Novel Scalable and Reconfigurable Optical Fronthaul Network for Converged Radio Frequency and Data Services Using Silicon Photonic Switching

Junfei Xia,[1,*] Tongyun Li,[1] Qixiang Cheng,[1] Shuai Yang,[1] Keren Bergman,[2] Richard Penty,[1]
[1]*Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, UK*
[2]*Department of Electrical Engineering, Columbia University, New York, NY 10027, USA*
[*]*Author e-mail address: jx248@cam.ac.uk*

Abstract: We propose and demonstrate a converged optical fronthaul network for RF and data services with scalable silicon photonic switching. A 1.5dB power penalty at a 10^{-9} BER and over 40dB RF dynamic range are demonstrated. © 2021 The Author(s)

1. Introduction

Recent advances in 5G networks have driven increasing demand for cost-effective, high-capacity and low-latency network architectures. Last-mile wireless coverage or fronthaul is a bottleneck in terms of bandwidth efficiency, network convergency and interoperability. Centralised Radio Access Network (C-RAN) and Distributed Radio Access Network (D-RAN) approaches offer digital radio over fibre (D-RoF) fronthaul solutions by carrying digitised Radio Frequency (RF) services over the optical fibre infrastructure using the Common Public Radio Interface (CPRI) and evolved CPRI (eCPRI) protocols [1,2]. Thus, 4G and 5G networks will gradually converge with conventional data infrastructures, such as Ethernet, allowing packet switching and statical multiplexing functionalities for radio over Ethernet (RoE). Nevertheless, high capacity and stringent latency requirements are major obstacles to practical implementation. As massive multiple input multiple output (massive MIMO), carrier aggregation (CA) and millimetre wave (MMW) technologies are adopted by service providers, switching technologies are desirable to enable smart and reconfigurable distribution of the increased capacity without the need for new or parallel network infrastructure. Currently, inefficient opto-electronic and electro-optic conversions impose power limitations on electronic switches, which, furthermore, suffer from latency and cost issues. It is widely believed that photonic switches can circumvent these bottlenecks, enabling greater bandwidth per port, reduced energy per bit and lower latency [3,4]. Leveraging the CMOS industry's highly developed fabrication and manufacturing infrastructures, densely-integrated silicon photonic switches may be favoured as a cost-effective solution, showing great potential for data centre interconnects [3] and future-proof 5G transport networks [4].

In this paper, we propose and experimentally demonstrate an all-optical converged fronthaul system using a highly-scalable micro-ring resonator (MRR) based SiP switch to allow both conventional digital data (metro and access) and data compressed multi-band digitised RF services to be switched from a centralised datacentre to designated remote sites. This system is also scalable to address a higher number of I/O channels and offers great promise for next-generation converged fronthaul networks.

2. Proposed Converged Optical Network for Digital Radio Fronthaul Links and Data Services

As shown in Fig 1(a), the proposed architecture comprises a central office (CO), housing optical line terminals (OLT) and baseband or distributed units (BBU or DU), a reconfigurable optical switching fabric able to route the data to digital data or D-RoF paths, and multiple flexible remote sites which can be configured into optical network units (ONU) or remote radio units (RRU)/active antenna units (AAU) by the remote users. The optical switching platform adopts the tailored switch-and-select topology using MRRs [5]. It offers strictly non-blocking connectivity but avoids coherent multi-path interference crosstalk, as shown in Fig 1(b). Scale-up of such a switch only requires adding bypass rings in the linear switch arrays at a tiny loss penalty per ring [5]. The linear switching arrays act as spatial (de-) multiplexers, but the wavelength-selective nature of an MRR unit additionally enables switching in the wavelength domain, creating a highly flexible wavelength-and-space switching platform [5].

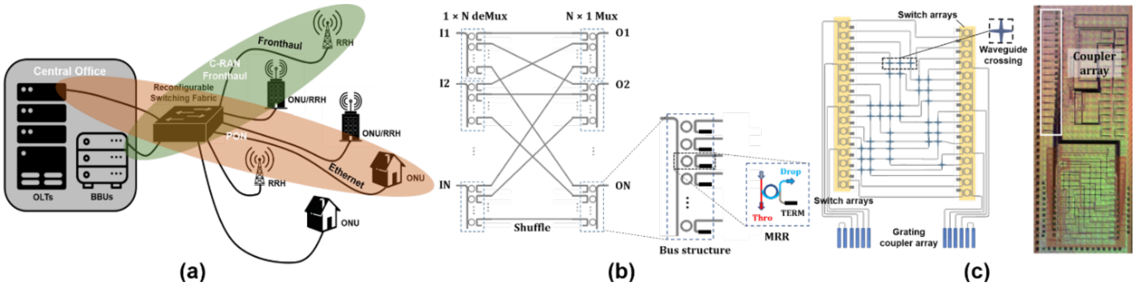

Fig 1(a) Proposed converged optical network for RF and data services. (b) N×N switch-and-select topology with MRR-based elements. (Reprinted from [5]). (c) Schematic of a silicon 4×4 MRR based switch. (Reprinted from [6])

A fully-packaged 4×4 silicon switch prototype, depicted in Fig 1(c), is used in this work. The switch is constructed by 32 ring resonators and can be tuned by wavelength in the C-band within a wavelength range of 25.4nm. The switch is similar to the one reported in [5], except that all the elements are fabricated in the silicon layer. The switch is thermally-actuated at this time, but electro-optic phase shifters can readily be employed for nanosecond switching in the future networks.

