DSP-enhanced Radio-over-fiber Xhaul Networks Toward Beyond-5G

Paikun Zhu[1], Yuki Yoshida[1], Atsushi Kanno[2,1], Kouichi Akahane[1], and Ken-ichi Kitayama[3,1]
1. National Institute of Information and Communications Technology (NICT), Tokyo 184-8795, Japan
2. Nagoya Institute of Technology, Aichi 466-0061, Japan
3. Hamamatsu Photonics Central Research Laboratory, Shizuoka 434-8601, Japan
pkzhu3@nict.go.jp

Abstract: We review recent progress on candidate DSP-enhanced radio-over-fiber techniques for Xhaul networks targeting 5G and beyond. Low-latency real-time link and layer-2 networking demonstrations will be discussed. © 2022 The Author(s)

1. Introduction

Modern applications such as video streaming on phone/pad and industrial Internet-of-things (IoT), as well as future scenarios like holographic communication and avatar, all require high-quality and ubiquitous wireless connectivity. Since 2020, 5G services have been commercialized at its initial phase. Meanwhile, discussions on beyond-5G have started to forecast new challenges and to seek potential solutions [1]. 5G-and-beyond (5G&B) with demanding data rates, low latency and reasonable cost would bring challenges to the radio access networks (RAN). Centralized/cloud RAN (C-RAN) paradigm continues to gain attention, in which the Xhaul networks [2] bridging central/computing units (CU) and remote/radio units (RU) are expected to be beyond point-to-point topology in 5G&B, and possibly serving as a multi-service platform. The use of traditional Common Public Radio Interface (CPRI) for Xhaul (mobile fronthaul (MFH) in particular) in 5G&B is hindered by the excessive bandwidth and cost. Radio-over-fiber (RoF) technologies are deemed promising and are being widely investigated. With the recent advances in ASIC, FPGA and data converters (DAC&ADC), RoF has been evolving from pure analog schemes to digital signal processing (DSP)-enhanced ones with increased flexibility and compatibility to SDN/virtualization [3]. In this work, we review DSP-enhanced RoF technique options for Xhaul targeting 5G&B, and discuss them from link and networking aspects.

2. Overview of DSP-enhanced RoF techniques: DSP-based IFoF, ADX-RoF and Delta-sigma RoF

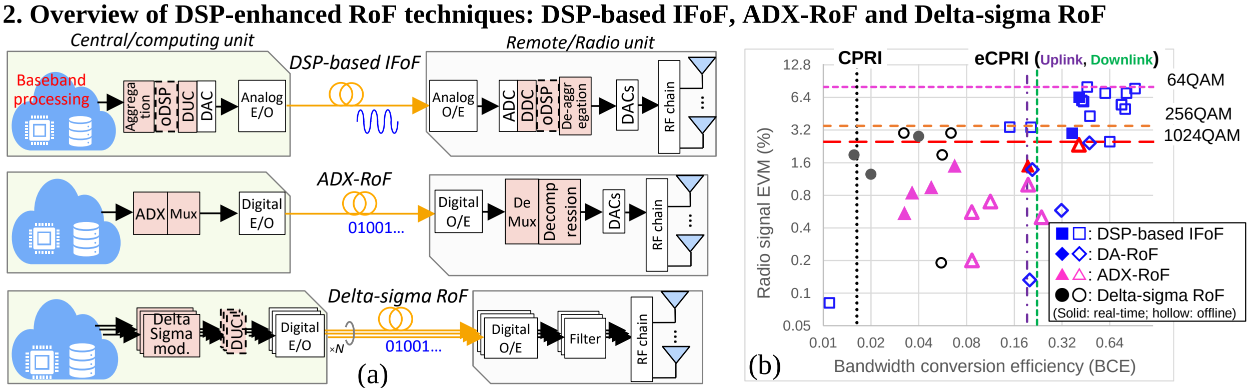

Fig. 1. (a) Schematic diagrams (downlink) of DSP-based IFoF, ADX-RoF, and Delta-sigma RoF. Red blocks are DSP-related; dashed are optional. DUC/DDC: digital up-/down- conversion. (b) Radio signal quality vs. BCE of DSP-enhanced RoF techniques. BCEs of CPRI and eCPRI (e.g., for functional split Option 7-2 [2, 3]) are also plotted as references.

The schematic diagrams of 3 DSP-enhanced RoF techniques, DSP-based intermediate-frequency-over-fiber (IFoF), analog-to-digital-compression (ADX-) RoF and Delta-sigma RoF, are shown in Fig. 1(a). *Performance* of the techniques may be characterized by error vector magnitude (EVM) of radio signals and bandwidth conversion efficiency (BCE, defined as radio signal bandwidth (BW) divided by optical transceiver BW [3]). A summary of recent demonstrations is given in Fig. 1(b).

