Sigma-Delta Radio-over-Fiber with Passive Opto-Antenna for Low-Power Short-Reach Optical-Wireless Downlink

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We demonstrate a very low-cost low-power solution for a short-reach optical-wireless downlink consisting of sigma-delta radio-over-fiber and a fully passive opto-antenna. An FPGA-based prototype, performing sigma-delta modulation at 7-GS/s and covering a wide frequency band from 3.3 to 3.7 GHz, achieves 218.75 MBd 64-QAM over 200 m OM4 multi-mode fiber and a wireless distance up to 80 cm with <5.8% EVM.

Introduction

The fifth generation wireless networks (5G), driving research in the direction of massive device connectivity, high data rates, decreased latency, and sustainable cost, requires rethinking the wireless access network architecture as well as its hardware realizations. Shrinking the cell size is a prominent feature of 5G, thereby increasing the number of remote radio heads (RRH). Cloud radio access networks (C-RAN) can be a key technology to coordinate these RRHs in a central office (CO), and radio-over-fiber (RoF) interconnections play an essential role to transport data between RRHs and CO [1]. Sigma-delta radio-over-fiber (SDoF) has been proven to be a competitive solution to their analog counterparts [2][3]. This paper provides a very low-cost low-power solution for short-reach optical-wireless applications [4] by employing the fully parallelized sigma-delta implementation technique proposed in [5] and the passive opto-antenna in [6]. By operating the photodiode at zero bias voltage, while omitting typical active components such as transimpedance amplifiers (TIAs), a fully passive RRH, requiring no external power supply, is demonstrated.

Proposed architecture

Fig. 1 schematically depicts three different RoF realizations, including digitized RoF (DRoF), analog RoF (ARoF) and SDoF. As shown in Fig. 1(a), DRoF uses Nyquist digital-to-analog converters at the RRH to retrieve the analog waveforms of baseband signals. At RRH, frequency upconversion is required to translate the baseband signal to radio frequencies. DRoF is less suited for large-scale deployments of RRHs due to its low bandwidth efficiency, and the high complexity and high power consumption of the RRH. ARoF delivers radio signals via fiber links as depicted in Fig. 1(b), which features simple, low-cost and low-power implementation of RRH, and high spectral efficiency. However, it imposes high linearity requirements on the E/O modulators. SDoF translates the signal-of-interest to a bi-level signal (non-return-to-zero (NRZ) or on-off keying (OOK)). As such, it leverages the benefits of both the DRoF (allowing low-cost telecom components) and ARoF (low-complexity RRH). By oversampling the signal with a closed feedback loop, the quantization noise is pushed to high frequencies by the lowpass sigma delta modulator (SDM), away from the band of interest, as shown in Fig. 2(b). In Fig. 2(c), a lowpass filter eliminates the out-of-band quantization noise and reconstructs the analog signal waveform.

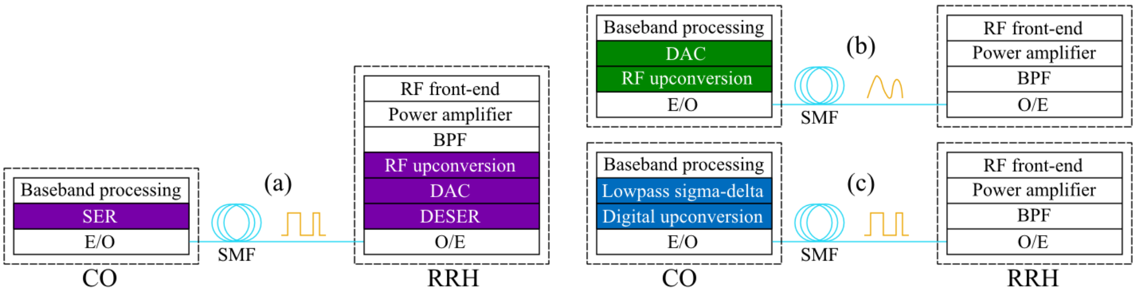


Fig.1. Different RoF realizations: (a) DRoF (b) ARoF and (c) SDoF.

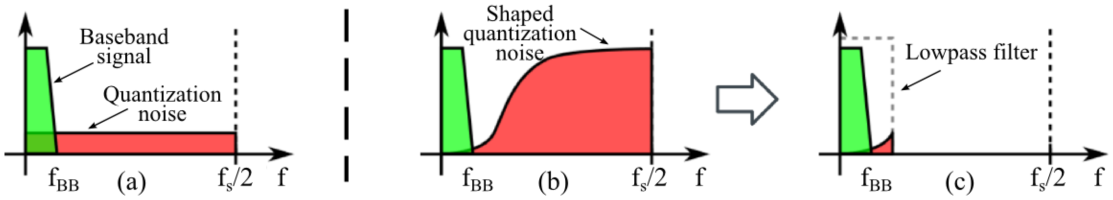


Fig.2. Operation principles of (a) Nyquist DAC and (b) lowpass sigma delta modulator. (c) Shaped quantization noise is removed by filtering.

