Silicon Photonics Enabling 5G Optical Networks over PON Infrastructures

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***Abstract*—Achieving the great leap forward in capacity targeted by 5G requires radio access networks to provide connectivity across multiple antenna sites. That connectivity relies on optical fronthaul with sufficient capacity. We discuss the use of analog radio over fiber signals in an optical access network equipped with a smart edge. We can minimize interference and maximize throughput at the edge of the network by collocating platforms that coordinate wireless transmissions. Silicon photonics provides a hardware platform well adapted to support optical fronthaul to increase capacity via radio over fiber, while keeping optical transceiver costs low. We highlight several issues in adopting silicon photonics and cite recent demonstrations in this area.**

***Index Terms*—Passive optical networks, Radio access networks, smart edge, heterogeneous services, microring resonator, microring modulator**

I. INTRODUCTION

THE deployment of fifth-generation (5G) is accelerating adoption and development of high bandwidth, and low latency applications. Expanding coverage of 5G while keeping latency low is a serious challenge. For example, supporting virtual reality targets latency below 10 ms, and autonomous vehicles could be even more demanding.

Adoption of a cloud-like paradigm for 5G is taking hold as one strategy to improve latency. For instance, multi-access edge computing (MEC) is local computing power for applications with strict latency limitations. Local means physically closer to mobile units, defining the smart edge. A second strategy is to pool physical (PHY) layer processing at the same smart edge. Essentially, we create a radio access network (RAN) so that tower sites can share their signals for better PHY processing. This coordinated processing is a signature feature of 5G networks and future generations as well.

II. RADIO ACCESS NETWORKS

To create elastic and flexible interfaces in 5G we turn to an optical access network centered on these systems. This is known as a radio access network (RAN). Add a smart edge, and we have a cloud RAN or C-RAN. Past generations had baseband units (BBU) that did all processing at the antenna site. Now we can split the same functionality into separate units: a central unit (CU), distributed unit (DU) and remote unit (RU). This works well with a smart edge for cloud type capabilities. Figure 1 gives some examples of how the functional splits could be deployed.

Deployed systems typically have all equipment at the remote antenna or the base of the tower. Latency is not an issue as processing is on-site. But the hardware is expensive and antenna sites can be notoriously difficult to service. This does not allow for coordination of RF signals across multiple antenna sites.

Suppose next that all RF baseband processing remains at the antenna site; again no signal coordination. However, we can put intelligence (a MEC) to handle some application processing at a smart edge of the network. A central unit at the smart edge could also support upper layer data. In essence

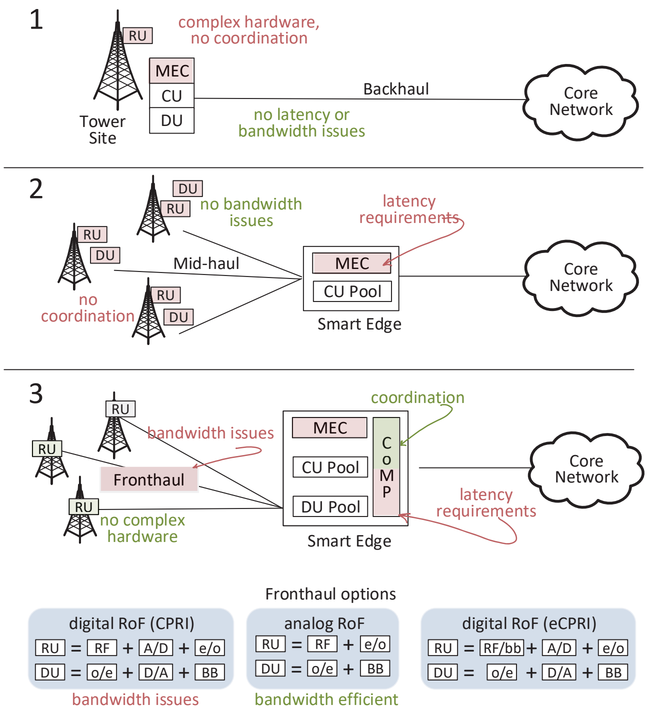

Fig. 1. Three RAN architectures; three options for optical fronthaul. A/D analog-to-digital, D/A digital-to-analog, o/e opto-electronic, e/o electro-optic, RF radio frequency, BB or bb baseband.