DSP-based IFoF: IFoF can aggregate multiple radio signals on re-allocated IFs and transports them by using only one optical channel cost-effectively. With advanced DSP hardware, it becomes feasible to manipulate signals in digital domain more flexibly compared with analog manner. Aggregation may be done by frequency-domain multiplexing (FDM) [4-7], time-domain multiplexing (TDM) [8, 9], and so forth. FDM/TDM combined with spectrum spreading (SS) techniques has been shown to trade optical bandwidth for radio signal quality [10, 11]; the recent digital-analog (DA-) RoF technique makes this trading more efficient, i.e., >10dB radio EVM gain per doubled optical bandwidth [12, 13]. Impairment mitigation of optical transceiver and links in such analog-type transmission is also an important topic (e.g., [6, 8, 9, 13]).

ADX-RoF reduces data rate of traditional digital RoF (primarily, CPRI- based) by reducing the number of radio channels and/or the number of bits representing each signal sample while meeting the fidelity requirement of radio signals. It has rich theoretical connections to the data compression techniques in audio/image field. ADX may be further categorized into (memoryless) scalar ADX [14], differential ADX [15, 16], vector ADX [17], and space-time ADX [18, 19]. The former three approaches focus on processing signal in time domain, while space-time ADX further reduces rate when there are fewer MIMO layers than the antennas. A minimal amount of optical link DSP is desired to reduce cost and latency, e.g., via joint optical-electrical processing [20].

Delta-sigma RoF transports radio signals at RF/IF frequency in a digital manner with very few bits per sample, while the large quantization noise is pushed outside of the signal band by high oversampling ratio and noise shaping [21-23]. At the receiver, radio signals can be retrieved by simple filters. This way, RUs can be simplified since DACs can be omitted.

From Fig. 1(b), the highest BCE was achieved by DSP-based IFoF; the BCE could approach 1 ultimately. For ADX-RoF, BCE better than eCPRI could be expected using space-time ADX and/or optical multi-level format. Delta-sigma RoF mainly aims to simplify AS, and its BCE is generally not high although signal quality can be very good. To push the performance toward bottom-right of Fig. 1(a), potential ways may include higher-order optical formats with Nyquist shaping [13, 17] and source coding [17]. Aside from performance, *latency and power consumption* of the DSP-enhanced RoF techniques must be thoroughly evaluated for practical deployment purposes, since Xhaul segment is latency and cost sensitive as a part of the base station. One example of analysis can be found in [3].

3. Real-time Xhaul links based on low-latency ADX-RoF

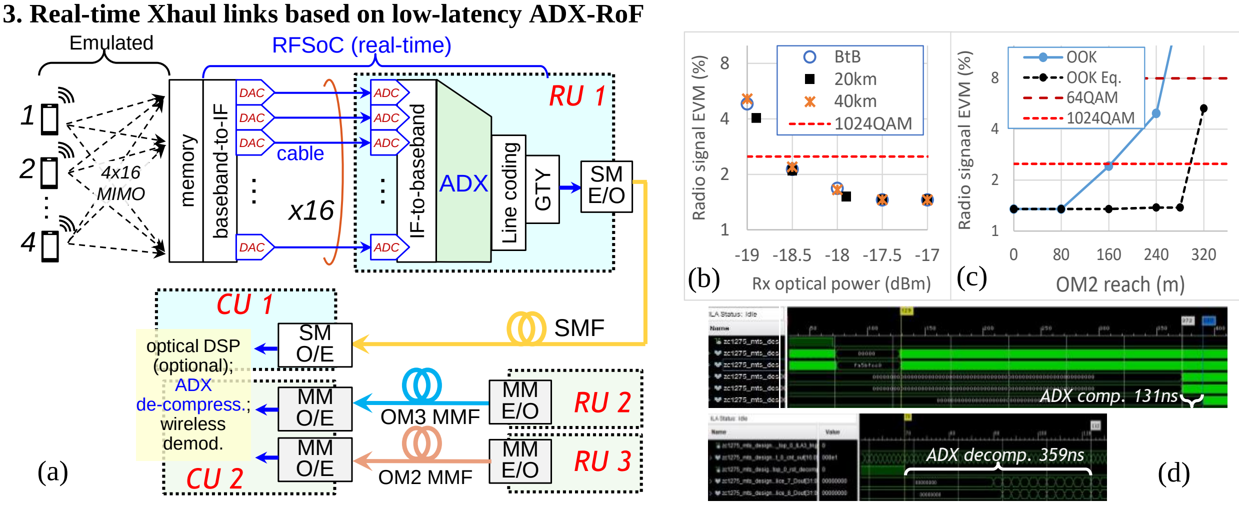

Fig. 2. (a) Experimental setup of real-time RoF MFH links. RU: radio unit. CU/DU: central unit/distribution unit. SM: single-mode. MM: multi-mode. E/O: electrical-to-optical converter. O/E: optical-to-electrical converter. (b) Experimental results of radio signal EVM vs. received optical power in SMF MFH scenario. (c) Measured radio EVM vs. MMF reach in OM2 MFH scenario. Eq.: decision-feedback equalizer with 25 feedforward taps and 5 feedback taps. (d) Measured compression (comp.) and decompression (decomp.) latency of the real-time ADX.