Fig. 3 shows the proposed downlink architecture where baseband I/Q signals are modulated by two lowpass SDMs. Second-order modulators are used to obtain a high signal-to-noise-and-distortion ratio (SNDR). A digital upconversion translates the baseband signals to a carrier frequency at 3.5 GHz, followed by the subsequent electrical-to-optical conversion.

In short-reach optical-wireless system, such as factory-of-the-future environments where RRHs are densely populated and integrated into the floor [4], the RRH transmit power through the antenna can be reduced thanks to the short wireless coverage required. Therefore, the RRH can be made fully passive to lower the cost and power consumption. Full passivity implies that photodiode (PD) is biased at zero voltage and that other active components such as TIAs are omitted. As shown in Fig. 3, the simple RRH only comprises a PD, an impedance matching circuit and the antenna. In this way, the RRH is entirely driven by optical power, leading to a maintenance-free and cost-efficient unit.

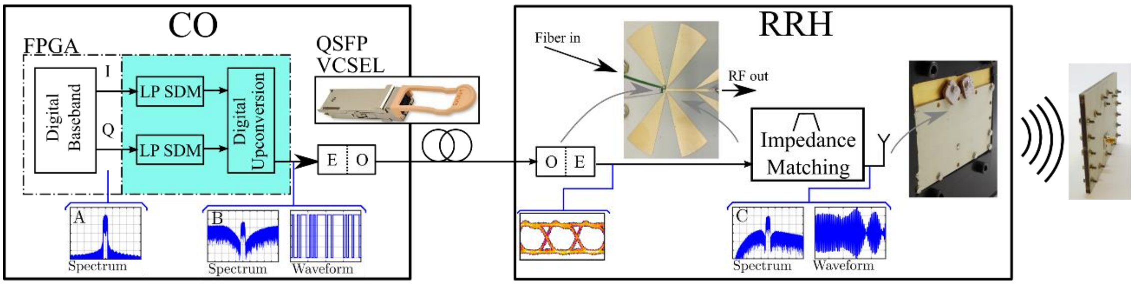


Fig.3. Block diagram of the short-reach optical-wireless downlink employing a fully passive RRH.

Hardware implementation and experimental results

The second-order LP SDM is realized by cascading a multi-stage noise shaping MASH-1-1 SDM with a bit reduction process. The MASH-1-1 SDM is shown in Fig. 4, comprising two identical first-order lowpass SDM. The signal transfer function is an all-pass filter and the noise transfer function is a second-order highpass filter $(1-z^{-1})^2$. A fully parallel, low latency implementation is realized on FPGA and serialized before transmission through the high speed FPGA interfaces. These interfaces drive the E/O modulator. The detailed implementation is referred to our prior work [5].

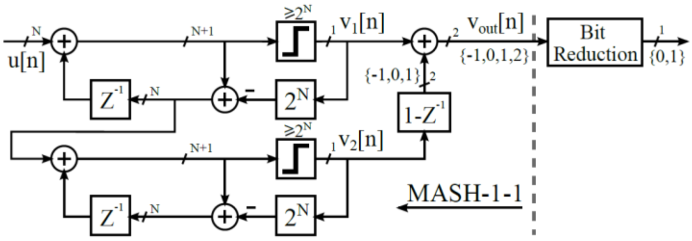


Fig. 4. The SDM topology with a MASH-1-1 SDM and the bit reduction process in cascade.

The antenna, implemented in air-filled substrate-integrated-waveguide (AFSIW) technology, is integrated into a multi-layer printed circuit board (PCB). The waveguide is formed by covering the edge-plated cavity on both sides with a conducting layer to form the top and bottom walls and by metalizing the sidewalls. Without introducing electrical amplifiers, the RF power transmitted by the antenna necessarily originates entirely from the time-varying photocurrent in PD. To maximize RF power extraction within the intended frequency band, the PD is connected to the antenna through a passive impedance matching network, in the meantime enhancing cost-effectiveness. Fig. 5 displays a high-level schematic overview of the passive RRH and its prototype. Details of the impedance matching network are given in [6]. Fig. 5(c) shows the measured and simulated transmission coefficient magnitude.

The main drawback of the proposed passive RRH is its limited transmit power and hence the limited optical and wireless coverage range. However, the signal power of the NRZ/OOK signal generated by SDM can be increased as it is less vulnerable to nonlinear distortions, which is the superior aspect of SDoF compared to ARoF. This has been experimentally verified in [3] where it was shown that the third order intermodulation products (IM3) component is 26 to 45 dB lower in the SDoF case when the fundamental power is between -35 dBm and -25 dBm for both ARoF and SDoF.

