Demonstration of Indoor 5G Fronthaul over Legacy Multimode Fiber Enabled by Real-time Analog-to-digital Compression (ADX)

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Abstract *An analog-to-digital-compression radio-over-multimode-fiber (ADX-RoMMF) scheme is proposed and experimentally demonstrated for high-fidelity, cost-effective indoor 5G-and-beyond access. Real-time fronthauling of 16-channel MIMO, 5G NR-bandwidth 1024QAM signals verify more than 4-fold MMF reach extension compared with conventional scheme, while maintaining 500ns one-way ADX latency.*

Introduction

Global wireless traffic is growing explosively with >70% occurring indoor [1]. Compared with 4G, dedicated indoor radio access networks (RAN), such as C-RAN with fronthaul (FH) [2], become increasingly important for 5G and beyond ((B)5G), since 5G signals outdoor with higher carrier frequency (even in sub-6GHz band) suffers from much more propagation and penetration loss when reaching indoor users [3, 4]. Multimode fibers (MMF, e.g., OM2 and OM3) deployed years ago still constitutes a large portion of cable infrastructures indoor, e.g., premises, shopping mall, factory, etc. [5-7]. Reusing these existing fibers for indoor 5G access could significantly reduce capital expenditure and deployment cycle. However, legacy MMFs typically have limited bandwidth-distance product, e.g., 2GHz*km EMB for OM3. If 4G FH interfaces like common public radio interface (CPRI) [8] are used, for example, an indoor radio unit (RU) with 16 antennas serving traffic with 5G new radio (NR) bandwidth of 50MHz [9] would require a link bandwidth of about 32Gb/s, which would limit the achievable distance to ~70m in OM3 case. This distance is far from enough to support typical in-building backbone MMF cables plus horizontal cables [6]. Analog radio-over-fiber (A-RoF) approach that can alleviate this issue has been discussed [10-12]. However, it is not easy to maintain a high signal fidelity or to support larger-scale MIMO.

Here we present an alternative solution path, namely, analog-to-digital-compression radio-over-multimode-fiber (ADX-RoMMF). In this scheme, radio signals received by multiple antennas of RU are jointly compressed and converted to digital stream, which can achieve significantly (e.g., 8~10-fold) better FH bandwidth efficiency by removing redundant information in both space and time domain. Such compression DSP and link coding/modulation are jointly designed and optimized. As a result, ADX-RoMMF can significantly increase the capacity and/or reach of RoMMF system, providing more operation margin and larger in-building coverage. Furthermore, its digital nature brings advantages over A-RoF, such as robustness to nonlinear link distortion and low-cost transceiver module. Note, in such digital-based schemes, it is indispensable to confirm the DSP-induced latency meets the stringent 5G requirement.

In this paper, we validate the potential advantages of ADX-RoMMF by real-time experimental demonstration. Uplink 16 MIMO channels of 1024QAM 5G NR-like radio signals (CPRI rate ≈32.4Gb/s) are processed by real-time field programmable gate array (FPGA)-based ADX prototype and successfully transported over 850m OM3 MMF. As comparison, conventional CPRI compression method cannot support MMF length of 200m. Moreover, we validate latency overhead of ADX DSP to be less than 500ns.

Indoor FH over legacy MMF and the real-time ADX prototype

Fig. 1 illustrates the schematic of a building with legacy MMF cable infrastructure, including backbone cables and horizontal cables [6]. The

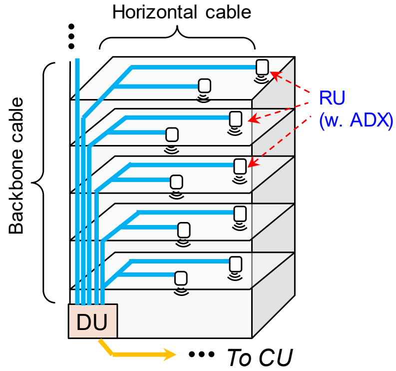

Fig. 1. Schematic of an in-building MMF-based radio access network.

topology may be point-to-multipoint or tree-like with switching/multiplexing. To circumvent the loss issue in 5G frequency band, the uplink 5G signals are not directly served by outdoor base stations. Instead, they are received by an indoor multi-antenna RU, digitalized (e.g., with ADX), and transmitted over MMF to a distribution unit (DU) in the equipment room of the building. After possible processing (e.g., decompression and/or functional split), the signals are then transmitted outside of the building, over another segment of RAN, to a central unit (CU) for centralized processing.

An example architecture of ADX is shown in Fig. 2(a). It consists of spatial compression which reduces the spatial channel count, time-domain (TD) compression which reduces number of digits per sample, and an optional optical spectrum efficiency (SE) enhancement stage (e.g., by PAM-*N* modulation). Space-time and wireless-wired part are jointly designed to optimize performance [13].

