Digital Optical Physical-Layer Network Coding for mm-wave Radio-over-Fiber signals in Fiber-Wireless Networks

Charoula Mitsolidou, Christos Vagionas, Student Member, IEEE, Kostas Ramantas, Dimitris Tsiokos, Amalia Miliou and Nikos Pleros, Member, IEEE

Abstract—We demonstrate a digital Optical Physical-layer Network Coding (OPNC) for mm-wave fiber-wireless signals modulated with up to 2.5 Gb/s On/OFF Keyed (OOK) data. The proposed OPNC concept uses an all-optical XOR gate comprising a Semiconductor Optical Amplifier-Mach Zehnder Interferometer (SOA-MZI) with SOAs being driven at low moderate electrical currents in order to perform the all-optical encoding between the OOK envelopes of the data, ignoring the high-frequency Sub-Carrier (SC) signal. In this scheme, network coding is performed on-the-fly at the Central Office (CO) and the resultant packet is broadcasted at the client nodes, where the decoding takes place. We demonstrate experimental results of OPNC using OOK data signals modulated on a 10GHz SC with the aid of a second all-optical XOR gate for the decoding process at the client’s site, reporting error-free performance for both synchronous/asynchronous data packets. The scenario of all optical encoding for 60GHz SC frequencies followed by electrical decoding at the end-users is evaluated via PHY-layer simulations. Going a step further and considering the network level, we present a performance improvement on the network throughput by using the proposed NC.

Index Terms—cross phase modulation, fiber wireless networks, millimeter wave communication, optical physical-layer network coding (PNC), Radio over Fiber (ROF), semiconductor optical amplifier-Mach Zehnder interferometers (SOA-MZI)

I. INTRODUCTION

The explosive growth of bandwidth-hungry applications, in combination with the evolution in the mobile connectivity, have created the need for higher capacity wireless access networks at Gb/s scales [1],[2]. Fiber Wireless (FiWi) networks have recently stepped in as a promising solution that would satisfy this requirement by seamlessly converging the ubiquity and mobility of the "last-meter" wireless networks with the high-capacity of optical access networks [3],[4], making remarkable steps mainly in the field of Radio-over-Fiber (RoF). RoF technology has managed to demonstrate several signal generation schemes, transmission demonstrations [5] and also more advanced functionalities related to end-user mobility, hand-off [6],[7] and recently to Network Coding (NC) [8]-[10]. NC has been proposed as the means to increase network throughput, reliability and security, by improving the capacity resource utilization and enabling bidirectional data transport [11].

Although NC has been under recent research focus, it has been demonstrated separately for wireless communications networks [12] or Passive Optical Networks (PONs) [13]-[15]. Regarding wireless networks, NC has relied on conventional electronic processing of the wireless data-packets at the relay at a higher application layer [12]. Similarly in PONs the optical signal is converted to electrical signal before encoding operation is performed at higher network layers introducing further complexity at the Central Office (CO) and additional latencies to the overall communication. RoF technology was introduced as the technology that can merge wireless and optical functionalities via Remote Antenna Units (RAUs) to deliver seamless end-to-end communication between the wireless user and the CO in an optical-wireless PON configuration. To fully comply with the requirements imposed by the trend of optical-wireless convergence, RoF-based PONs should be able to implement unified NC between the optical network and the wireless user. In parallel, concepts satisfying the above requirement are expected to relax CO complexity and enhance overall network efficiency when implemented directly in the optical domain at the CO side. However, till now most of the PHY-layer optical NC (ONC) demonstrations have relied only on simple optical modulation formats, such as On-Off Keying (OOK) and Differential Phase Shift Keying (DPSK) signals, targeting application in telecommunication links or wired PONs [16]-[18].

In parallel, only a limited number of PHY-layer ONC demonstrations offer compatibility with RoF, targeting to overcome the bottleneck of optoelectronic conversion of conventional electronic NC at the relay. These demonstrations utilize orthogonal polarization multiplexing and optical power addition [8]-[10], yet favoring analog PHY NC in order to
cope with the increased NC complexity associated with RoF signals. Recently, we demonstrated the first digital ONC scheme capable to handle the complexity of SCM-On/Off Keyed (OOK) signals, using a SOA-MZI as an all-optical XOR encoder suitable for on-the-fly encoding at the CO [19].