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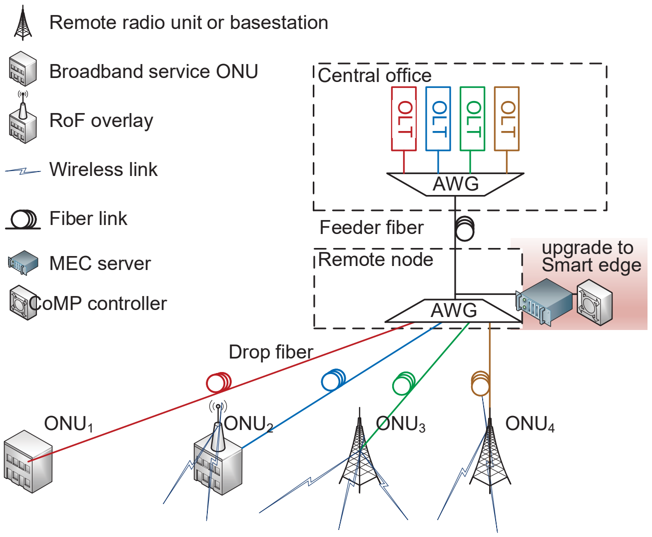


Fig. 2. A proposed optical access network supporting heterogeneous services.

we have a ”mid-haul” from the tower to the smart edge for the upper layer data; this mid-haul only imposes moderate bandwidth requirements. The purpose of edge computing is to offload calculations to the MEC instead of user equipment. This is the same approach as cloud computing, but lower latency and much more information on computing context. Edge computing, like cloud, prolongs battery lifetime.

Now we get to scenario of interest for 5G. The wireless PHY hardware is located at the smart edge where we could also house the MEC and CU pool. This allows a separation of baseband processing (at the DU at the smart edge) and RF chains (at the RU). With this separation, we can exploit commodity hardware. Also this separation puts equipment at physical locations that are easy to reach. Fronthaul bandwidth is now vary demanding compared to other solutions.

For 5G we need spatial densification and spectral aggregation [1]. Spatial densification means ultra dense picocells for better coverage. Spectral aggregation means adding new radio capacity (think millimeter wave). Antenna sites must proliferate for densification. This proliferation can only occur if each antenna site cost is kept low.

Denser cells leads to signal overlap and inter-cell interference. The box marked CoMP (for cooperative multipoint technologies) [2] deals with these issues. The edge allows coordination between antenna sites. Only optics, an optical access network (OAN), can provide the necessary bandwidth for fronthaul. Since the CoMP controller is located at the smart edge, the fundamental latency is reduced. The 5G signals can be carried on dedicated optical subbands to reduce CoMP spectral overhead.

We summarize fronthaul solutions at the bottom of Fig. 1. The current solutions are common public radio interface (CPRI), and an updated version known as enhanced CPRI (eCPRI). The very poor spectral efficiency of CPRI is improved in eCPRI, but at the cost of delay and heavy processing. There is also higher RU complexity and cost [3]. We discussed at greater length in [4] the advantages of analog radio-over-fiber (RoF) over CPRI and eCPRI digital RoF [5].

III. EXPLOITING DEPLOYED FIBER INFRASTRUCTURES

In Fig. 2 we illustrate our concept for a shared deployed fiber infrastructure. We see a central office that houses a WDM optical access network with a tree architecture. There is a single feeder fiber. The remote node follows the feeder and splits the wavelengths for distribution to clients that are clustered geographically. The passive optical network would have an arrayed waveguide network (AWG) separate wavelengths; passive splitters could also be used at each AWG output. Typically ONUs would be digital subscribers. However, we also could reserve certain wavelengths to service radio access networks (see ONU3 and ONU4). The PON provides backhaul to the network.

Another usage scenario is to imagine the remote node replaced by a smart edge. In this case the radio access network encompasses at the least ONU3 and ONU4. The links between the smart edge and the ONUs become fronthaul links carrying radio signals, and the feeder line is the backhaul. The smart edge houses not only an AWG, but active (not passive) components such as the digital signal processing to coordinate wireless signaling at antennas at ONU3 and ONU4. In fact, we could piggyback radio signals in wavelength bands occupied by digital subscribers.

Consider ONU2. This client location could host a basic antenna to provide more dense coverage for 5G. The centralization of RF signals at the smart edge could enable high performance beam forming even for a low complexity remote radio unit. For this link, the digital services and radio over fiber coexist for heterogeneous services.