In this work, the real-time ADX circuit design is based on the concepts of subspace tracking spatial compression and TD adaptive quantization [13]. A challenging issue is to overcome the feedback loop delays in the concepts, and to achieve a circuit throughput sufficiently high for 5G signal bandwidth, thereby eliminating any buffering latency prior to processing and minimizing the latency overhead of ADX. To this end, we have designed the spatial compression circuit to be a feedforward-feedback separated structure, where the forward spatial filter is updated every *L* incoming radio samples (*L*=10 in the implementation) for 61.44MHz throughput. Meanwhile in TD ADX, subbanding filters were designed before adaptive quantizer for parallelization-based throughput boosting. Overall, an entire 61.44MHz ADX throughput was achieved at 122.88MHz clock frequency, which matches 5G signal bandwidth [14].

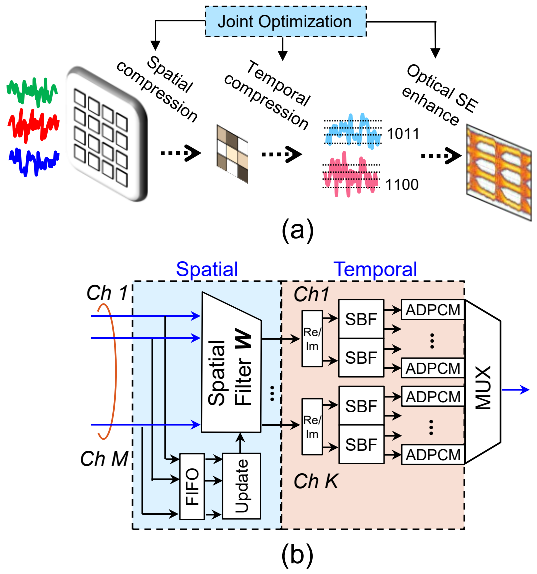

Fig. 2: (a) An example schematic of ADX. (b) Schematic of the designed real-time ADX hardware (M=16, K=4).

Experimental setup and results

We conducted experiments to investigate the performance of real-time ADX-RoMMF in an indoor 5G uplink access scenario. The setup is depicted in Fig. 3. At wireless side, 4 independent 5G-like signal streams were transmitted over 4×16 MIMO i.i.d. Rayleigh fading channel [13], resulting in 16-channel signals received by remote unit (RU). Each stream used 1024QAM-OFDM format with 4096-point FFT size, 3300 data subcarriers, 512-sample cyclic extension, and 50MHz bandwidth. 768-sample preamble was added to assist the convergence of the spatial compressor. Noise was then added, and in order to focus on the RoMMF transport performance, signal-to-noise ratio (SNR) was set at 50dB. The 16 channels were loaded in the memory of the real-time hardware. We developed the prototype based on Xilinx RFSoC hardware platform (XCZU29DR), which integrates 16-channel, GHz-bandwidth DAC&ADC array, digital RF chain and FPGA on a single chip. The 16-channel signals were up-converted to an intermediate frequency (IF) of 100MHz and emitted by the on-chip 14bit DAC array operating at 983.04MSa/s.

In RU, the on-chip 12bit ADC array digitized these 16 IF channels at 983.04MSa/s, followed by down-conversion to baseband. The real-time ADX with 16-to-4-channel spatial compressor and 8-bit TD compressors performed MIMO compression. In this scenario, the CPRI equivalent rate is 61.44(MHz)×(15×2)×16×overhead=32.4Gb/s, where the control word overhead of 16/15 and

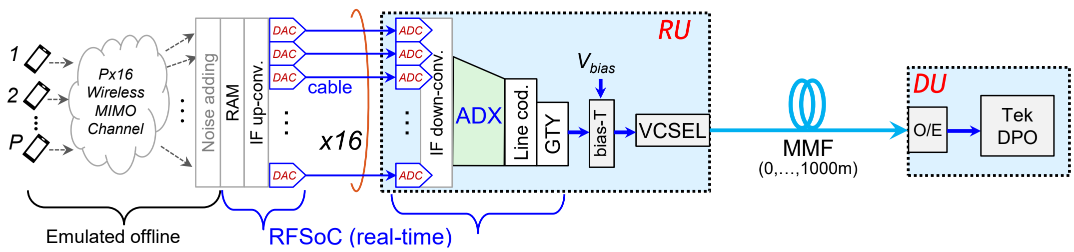

Fig. 3: Experimental setup (*P*=4).