In this paper, we extend our previous work by evaluating the performance of the OPNC scheme in a complete optical link for up to 2.5 Gb/s OOK data modulated over a 10 GHz SC. Our experimental setup uses a SOA-MZI XOR gate as the CO encoder between two SCM-OOK data streams, exploiting the low-pass filtering response of a SOA-MZI [20] in order to process the data envelope while discarding the 10 GHz SC. For validation purposes, the optical encoding operation is further evaluated by deploying a second MZI-XOR gate to decode the signal and retrieve the original information. We also extend the same encoding concept in a 60 GHz SC to encode information coming from users located in different cells, which is not feasible with current wireless NC. While normally an electronic decoding process would be adequate at the user and since such a circuit was not available at our lab, we used a second optical XOR gate instead for carrying out the decoding.

Fig. 1(c), (d) depict the frame scheduling without NC and the proposed OPNC-based scheduling, respectively. In both cases, each RAU transmits the uplink data on a different wavelength utilizing wavelength division multiplexing (WDM), while the CO uses only one wavelength for the downlink traffic. As shown in Fig. 1(c), when no NC is applied, Users A, B transmit their packet to the CO during the first timeslot. In turn, the CO forwards packet from User B to A and packet A to User B in two successive time slots over the same wavelength. In this way, a total number of three time slots is needed for a complete session. On the other hand, by utilizing the OPNC, the two packets reaching the CO are encoded through an all-optical XOR gate and the resultant packet is broadcasted in the same time slot to both users, reducing the timeslots for a single bilateral communication, from three to two. This concept assumes frame-level synchronization, where each packet may include preamble and postamble in the leading and trailing part of the packet [23].

Fig. 2(a) shows the encoding and decoding operation for: (a) synchronous and (b) asynchronous data with a time offset of a sub-bit delay Δt. The rest of the paper is organized as follows: Section II describes the proposed OPNC scheme, Section III presents the experimental setup and results, while Section IV presents the PHY-layer simulations at 60 GHz. Network throughput enhancements and a power budget study are included in Section V, while conclusions are addressed in Section VI.

II. CONCEPT OVERVIEW

Fig. 1(a),(b) opposes the proposed ONC scheme in a RoF optical wireless networks and a wireless network with conventional electrical NC performed, respectively. In Fig. 1(b) User A and B transmit their data to a router, which in turn performs an electronic XOR-NC operation at the relay and broadcasts the XOR-ed packet. Fig. 1(a) also illustrates the proposed OPNC-based RoF network, comprising the NC unit at the CO and the two hypothetical wireless end-users connected with the respective RAUs. In this case, user A, B transmit wirelessly their packet to the RAUs, where they are converted from electrical-to-optical (e/o) data streams through the modulation of a Laser Diode (LD). The SCM optical signal from both User A, B are coupled together and sent to the CO through the optical fiber for an all-optical on-the-fly XOR-NC operation. The encoded packet is broadcasted back to both RAUs, de-multiplexed from the uplink traffic and converted from optical-to-electrical (o/e) by means of a photodiode (PD). In this way, we propose an ONC technique at the CO, capable to encode information coming from users located in different cells, and since such a circuit was not available at our lab, we used a second optical XOR gate instead for carrying out the decoding.

Fig. 2(b) illustrates the concept of encoding and decoding operation for: (a) synchronous and (b) asynchronous data with a time offset of a sub-bit delay Δt.
data. Fig. 2(b) depicts the asynchronous encoding and decoding, where a sub-bit time delay of $\Delta t$ is induced for Data B. As it is marked in the encoded data packet, a short optical pulse with duration equal to $\Delta t$ is generated. However, the final decoded packets from the second XOR operation can still be correctly recovered by both end users through a second XOR operation, without any data loss, showing similar performance for the asynchronous functionality of the OPNC.

III. EXPERIMENTAL DEMONSTRATION

A. Experimental Setup

Fig. 3 shows the experimental configuration, exploiting two SOA-MZI gates, the first for the encoding process at the CO and the second for the decoding XOR operation that in realistic RoF is performed at the end-user. The Continuous Wave (CW) signals at $\lambda_1=1549.8$ nm, $\lambda_2=1553.1$ nm and $\lambda_3=1553.6$ nm were emitted by three Tunable LDs (TLDs), multiplexed by an Array Waveguide Grating (AWG) and modulated by an electro-absorption modulator (EAM) by a 10 GHz electrical clock signal for the SC generation. The output of the EAM was amplified by an Erbium Doped Fiber Amplifier (EDFA) and de-multiplexed by means of an AWG. Signals $\lambda_1$ and $\lambda_2$ were further OOK-modulated by two LiNbO$_3$ modulators, which were driven by a programmable pattern generator (PPG) loaded with a 1Gb/s or 2.5 Gb/s NRZ 2$^7$-1 Pseudo Random Bit Sequence (PRBS), so as to form the SCM OOK uplink Data A and B signals, that in principle are e/o converted at the RAU as it is shown in Fig.1(a). These uplink signals were transmitted through spools of Single Mode Fibers (SMF) with lengths of 3.9 km and 4 km, emulating the uplink connections between the RAUs and CO. An Optical Delay Line (ODL) was employed at the branch carrying the Data B stream, in order to enable bit-level synchronization during synchronous operation and insert time offsets at the asynchronous operation. Stream $\lambda_3$ was not modulated with data in order to emulate the SC produced at the CO and used for the downlink traffic. Variable Optical Attenuators (VOAs) and Polarization Controllers (PCs) were also employed for power regulation and polarization adjustments, respectively.

