigma-delta modulated I and Q signals are 2×-up-sampled and digital up-converted[16] to the carrier frequency on the FPGA. Then, band-pass filters on the AAU filter out the quantization noise, which is pushed out of the band of interest by the SDMs. The radio-frequency (RF) signals centered at 3.6864 GHz are amplified and transmitted wirelessly.

The workflow is similar to the one of our previous ECOC demonstration[13]: a training phase for channel estimation followed by a data transmission phase. For the DL transmission, the carrier frequency synchronism between all transmit antennas is guaranteed by using the clock information contained in the received bitstreams. For both RRUs, the clock and data recovery (CDR) modules of the *Xilinx* GTY transceivers retrieve the clock information from the bitstreams and use the recovered clock on both FPGAs.

### Uplink (UL) Transmission

The UL data transmitted by mobile users is received simultaneously by all antennas at RRUs. The lower half of Fig. 1 depicts the data path.

1. Remote Radio Unit (RRU)
   The received RF signals from the antennas are amplified, down-converted, and sampled at 92.16 MSps by the AAU. Afterward, same as the DL paths, the FPGA up-samples and sigma-delta modulates the baseband signals into 3.6864 GSps bitstreams. Two sigma-delta modulated I-Q pairs and one control sequence are time-interleaved and transmitted to the DU over one fiber.
2. Distributed Unit (DU)
   The DU FPGA de-interleaves the electrical signals, filters out the quantization noise, and down-samples the signals to 92.16 MSps. The signals are sent to the PC via the PCIe interface for offline processing.

The recovered clocks from the DL bitstreams are used at the AAUs to guarantee the carrier and sampling frequency synchronism between all UL paths. Fig. 4 demonstrates the RRU synchronism. A 3.6914 GHz sine wave ($f_c + 5$ MHz) was provided to one of the RF-in connectors of both RRUs. The DU received two sine waves (one from each RRU). A phase shift is applied to one sine wave and the phase-shifted sine wave is used to cancel the other sine wave. About 40 dB suppression can be reached. From the cancellation result, it can be observed that the two sine waves have mainly correlated phase noise, which originates from the sine wave generator and the references extracted from the DL bitstreams generated with a central clock source at the DU. Note that the spikes at 5 MHz $\pm$ 500 KHz are caused by the power supplies of the AAUs.

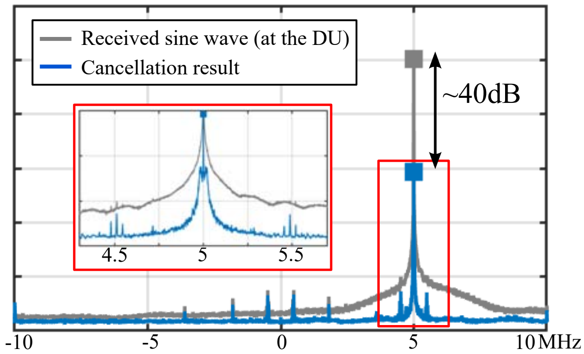

**Fig. 4:** Spectra of the received sine wave and the cancellation result in dB.

### Conclusions

We implemented a radio-over-fiber-enabled distributed antenna system targeting 5G sub-6 GHz applications. The proposed bit-interleaved sigma-delta-over-fiber (SDoF) architecture increases the optical bit-rate efficiency while keeping one of the important advantages of SDoF links—the bi-level optical signals. Optical and electrical components with relaxed linearity requirements, e.g. commercial QSFP modules with VCSELs, can therefore be used in this setup. Moreover, the clock information contained in the bitstreams can be extracted by clock and data recovery modules and used for synchronization.

The proof-of-concept setup is a highly scalable radio access network (RAN) implementation that can be extended to a distributed massive MIMO system. The demonstration will show that this setup is a feasible fronthaul network solution for the 5G enhanced mobile broadband service.

### Acknowledgements

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