IV. SILICON PHOTONICS IN 5G-OAN

To support the aforementioned RAN functions, silicon photonics are envisioned to play critical roles in almost every subsystems of 5G-OAN. Principal functionalities include the optical broadband signal generation at the central office; 5G services overlay at distribution units, with which the traditional remote node is reformed into a smart edge. Downlink signal drop and separation, as well as uplink signals are handled at the ONU. We propose a framework which realizes almost every functional block of 5G-OAN with silicon photonics. With such a framework, SiP can provide low-cost, high-compactness, wavelength-division multiplexed and CMOS-compatible solutions to 5G-OAN subsystems, for both newly deployed OAN and existing fiber infrastructures.

The main components in such a framework are microring resonators. In the passive mode, they can function as wavelength selective filters for WDM or sub-WDM channel drop. Their active form, microring modulators, enable wavelength-selective modulation to only selective WDM channels, and facilitate 5G services overlay with minor interference to the existing broadband signals. This section provides detailed descriptions of SiP in different subsystems of 5G-OAN.

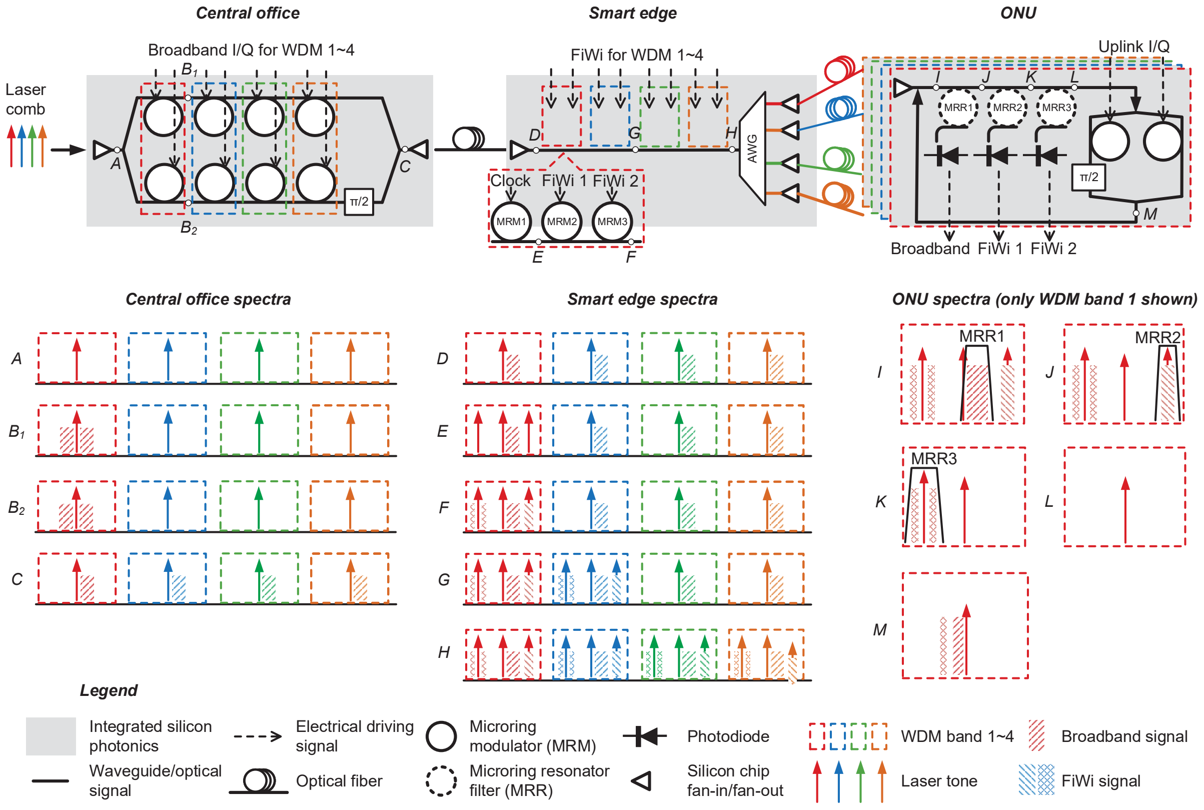


Fig. 3. The proposed framework and the spectral allocation strategy to support heterogeneous services.

Figure 3 provides a general illustration of the framework proposed, based on a common OAN tree-topology seen in Fig. 2. The spectral sharing strategy is also illustrated. In Fig. 3, the grey shading indicates SiP blocks. At points labeled A through M in the block diagrams, the spectra varies as illustrated in the sketches just below.