3. Experiment Setup and System Characterisation

The experimental setup is illustrated in Fig 2. For the RF fronthaul path, a 20MHz 4G-LTE signal with 64 quadrature amplitude modulation (64-QAM) and carrier frequency at 1.8GHz is generated using a vector signal generator (VSG). The signal is then down-converted to a 37.5MHz intermediate frequency (IF) using an RF mixer. A 14-bit 150MSPS analogue-to-digital converter (ADC) and digital-to-analogue converter (DAC) pair is used for converting the signal between digital and analogue formats. As described in [7], the digitised RF is subsequently processed on an FPGA platform for data compression and packetisation for optical transmission. 16 replicated LTE streams are created and packetised into a serialised data channel with a line rate of 8Gbit/s. A 10G small-form pluggable plus (SFP+) transceiver module with an optical carrier at 1538.65nm is used to transfer the digitised LTE signal onto an optical fibre. At the RRU, the received data is depacketised, decompressed and recovered to an IF signal which is subsequently upconverted to an RF at 1.8GHz frequency and then measured by a vector signal analyser (VSA) [8].

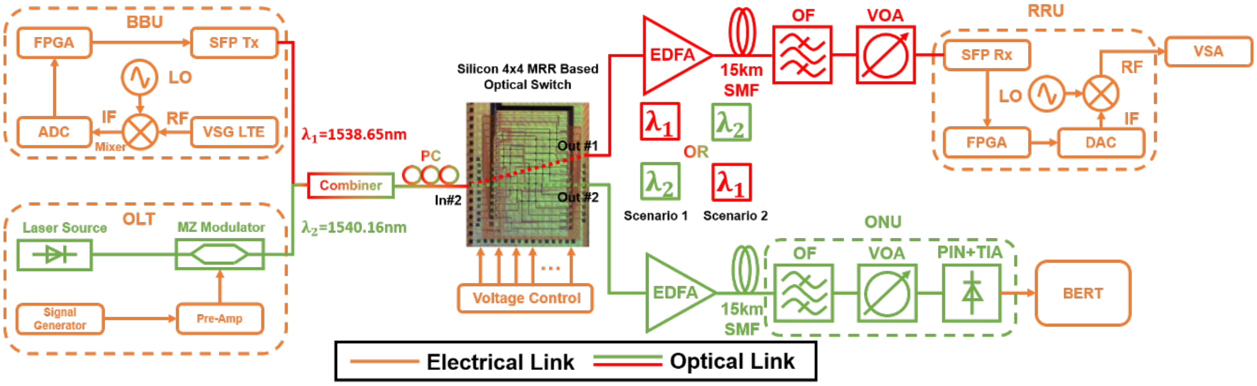

Fig 2. Schematic experimental block diagram with silicon MRR based switch layout. (red line and green line represent optical carriers at 1538.65nm and 1540.16nm, respectively)

To emulate an OLT, a Mach-Zehnder Modulator is used to modulate a 1540.16nm light source with 10Gb/s digital data. An optical combiner with a 3.8dB loss is used as a two-port wavelength multiplexer, followed by a polarisation controller with a 0.2dB loss. The combined signal is then fed to the switch fabric (Fig 3a). For tunning the optical signal at 1538.65nm and 1540.16nm, the MRR elements are biased at ~2.9V and ~3.2V, respectively. At the ONU, a PIN-TIA converts the digital signal to an electrical signal which is then analysed by a bit error rate (BER) analyser.

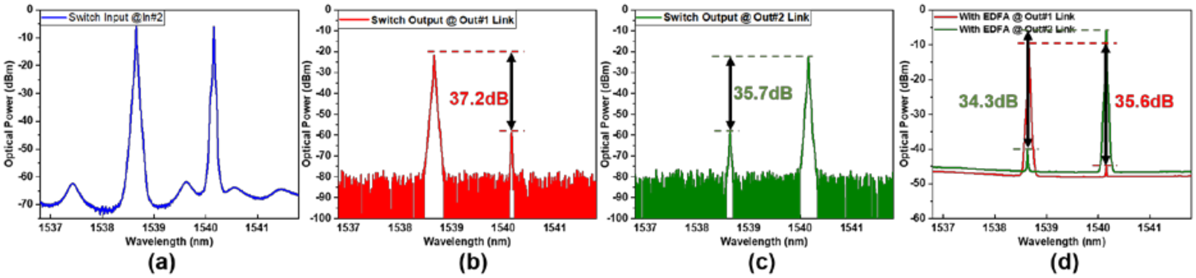

Fig 3 Optical carriers spectra at different locations of the link 1:(a) spectrum at the input port 2; (b) spectrum at output port 1; (c) spectrum at output port 2; (d) spectra after EDFA (red line at output port 1, green line at output port 2)