The data streams ($\lambda_1$-$\lambda_2$) were injected into the control ports A, D, while $\lambda_3$-SC was applied at the port C of the SOA-MZI1. The input power levels were measured 800μW(-1dBm) for $\lambda_1$, $\lambda_2$ and 400μW(-4dBm) for $\lambda_3$. The SOA-MZI was biased in such a way so that Port G acts as the switching port. Hence, when only one of the two data is present, a $\pi$-shift between the two SOA-MZI branch signal constituents is obtained by cross-phase modulation (XPM) and $\lambda_3$ emerges with a logical "1" at the output port G. Otherwise, when both data signals are equal, then $\lambda_3$ bears a logical "0", confirming the implementation of an all-optical XOR gate by means of a SOA-MZI. The output port of the first XOR encoding gate was filtered and launched into port D of the second SOA-MZI XOR gate, which acts as a decoder. A part of Data A was connected with Port A for decoding Data B, while a CW signal launches Port C ($\lambda_4=1548.4$nm). Equivalently, when Data A is decoded, Data B is connected to Port A of the second SOA-MZI. The input power levels were measured -1dBm for the control signals $\lambda_1$,$\lambda_3$ and -4dBm for $\lambda_4$. SMF and ODL were used for pattern and bit-level synchronization. The output of the XOR2 gate was filtered by a 0.65 nm filter and monitored by an optical sampling oscilloscope (OSC).

The SOA-MZIs featured two 1600 μm long hybridly integrated SOAs, both operating at moderate current values of 160 mA and 180 mA for data rates of 1 Gb/s and 2.5 Gb/s, respectively. The SOA gain recovery values at driving conditions were 200 ps and 180 ps, respectively for both SOA-MZI XOR gates, significantly longer than the 100 ps period of the SC signal. In this way, the SOA-MZI response of the both XOR gate, is turned into a low-pass filtering [20] so as to neglect the 10 GHz SC of the optical control Data A, B signals, while still allowing the SOA gain and phase characteristics to successfully respond to the changes induced by the lower-rateOOK data envelope.

B. Synchronous Operation

Fig. 4 illustrates the experimental results obtained for the synchronous encoding and decoding operations between two 1 Gb/s data streams. Fig. 4(a), (b) show the input traces of Data A and B, while Fig. 4(c) depicts the XOR stream at the output of the first SOA-MZI. The encoded stream featured a logical "1", only when Data A and B featured different logical values, while it is equal to "0" when the two data have the same logical value. Fig. 4(d), (e) depict the decoded Data A and B at
the output of the second SOA-MZI, after the XOR operation between the encoded signal and either the Data B or Data A, respectively. As it is shown, the decoded streams featured sub-bit dips between successive "1"s, resulting from the XOR operation when logical "1"s generated by the transition from differential phase $+\pi$ between the SOA-MZI branches to $-\pi$.

However, the initial data patterns were retrieved successfully, confirming the successful operation of the overall experimental circuit. Fig. 4(f), (g) show the eye diagrams of SCM input Data A and B, while Fig. 4(h) the output XOR signal, revealing an Extinction Ratio (ER) of 10 dB and an Amplitude Modulation (AM) of 0.45 dB. Eye opening with an ER of 8.5 dB and an AM of 1.1 dB was also obtained for the decoded Data A and B in Fig. 4(i), (j), respectively.

Similarly, Fig. 5 depicts the synchronous operation for 2.5 Gb/s data signals. Fig. 5(a), (b) show the input time traces of Data A and B, while the XOR stream is shown in Fig. 5(c). Fig. 5(d), (e) illustrate the decoded Data A and B, confirming the successful decoded process also for 2.5 Gb/s data rates. Fig. 5(f), (g) show the eye diagrams of OOK-SCM Data A and B, while Fig. 5(h) represents the eye diagram of the XOR signal at the output of the first SOA-MZI. It reveals an ER of 9.6 dB and an AM of 0.5dB. The eye diagrams of decoded Data A, B, shown in Fig. 5 (i),(j), exhibit an ER equal to 8.2 dB and an AM of 1.2 dB, with the dips at the beginning of the bit-pulses appearing as jitter of the rise time.