A. Central office

In the central office of a WDM network, multiple wavelength laser tones are modulated to serve different ONU. The multiple wavelengths can be from multiple laser diodes or from a comb laser source (for example, a mode lock laser [6], a electrically generated CLS [7], or other comb source that are cost-efficient).

As comb laser source (CLS) technology is potentially lower cost and offers higher flexibility. It is an important candidate of light source in various optical networks, including optical access networks [8], [9]. This trend inevitably promotes MRM adoption, because of its compatibility with comb laser.

A simple SiP-based central office subsystem is depicted in the first column of Fig. 3. In this configuration, we use I/Q modulation to generate single sideband modulation (SSB), with three-fold benefits. Firstly, it avoids power fading from chromatic dispersion. Secondly, SSB enables 5G service overlay by emptying one side of the carrier; this is useful to avoid overlay interference, as explained in the next subsection. Thirdly, it also leaves a spectral slot for uplink with a different spectral band from downlink, and alleviates Rayleigh backscattering.

The example shows four pairs of MRM at the central office. All the MRM have identical designs, with each pair work in the same WDM channel. The four MRM pairs cover four WDM channels, represented by different colors. The working wavelength of the MRM can be adjusted by thermal tuning [10]. In consequence, each pair can be aligned to one wavelength, and a collection of four pairs can be allocated to four different wavelength slots. A $\pi/2$ phase shift between the two branches makes an I/Q configuration, and SSB modulation can be realized by driving each pair of MRM with a Hilbert transform pair [11]. In other words, the spectra of the leftest WDM channel in B_1 and B_2 in Fig. 3 are a Hilbert transform.

The adoption of MRM over Mach-Zehnder modulator (MZM), in combination with comb laser, significantly simplifies the transmitter composition. In Fig. 4(a) is the MRM-based OLT transmitter, its counterpart using MZM technology is shown in Fig. 4(b). The MZM would need a WDM demultiplexer (DEMUX) to separate the laser tones, modulate each one, and recombine all WDM with a WDM multiplexer (MUX). An example of WDM MUX/DEMUX is an arrayed waveguide gratings (AWG), whose footprint on silicon is large, and loss is high, especially when the channel spacing shrinks. Furthermore, each WDM channel would need a $\pi/2$ phase

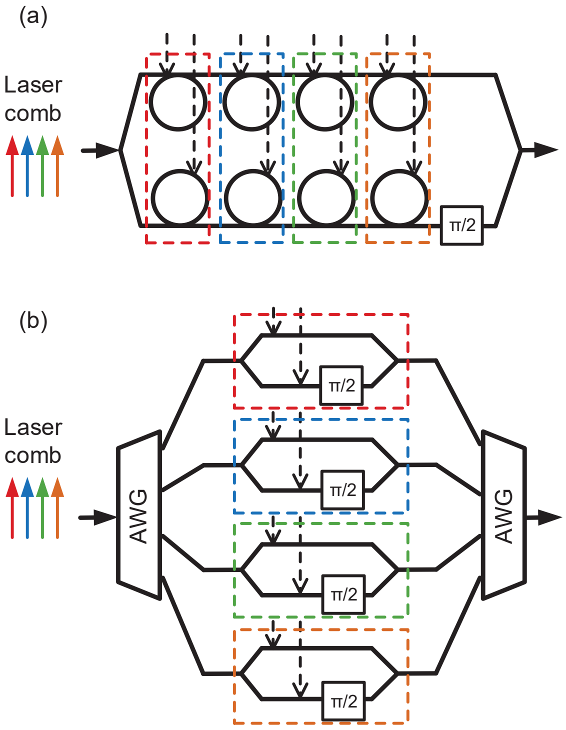


Fig. 4. Comparison of (a) MRM-based OLT; (b) MZM-based OLT.

shift for SSB modulation. In comparison, Fig. 4(a) only needs one phase shift for all the WDM channels, since the phase shift of all WDM channels in C-band (1535 nm to 1565 nm, 30 nm span) is only 2% different. Moreover, because of the large footprint of MZM compared to MRM (mm to μm), the MZM not only has greater loss, and the power consumption is also several orders of magnitude higher (picojoule vs. femtojoule) [12]. All these differences make OLT with CLS-MRM a promising candidate for an optical access network.