The experiment is carried out under 2 scenarios: scenario 1 is for routing the digitised RF signal from input port 2 to output port 1 while switching the data service to output port 2. Scenario 2 is performed by switching the two signals to the other outputs. Fig 3b and Fig 3c show the spectra at output port 1 and output port 2 respectively, showing that 37.2dB and 35.7dB crosstalk ratios are achieved following switching. A 14.3dB fibre-to-fibre on-chip loss is measured, which is mainly due to the fibre coupling from/to the chip. Two EDFAs, each with a 16dB gain are placed at the outputs to compensate for the loss. As shown in Fig 3d, crosstalk ratios after the EDFA are decreased to 35.6dB and

34.3dB on the links via output port 1 and output port 2, respectively. Both signals are then transmitted over a 15-km single-mode fibre (SMF) with an optical filter and an optical variable attenuator to adjust the received optical power before detection by a pin-TIA module.

4. Experimental Results and Discussion

Fig 4a shows BER curves, demonstrating a power penalty of 1.2dB in scenario 1 and 1.5dB in scenario 2 at a 10^{-9} error rate. Error vector magnitude (EVM) results are measured at different RF input powers as an indicator of the RF performance. As shown in Fig. 4b, the RF input power dynamic range is over 40dB for <8% EVM (64-QAM requirement specified by 3GPP [9]), with an EVM minimum of 1.55%. The optical power dynamic range is measured by varying the VOA as illustrated in Fig 2. As shown in Fig 4c, the rapid increase of EVM only occurs when the optical power is attenuated to below -19dBm for both scenarios, indicating that over 15dB optical link budget is available for future scaling up of the switch.

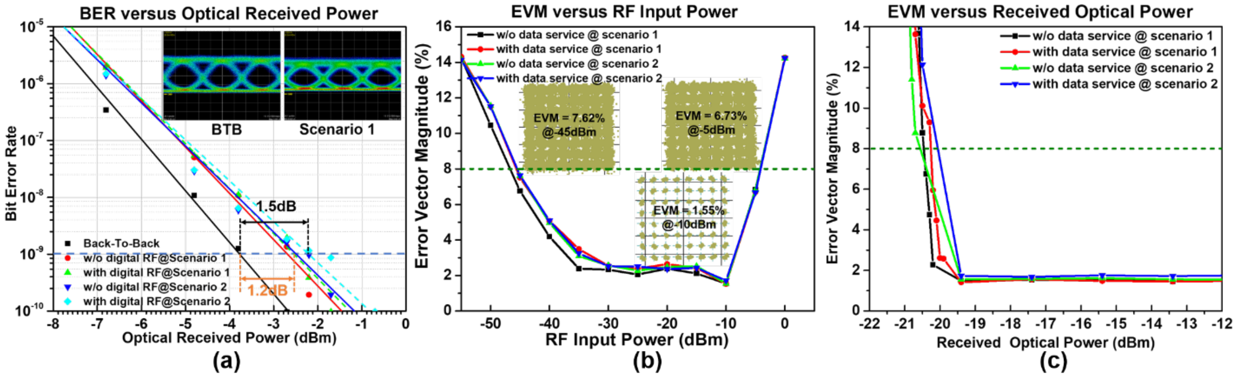

Fig 4 (a) BER curves and eye diagrams for with/without digital RF channels in 2 scenarios. The inset shows the BTB and scenario 1 received eye diagrams at a power level of -4dBm. (b) EVM vs RF input power with/without data service in 2 scenarios with the received constellation diagrams. (c) EVM vs received optical power with/without data service in 2 scenarios.

The tailored switch-and-select design maintains the number of the number of drop (i.e., resonating) microrings in any path at two, while scaling-up of the switch merely adds through (i.e., off-resonating) rings in the spatial (de-)multiplexers. The loss for the MRR drop and through states has been measured to be 0.5 dB and 0.1 dB, respectively, for tape-outs in a commercial foundry [5]. This potentially yields silicon photonic switches with over 100 port counts for future all-optical converged fronthaul networks. Moreover, the development of gain-integration techniques on the silicon platform can further circumvent the insertion loss penalty [10].

5. Conclusion

In this paper, we propose a novel scalable, reconfigurable and converged optical fronthaul network for digitised RF and data services. The experiment shows that 37.2dB and 35.7dB crosstalk ratios can be achieved by using an MRR silicon photonic switch. For a 10Gb/s NRZ modulated digital data stream, a maximum power penalty of 1.5dB is observed at a BER of 10^{-9}. The switch-induced crosstalk does not affect the RF dynamic range which is over 40dB for <8% EVM. An over 15dB optical link budget and the low power penalties could enable scaling up the switching ports to >100. Further expansion of port count can be realised by the heterogeneously integrated optical switch with SOAs. This will be a focus of future study and is expected to make a significant impact on converged fronthaul in 5G and beyond.

6. Reference

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