The successful encoding and decoding operations were also verified with the aid of Bit Error Rate (BER) measurements. Fig. 6(a) and (b) show the BER curves carried out at various stages of the system, for 1 Gb/s and 2.5 Gb/s data streams respectively. Both data rates show error free operation after the decoding and down-conversion performed by the SOA-MZI2. The power penalties for the decoded Data A and B with respect to the initial OOK data at 10$^{-9}$ are equal to 3 dB and 3.2 dB for 1 Gb/s and 2.5 Gb/s data, respectively, implying similar performance of the proposed circuit for the two different data rates. This is partially attributed to the SC modulation of the Data A, B, which introduces a power penalty of 1.7 dB for 1 Gb/s data and 2 dB for 2.5 Gb/s, respectively. BER curves for the encoded XOR stream exiting the first SOA-MZI, were also carried out for two cases: 1) when the SCM-DATA are inserted into the encoder without the use of extra fiber and 2) when fiber spools are inserted between the SCM-DATA and the first XOR gate in order to emulate the uplink connection. The power penalty between these two BER curves is negligible. As it can be seen in Fig. 6(a), by comparing the XOR curves with the OOK SCM data, the power penalty at 10$^{-9}$ is approximately 0.5 dB. Similarly, the XOR signals in Fig. 6(b) exhibit a power penalty of 0.7 dB.

C. Asynchronous Operation

Possible asynchrony between the two data streams reaching the encoding unit, was also examined by introducing various sub-bit temporal delays at Data B, as may potentially be introduced by mobile users. Fig. 7 shows the experimental time traces of the encoding and decoding operation using sub-bit delays of 0.25 bit (250 ps) and 0.5 bit (500ps) for 1 Gb/s data signals. Fig. 7(a), (b) depict the input traces of Data A and Data B delayed by 0.25 bit, while Fig. 7(c) shows the resultant XOR trace. The data asynchrony generates short "parasitic" pulses of 0.25 bit duration at the encoded XOR stream. Despite those occurrences, by performing a second XOR operation between the encoded XOR and the delayed Data B, the trace of the decoded Data A can be successfully retrieved, as shown in Fig. 7(d). Similarly, in Fig. 7(e) Data B was also correctly decoded by the XOR operation between the encoded stream and Data A, after a time delay of 0.25 bit duration. Fig. 7(f)-(j) illustrate the respective time traces for a 0.5 bit offset. As shown in Fig. 7(j) the decoded Data B was successfully retrieved with a delay of 0.5 bit.

![Fig. 5. Experimental results for 2.5 Gb/s data. Traces (400 ps/div): (a) Data A, (b) Data B, (c) encoded XOR signal, (d) decoded Data A and (e) Data B and (f)-(j) respective eye diagrams (80 ps/div).](image-url)

![Fig. 6. BER curves for: the OOK Data without SC, the SC modulated-OOK Data, the encoded XOR with and without fiber spools after the Users and the decoded output OOK data for: a) 1 Gb/s and b) 2.5 Gb/s data rates.](image-url)

![Fig. 7. Experimental time traces of asynchronous 1Gb/s operation for two different time offsets. Time traces (1 ns/div): a) Data A, b) Data B delayed by 0.25 bit, c) encoded XOR signal, d) decoded Data A, e) Data B. For 0.5 time offset: f) Data A, g) Data B delayed by 0.5 bit, h) encoded XOR signal, i) decoded Data A, j)Data B. Magnified insets highlight time offset.](image-url)
The principle of operation of our OPNC module relies on lowering the speed characteristics of the SOA-MZI-XOR unit in order to turn the SOA gain and phase characteristics insensitive to the high-speed SC, while still retaining their sensitivity to the lower-speed data envelope. This principle therefore suggests that the application of the proposed OPNC module may be extended to signals with higher SC frequencies including 60 GHz. In this context, the suitability of the OPNC scheme was verified for 60 GHz Wi-Fi networks by carrying out PHY-layer simulations with the aid of VPI Photonics software relying on a custom-made SOA-MZI model that follows closely the experimental behavior of the SOA and has been described in [24]. In the simulations, a 60 GHz SC was employed, while electrical decoding was applied in order to emulate the decoding unit that in principle performed at the wireless end user. Fig. 10(a) illustrates the simulation setup, consisting of a SOA-MZI that resides at the CO, performing an all-optical XOR encoding between the SCM OOK Data A and delayed by τ Data B. These Data come from Users A and B, respectively and transmitted by the RAU to the CO after the e/o conversion, that was performed by the modulation of a LD, as it is shown in Fig.1(a). The XOR-ed signal is transmitted back to the RAU comprising a Photodiode (PD) for o/e conversion, and an electrical Band Pass Filter (BPF) centered at 60 GHz. Then, the electrical signal was directed at the decoding stage (assuming a wireless transmission in between) that resides at the User, multiplied with a 60 GHz Local Oscillator (LO) for electrical down-conversion and inserted into a Low Pass Filter (LPF). The signal was decoded by an electrical XOR gate using a copy of the transmitted data.