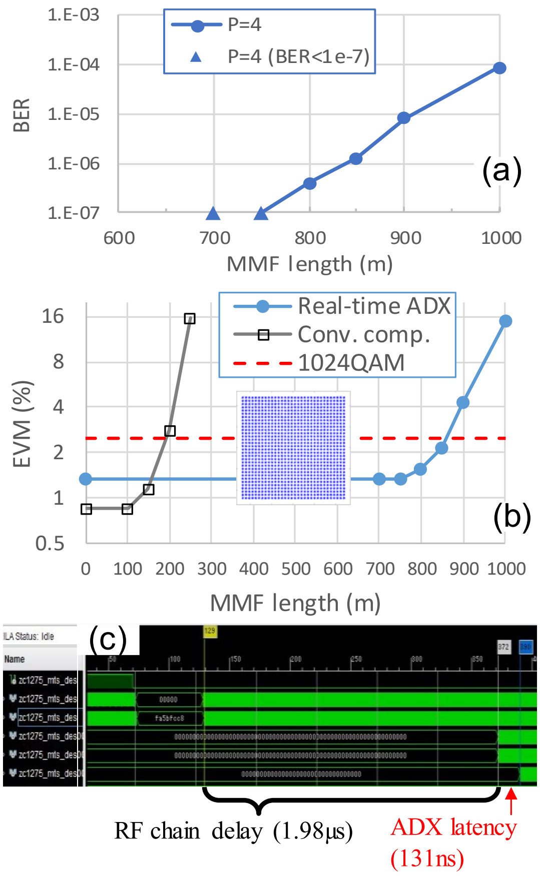

Fig. 4: Experimental results. (a) Link BER vs. MMF length. (b) Radio signal EVM vs. MMF length. "Conv. comp.": conventional compression technique. (c) Vivado ILA measured latency.

line coding overhead of 66/64 were assumed. The compression ratio of ADX compared with CPRI is $4/16 \times 8/15 \approx 13.3\%$, which means that the required FH bandwidth can be reduced by nearly 90%. The compressed data stream was then line coded and output by an on-board serial transceiver (GTY) module with peak-to-peak amplitude of about 400mV. This 4.05504Gb/s electrical OOK encapsulating MIMO waveforms was converted to optical signal employing a directly modulated vertical cavity surface emitting laser (VCSEL) at 850nm band, and then transmitted over OM3 MMF to the distribution unit (DU). The bandwidth of the VCSEL is around 21GHz, and the bias current was 6mA.

At DU, the OOK signal was received by a photodetector (PD, bandwidth about 25GHz) and captured by a Tektronix oscilloscope operating at 12.5GSa/s. Offline processing includes down-sampling, OOK bit decision, line decoding, ADX decompression, MIMO demodulation, and EVM evaluation. Neither forward error correction (FEC) nor electrical equalizer was used.

Fig. 4(a) shows the ADX-RoMMF link bit error rate (BER) versus tested MMF distance. The system bandwidth reduced with increased MMF length, which caused inter-symbol interference (ISI) and bit errors. Fig. 4(b) shows signal EVM after decompression and demodulation versus MMF distance. The ADX substantially reduced link data rate from 32Gb/s (CPRI case) to only about 4Gb/s. Consequently, 850m RoMMF can be supported while satisfying 1024QAM EVM requirement of 2.5% [15]. The inset shows a sample 1024QAM signal constellation at MMF distance of 750m.

For comparison, we also tested the RoMMF transport with conventional compression technique, such as a differential quantizer [16]. In this case, the 16 MIMO channels were compressed individually and multiplexed. Quantizer resolution was 8-bit to support 1024QAM, and bit rate is about 16Gb/s with line coding. A bit pattern generator (BPG) output the multiplexed OOK stream, and the oscilloscope worked at 50GSa/s. The hollow square in Fig. 4(b) shows the corresponding EVM, which cannot meet the 1024QAM requirement at an MMF distance of 200m. This highlights the attractiveness of the ADX-RoMMF scheme, as it provided over 4-fold reach extension for more operation margin and larger in-building coverage.

Finally, we confirmed the latency induced by the ADX operation. Fig. 4(c) shows the ADX compression latency of 131ns or 16 clock cycles experimentally measured by Xilinx Vivado Integrated Logic Analyzer (ILA). In addition, ADX decompression latency at DU is 359ns or 44 clock cycles, according to Vivado FPGA simulation. In total, the one-way ADX processing latency is less than 500ns. As reference, the RAN propagation delay (indoor plus outdoor) is about 5μs/km. The low ADX latency overhead is beneficial for indoor fronthaul latency requirement.

Conclusions

We have proposed an ADX-RoMMF scheme for indoor (B)5G radio access which reuses existing MMF infrastructure. Real-time experimental results have shown that 16-channel MIMO, 5G NR-bandwidth radio signals can be transported over 850m OM3 MMF satisfying 1024QAM EVM requirement, which is over 4-fold more than conventional method. One-way ADX processing latency of <500ns has also been confirmed.

Acknowledgements

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