A major challenge for 5G&B MFH is the tight latency requirement [24]. However, most DSP-enhanced RoF techniques were verified by simulation or offline experiment, in which the processing delay of DSP is difficult to evaluate. Real-time hardware demonstration is of particular importance. To this end, we have investigated ADX-RoF on 2 real-time testbeds, one emulating 10s km-scale outdoor MFH based on standard SMF and the other for 100s meter-scale in-building MFH segment reusing the legacy OM2/OM3 multimode fibers (MMF) [19]. The experimental setups are depicted in Fig. 2(a), in which we built real-time RUs on Xilinx RFSoC platform with on-chip DAC&ADC array and FPGA-based space-time ADX, supporting up to 4-MIMO-layer, 16(antenna)*50MHz radio signal processing or CPRI-equivalent rate of 32Gb/s. Fig. 2(b) shows the experimentally measured radio EVM vs. received optical power from RU1 to CU1, which supported 20km/40km MFH transport with negligible transmission penalty owing to ADX compression. Fig. 2(c) shows EVM vs. OM2 MMF reach from a 3-sector RU3 (CPRI-equivalent rate of 96Gb/s) to CU2, indicating the benefit of involving digital equalizers with low cost/latency overhead to extend the reach in such bandwidth-limited legacy links. The measured ADX latency shown in Fig. 2(d) confirmed sub-500ns latency overhead including compression and decompression.

4. Multi-service, time-sensitive layer-2 Xhaul network

ADX-RoF with digital optical formats and RU-side de-framing capability has good compatibility to mature networking/switching technologies, e.g., the layer-2 Ethernet. Meanwhile, the capacity and latency requirements on

5G&B Xhaul calls for new technologies while trying to keep cost-effectiveness. Recently a beyond-best-effort multi-service layer-2 Xhaul platform was demonstrated for the first time [25, 26]. Autonomous time-aware shaper (iTAS), gate-shrunk TAS (GS-TAS) and rate-adaptive low-latency ADX-RoF techniques are incorporated to accommodate both latency-sensitive 5G-class MFH traffic and bursty massive IoT backhaul (BH) traffic with cooperative bandwidth sharing. The testbed is illustrated in Fig. 3(a) with a photo of RUs in Fig. 3(b). It was experimentally confirmed that the 59Gb/s CPRI-equivalent-rate MFH traffic was transported over an economical 10GbE Xhaul network with <80-µs bounded low latency over 4 switches and 10-km optical fiber; meanwhile the IoT BH traffic aggregating >1000 IoT devices was also supported.

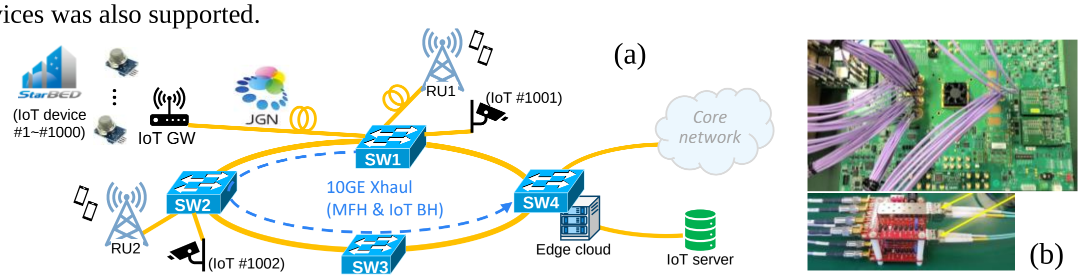

Fig. 3. (a) Illustration of experimental testbed of multi-service layer-2 time-sensitive Xhaul network [26]. SW: layer-2 switch. (2) Photo of real-time FPGA prototype with optical transceivers, which emulates the two RUs.

5. Conclusion

We have reviewed recent advances on DSP-enhanced RoF techniques for Xhaul networks targeting 5G and beyond, such as DSP-based IFoF, ADX-RoF and delta-sigma RoF. Low-latency real-time links and layer-2 networking demonstration have been presented. We believe a lot of research opportunities remain in 5G&B Xhaul networks orchestrating multiple techniques including DSP-enhanced RoF, which is one of the most converged/harmonized fiber-wireless networks.

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