Low Complexity FDM/FDMA Approach for Future PON

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Abstract: FDMA PON allows the ONU complexity and cost to be tailored to the service level targeted per customer while achieving high per wavelength throughput (35-39Gbps downlink).

1. Introduction

In the future, Passive Optical Networks (PON) shall provide a universal sustained connectivity to end users in the Gbps range. For instance, NG-PON2 targets a capacity of 40 Gbps downlink and 10 Gbps uplink per feeder shared between 64 and 1000 users, with a passive reach of 20 to 40 km [1]. From the operator’s point of view, these future systems shall be able to coexist with older generations of systems and consequently shall be able to operate over a strictly power splitter based optical distribution network and over the remaining narrow optical bands which are still available. As a result, it seems very relevant to use Wavelength Division Multiplexing (WDM) in combination with another per wavelength shared access mechanism such as for instance Time Domain Multiplexing and Multiple Access (TDMA/TDMA) [2] which has been selected for NG-PON2 [3] or Orthogonal Frequency Division Multiplexing and Multiple Access (OFDM/OFDMA) [4]. However, in such solutions, there is an increased discrepancy between the data rate that users are allowed to transmit at in average (~1Gbps) and the line rate at which they must transmit (~10 to 40 Gbps) which is source of cost and large power consumption. Furthermore, considering that, as Fiber To The Home (FTTH) becomes more and more adopted, there is a need to offer economically suitable solutions to users that are not as bandwidth hungry than the early adopters. Indeed, operators are looking to decommission completely the copper local loop in the future [5,6] and thus are eager to find solutions to shift even the most basic customers (e.g. telephone only service) to the optical local loop. A “one size fits all” ONU may not be economically viable in the long term, on the contrary, it will be necessary in the future to design different classes of ONUs for different classes of services. We are thus looking for a solution that can adapt in a simple manner the amount of processing and minimize the required bandwidth to be used at the ONU side while maintaining a large aggregated throughput per wavelength in order to spare the spectral occupation. As a result, we have proposed a dual-wavelength FDM/FDMA scheme that can provide some significant simplification over WDM-TDMA and -OFDMA. In previous papers [7], we have proposed a polarization independent reflective Mach-Zender Modulator (R-MZM) capable of providing optical carrier suppression modulation which is suitable for single wavelength FDMA in the uplink direction of PONs. By using such technique, the ONU could be realized completely in Silicon Photonics, integrating CMOS/BiCMOS electronics thus reducing considerably its cost and making it suitable for a mass market such as the Optical Access one. But, also, FDM/FDMA can be a very interesting alternative as it removes the need for burst mode operation and also decreases significantly the wavelength definition and bandwidth of the electronic stages required in the Optical Network Unit (ONU) thus reducing its complexity, cost and power consumption.

On the way to demonstrating the potential of an FDM/FDMA PON, we have previously reported on the operation of the R-MZM, proved an uplink capacity of 16 to 20 Gbps over a class B+ 64 split Optical Distribution Network (ODN) with only 500 MHz of bandwidth maximum per user and also reported on the potential to realize the ONU fully in Silicon [7]. We will, in this paper, report our experimental results for the downlink (currently 35 to 39 Gbps) then show our initial results towards the development of a full Silicon integrated R-MZM.

2. Downlink experimental results

Our experimental test bed for downlink performance evaluation is represented on figure 1.
A Distributed Feed-Back (DFB) laser at 1.5µm emitting +9dBm of continuous optical power is externally modulated by a MZM biased at quadrature. The modulating signal is generated by the Downstream Transmitter (DS TX) and is a broadband signal whose spectrum extends from 300MHz to 12GHz. In the experiment, this signal contains two parts. The first one is a reference signal with 250MHz of bandwidth and QPSK modulation that is used for performance evaluation and that represents the downstream traffic for a particular user. Its center frequency $f_{\text{user}}$ is varied from 300MHz to 12GHz. Around this user signal, a complementary signal is produced to cover the rest of the RF band and to represent the traffic destined to the other PON users. A frequency guard band of 15MHz is maintained between the two to avoid crosstalk. The power spectral density (PSD) of the user and complementary signals are equal in order to probe the system performance versus frequency while simulating the presence of the other traffic channels. When $f_{\text{user}}$ is below 5GHz, the complete modulating signal is produced by an Arbitrary Waveform Generator working at 10GS/s. The image signal (above 5GHz) is not filtered out but is used to create the complementary signal above the Nyquist frequency. Due to the RF bandwidth of the AWG output, this signal has rapidly decreasing amplitude and disappears completely under the noise above frequencies of 15GHz. When $f_{\text{user}}$ is above 5GHz, we use a dual output 1GS/s AWG along with an IQ mixer and Local Oscillator (LO) to create the user signal. In this case, the complementary signal is created by the 10GS/s AWG followed by an up-conversion mixer fed with an LO at 8.5GHz. In such a way, it is possible to generate a clean user signal while, at the same time, produce a complementary signal with a correct strength to match the PSD of the user signal up to frequencies of 12GHz. After being modulated, the optical signal is amplified to +10dBm by an Erbium Doped Fiber Amplifier (EDFA) and launched into 20km of Standard Single Mode Fiber (SMF) followed by a Variable Optical Attenuator (VOA) that mimics the PON network. In the ONU, a PIN-TIA photo receiver with around 7GHz of electrical bandwidth is used. When $f_{\text{user}}$ is below 6GHz, the photo-detected signal is captured by a Tektronix oscilloscope (MDO4000) containing an RF down-conversion stage and a dual 2.5GS/s Analogue to Digital Converter (ADC). When $f_{\text{user}}$ is above 6GHz, a sampling oscilloscope with an ADC operating at 40 GS/s is used.