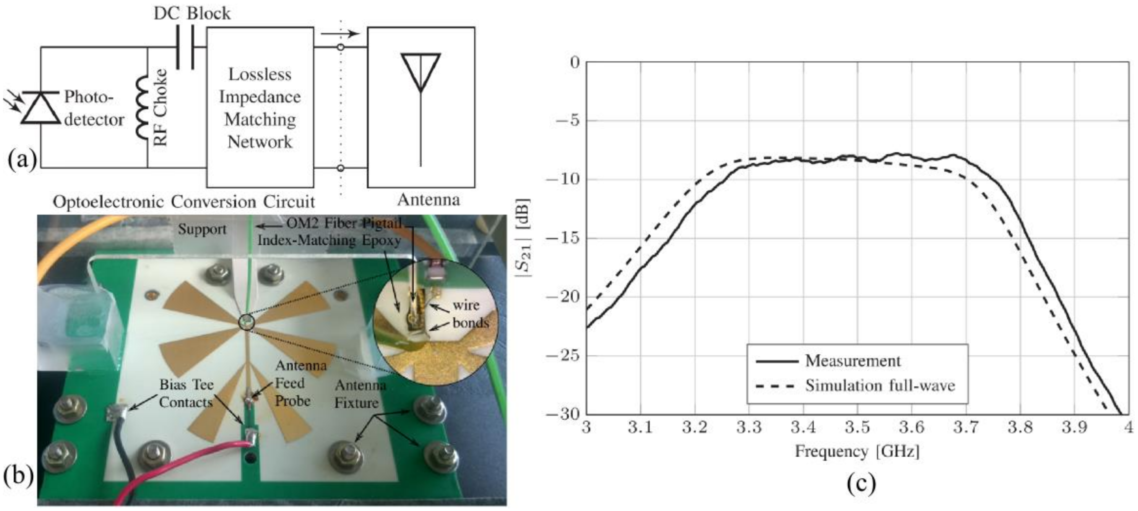
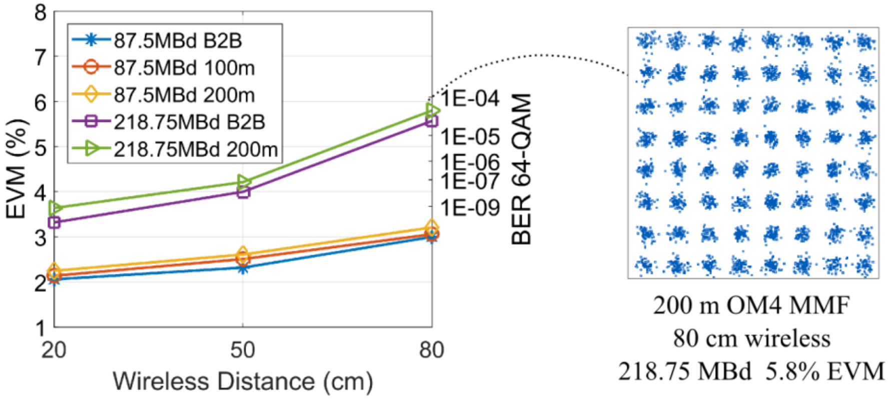


Fig. 5. (a) High-level schematic overview and (b) prototype of passive RRH. (c) Measured and simulated transmission coefficient magnitude $|S_{21}|$ [dB].

The digital baseband generators, LP SDMs and digital upconverter, as shown in Fig. 3, were implemented on a *Xilinx Virtex Ultrascale* FPGA (VCU108). For the electrical-optical conversion, we used a commercial QSFP-100G-SR4 (850 nm) module to transmit the NRZ/OOK signal over OM4 multi-mode fibers (MMFs). Each module consists of 4 individual transmitters and each transmitter contains a clock and data recovery (CDR) circuit to resample the data, a laser driver and a vertical-cavity surface-emitting laser (VCSEL). The out-of-band quantization noise generated by the SDM is suppressed by the bandpass matching circuit and the opto-antenna. To demodulate the QAM-signals at the output of the receive antenna, an Anritsu vector signal analyzer is used. Very low root-mean-square values of the error vector magnitude (EVM) have been measured (<3.2%) for 87.5 MBd 64-QAM signals, as depicted in Fig. 6. The signal quality even enables the reception of 218.85 MBd 64-QAM over 200 m OM4 MMF up to 80 cm wireless distance with an EVM of 5.8%. When the wireless distance is above 80 cm, the EVM increases faster due to the limited transmit power.



(a) (b)

Fig. 6. (a) Measured EVM vs wireless distances for different fiber spans and symbol rates. (b) Demodulated constellation of 218.75 MBd 64-QAM.

Conclusion

We have demonstrated the practical feasibility of a fully passive downlink RRH driven by sigma-delta modulated NRZ/OOK signal through a low-cost E/O converter, which leads to a compact, cost-effective, and energy-efficient solution for large-scale deployments of RRHs. The low transmit power limits the coverage range of this system for a given receiver noise floor and SNDR, limiting its application to short-reach optical-wireless systems.

Acknowledgements

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