B. Smart edge

The remote node (RN) in a traditional optical access network, for instance, passive optical network, is located where the trunk fiber branches to subscribers. In WDM-OAN, it usually includes an AWG to split and direct WDM channels to destinations. It is updated to a smart edge (SE), by not only housing MEC server and CoMP controller as shown in Fig. 2, but also providing physical channels to transport radio signal to the CoMP.

The SiP subsystem for smart edge is depicted by Fig. 3 second column. Like the RN in some OAN variations, the smart edge is activated by introducing modulators. In light of this, optical amplifiers such as erbium-doped fiber amplifier could also be employed to compensate the transmission loss.

As illustrated in the second column of Fig. 3, the bus waveguide has been equipped with groups of MRM, each group of which works in one WDM channel. Thanks to the wavelength selectivity, an MRM only modulates the optical signal in its working spectrum, not only among WDM channels, but also within each WDM channel.

Each group of MRM, for one WDM channel, consists of three MRMs. In the spectrum of one WDM channel, there is an optical carrier and a broadband optical signal as the downlink service. Driven by a clock signal, the first MRM modulates the optical carrier to generate two subcarriers, without significant interference to the broadband optical signal. The second and the third MRM modulates the two optical subcarriers with two independent 5G services that are initiated by the MEC and/or CoMP. The same process also happens in other WDM channels. In this way, physical channels supporting 5G services is constructed.

Such dedicated physical channels, or tunnels, provide high-bandwidth and low latency for 5G services such as smart transportation, virtual reality and so on. Chip fabrication and experimental demonstration has been reported in [13]. An alternative scheme directly modulates the optical carrier with 5G services in intermediate or radio frequency. The receiving of broadband and 5G services both rely on the central carrier at ONU, as reported in [14].

The usage of optical carrier in such a frame work is three-fold: the modulation of the downlink broadband signal, the overlay of 5G service, and the carrier reuse at ONU for uplink modulation. In [14] we report the carrier allocation among these services, and reveal that more than 60% of the optical carrier can be left for uplink remodulation, even after the drop of both broadband and 5G services.

One problem in the operation of MRM is its resonance drift, along with ambient temperature or self-heating. In [14] we design a monitoring photodiode (MPD) at the drop port of MRM, to follow and stabilize the resonance of MRM.

C. ONU

The implementation of SiP at ONU is illustrated in column three of Fig. 3. After the demultiplexing at the smart edge, only one WDM channel is fed to an ONU. Cascaded microring resonator filters (MRR) are used to demultiplex the optical broadband services, as well as the two 5G services overlaid in the same wavelength channel. The MRR profiles are sketched in the spectra.

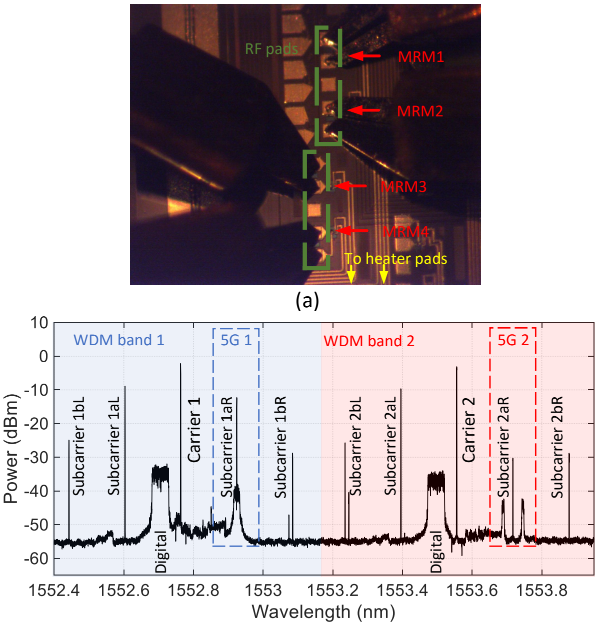
While the drop of 5G services filters out both 5G service signals and subcarriers, the drop of the broadband signal still leaves a portion of the main carrier, to be reused for the uplink service modulation. This excludes the necessity of laser sources at ONU, and enables a totally colorless ONU without need of a laser, for a significant cost reduction. An IQ MRM modulates the uplink signal to the unoccupied sideband, left fallow by the downlink broadband signal. This is an efficient way of avoiding Rayleigh backscattering interference.