We measure the Error Vector Magnitude (EVM) of the user signal versus $f_{\text{user}}$ and the Optical Budget (OB, ranging from 13 dB to 28dB – example of result given on figure 2 left). From these results and for a target Bit Error Rate (BER) of $10^{-3}$, we can determine [7] the overall system capacity for a set of $N$ users connected to the PON (represented by a random choice of $N$ OB values, $OB_{\text{user},n}$) to which we have allocated an adequate frequency $f_{\text{user},n}$, bandwidth $P_{\text{user},n}$ power $P_{\text{user},n}$ and modulation level $M_{\text{user},n}$ with $n\in[1,N]$. The random choice of OB follows the statistics of the field deployed data (mean of 21 dB and standard deviation of 2 dB – Figure 2 center). By repeating this OB random choices and allocation processes we can derive the overall system capacity and find it around 35 to 39Gbps (figure 2 right). The mechanism by which, from a random choice of OB, an optimal set of allocated parameters is found is crucial to maximize the expected capacity of the system.

![Fig. 1: downlink experimental set-up.](image)

![Fig. 2: Left; SNR (=1/EVM) versus MZM RF drive power for OB of 13, 20 and 28dB at $f_{\text{user}}$=5GHz. Center: random distribution of the OB seen by 4800 typical PON users. Right: capacity aggregated on one DS wavelength for each individual random choice of OB.](image)

### 3. Silicon MZM initial results

In this section, we will report on our first progress towards the realization of the ONU fully on CMOS-Photonics technology platforms that was initiated in [7] and that would allow a tight integration with Bi-CMOS/CMOS electronic drivers, with the benefit of mass-manufacturability. The photonic circuit mainly makes use of a mature Germanium-on-Silicon photo-detector as a receiver for the downstream transmission and a full Silicon R-MZM as the emitter for the upstream direction. Focusing on the R-MZM whose description can be found in [7], mainly based on a 2D surface grating coupler [8] and a Silicon modulator, several tradeoffs are to be made. We will detail below the electrode length tradeoff for the MZM.

We fabricated two MZMs made of two branches each made with a Traveling Wave (TW) phase modulation electrode with length $L_{\text{el}}$ being either 1mm or 3.5mm. In our scheme, where the MZM is used in a bi-directional fashion, one can show that the overall amplitude modulation efficiency of the R-MZM is proportional to the
difference between the co-propagating and counter-propagating phase modulation efficiencies. The frequency band over which a R-MZM is usable (with sufficiently high modulation efficiency), will thus be limited, in the low frequency range, by the fact that the counter-propagating modulation efficiency is high at low frequencies (long RF wavelength compared to $L_{ed}$) and, in the high frequency range, by the fact that the co-propagation modulation efficiency decreases with increasing frequency due to the velocity mismatch between the optical and radio waves and also mainly because of increasing RF loss. Figure 3 shows the measured co and counter-propagating relative modulation efficiencies for the two Silicon MZM with $L_{ed}$ of 1mm (left) and 3.5mm (center). As a comparison, the same measurements are reported for a commercially available LiNbO$_3$ modulator ($L_{ed}$ of 38mm – right).

As can be seen on figure 3 left, for short electrodes (1mm), the overall usable bandwidth for the Silicon R-MZM is shifted towards higher frequencies but the difference between the co and counter-propagating efficiencies remains low (< 2dB over DC to 25GHz). For a longer $L_{ed}$ (3.5mm – center) the contrast between co and counter modulation efficiencies is high (> 3dB) from 3GHz onwards. Compared to a LiNbO$_3$ MZM (left) where the contrast is greater than 3dB from 800MHz onwards, the usable bandwidth remains comparable as the roll off of the co-propagating efficiency is lower at high frequencies for the Silicon MZM. Some tradeoff will anyway have to be found in order to guarantee the 7 GHz of bandwidth necessary to achieve an overall uplink capacity of 20 Gbps [7].

4. Conclusion
In this paper, we have completed the description of our proposed FDMA PON system including the experimental measurement of the PON’s downlink capacity, namely 35-39 Gbps, and presented some initial results regarding Silicon MZM for use as reflective MZM in the FDMA PON architecture. Along with our previous demonstrations of 16-20Gbps uplink capacity and potential for full Silicon integration of the ONU, we aim at showing that FDMA PON represents a way to respond to the evolving broadband access needs while providing different classes of customer service for universal optical access without compromising the cost and complexity of the ONU.

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6. References