As has been introduced in the last subsection, the carrier allocation should be carefully designed to both detect the broadband/5G signals, and modulate the uplink signal. The carrier drop ratio is changed by the design of both the profile and the central wavelength of each MRR. While the reported residual carrier percentage in [14], more than 60%, is sufficient to be reused to modulate the uplink signal, and for the uplink signal recovery with direct detection, it is also possible to be detected in the central office with coherent detection, because of the availability of laser source in the central office.

V. EXPERIMENTAL DEMONSTRATIONS TO DATE

A. *RoF at the smart edge*

We have conducted several experiments [13], [14] to establish the viability or our approach to a SiP enabled smart edge. We have focused on overlay of analog RoF on broadband OFDM PON signals. For instance, in [13] we intercepted the downlink digital wideband signals at the smart edge and add 5G signals. We used cascaded modulators that we designed and had fabricated. The photo in Fig. 5(a)) show the chip with a dedicated subsystem to produce the overlay spectrum that was recorded and is presented in Fig. 5(b). Note that this spectrum corresponds to the point G in Fig. 3. We have included two WDM bands at 100 GHz separation .



(a)

(b)

Fig. 5. (a) Smart edge subsystem fabricated chip and (b) measured WDM overlay spectra generated experimentally by the chip.

The wideband OFDM signals carried 14 Gb/s QPSK. We studied the MRM bias and heating conditions for good subcarrier generation. MRM1 generates two subcarriers in the first WDM band at 20 GHz separation. MRM2 modulates one subcarrier with narrow band (RF) baseband OFDM signal. Note that it could be upshifted to the 5G carrier frequency at the antenna site. We thermally tune MRM3 and MRM4 to achieve WDM operation. The 5G signal is in passband on a 3 GHz wireless carrier. All ONU functions were emulated via a real-time oscilloscope and offline processing.We experimentally validated the successful coexistence of both types of 5G signals (baseband and passband) with the broadband signal.

B. *Detecting RoF and downlink traffic separately*

We have also performed several demonstrations for the SiP enabled ONU [15]–[17] In [17] we reported a receiver for the customer premises that separated and independently detected the wideband digital signals and the 5G RF signals. Again we used chips we designed and had fabricated. the SiP chip shown . The chip is shown in Fig. 6. It encompasses the ONU subsystem that we described in the previous section. The spectral allocations are shown in Fig. 3. The photo is dominated by the large RF pads, but the MRR, MRMs and photodiodes (PDs) are quite small. The MRM design is shown as an inset.

Recall that the remote node combines the digital broadband and analog RoF signals on one WDM channel. We used a signal generator to create these combined signals. We prepared five 125 MHz RF signals spaced at 250 MHz in addition to the OFDM (orthogonal frequency division multiplexed) signal at 16 Gb/s.

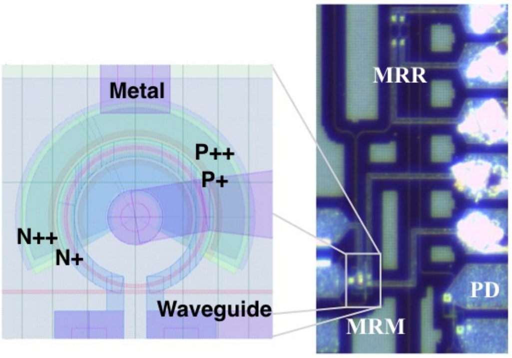


Fig. 6. Photo of fabricated ONU SiP subsystem (right) with an inset (left) showing the top view of our microring modulator design

We were able to successfully detected the analog RoF as well as the broadband digital signal. Our bit error rate (BER) remained below the typical 7% forward error correction (FEC) threshold. We were especially careful to preserve carrier power of the uplink remodulation. Our analog RoF reception on reduced the received carrier by 4 dB. For the broadband detection we were able to use a small additional reduction of 2 dB o, and carrier was remodulated and successfully detected. The uplink signal was 13 dB above any residual downlink signals.

VI. CONCLUSION

We can merge 5G fronthaul and broadband WDM signals in a new optical access network. The classic PON tree hierarchy, distributed carrier, remote nodes, etc. are conserved. The network is no longer passive as we upgrade the remote node to a smart edge. The smart edge accomplishes the division of local vs. remote (cloud) processing. It is also a physical structure than can house 5G digital signal processing with commodity equipment.

We examined access networks compatible with WDM. We focused on integrated SiP solutions that are inherently small, microring resonator structures. We see the many functions in the proposed architecture that can benefit from MRRs and MRMs. Finally we cited current research examining their capabilities for this application, and where current research questions remain.

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