Figs. 10(b), (c) summarize the time traces of the synchronous and asynchronous operation for data rates of 1 Gb/s and 2.5 Gb/s, respectively. In particular Fig. 10(b) shows from top to down, the Data A trace, Data B for 0, 0.25 and 0.5 bit time offsets and the successfully encoded XOR stream, where it is shown that a logical "1" is obtained when Data A and B have different logical values and a logical "0", if Data A and B are equal. Moreover, it shows the respective decoded Data A and B after the electrical XOR between the incoming encoded trace and a copy of the user Data B and A, respectively. The encoded XOR signal features an ER of 12 dB, implying a performance improvement at a high SC frequency. The green markers highlight that the short "parasitic" pulses generated at the encoded signal for sub-bit offsets of 0.25 and 0.5 bit. Once again, the simulation traces verify that the transmitted data can be retrieved successfully by the encoded XOR by both end users for synchronized and non-synchronized streams. Similar results were obtained also
for a data rate of 2.5 Gb/s, as shown in Fig. 10(c).

V. OPNC IN PASSIVE OPTICAL NETWORKS

A C++ based Network Level Simulator by IQUADRAT Informatica [25] was used to evaluate the enhancements that can be achieved with the OPNC module in a PON, where the GPON mechanisms have been adopted only in the MAC layer. All wavelengths used are allocated in the C-Band, supported by the OPNC module. Specifically a PON-based network was implemented, with 4 RAUs connected to a CO with a 15km feeder fiber and a passive splitter. Two wavelengths are employed for the uplink and one for the downlink traffic, denoted as $\lambda_1$ (1549.8 nm), $\lambda_2$ (1553.1 nm) and $\lambda_3$ (1553.6 nm) respectively, each of them using a rate of 1 Gb/s for data transmission. A Dynamic Bandwidth Allocation (DBA) algorithm is also employed to efficiently utilize the uplink capacity. The OPNC module, detailed in previous sections, was deployed at the CO as shown in Fig. 11. The OPNC module transmits the XORed packet at $\lambda_3$, which may also be used by the OLT for downlink transmission of data coming from the backhaul network to the RAUs. The decision about who will use $\lambda_3$ is dictated by the OLT. When two RAUs are signaled to exchange packets using the NC unit, they simultaneously transmit a packet and start receiving the coded packet after a delay equal to the Round Trip Time (RTT), at the downlink wavelength $\lambda_3$. It must be noted that an extra wavelength is required for inter-RAU communication, denoted as $\lambda_2$. A tunable laser is assumed at each RAU, which allows it to tune to $\lambda_1$ to transmit to the OLT and to either $\lambda_1$ or $\lambda_2$ to transmit to another ONU. Moreover the control plane of the OLT, that typically runs the DBA algorithm, is responsible for orchestrating the operation of the OLT and NC unit and the allocation of $\lambda_3$ to OLT or NC for downlink traffic, so as to avoid collisions in the optical downlink. Specifically, when a pair of RAUs exchange inter-ONU traffic, $\lambda_3$ is assigned to the NC. On the other hand, when the OLT forwards traffic from the backhaul network to one RAU, the NC unit should remain silent. To guarantee this, the NC module should turn on its laser only during inter-ONU communication, which can be signalled by the OLT.

It must be noted that if the half-duplex constraint applies at the wireless domain (i.e., RAUs and Users are not allowed to wirelessly transmit and receive at the same time), then for a bidirectional transmission, the data that can be exchanged in the proposed scheme is constrained by the bandwidth-delay product. For example, if we assume that in Fig. 11 both User A and B start exchanging packets, they should both stop transmitting after a time duration equal to the RTT (that is, when the first bit of the XORed packet arrives at the RAUs) to avoid collision at the wireless domain. However, even for a bidirectional inter-RAU communication the half-duplex constraint can be lifted with the Frequency-Division Duplexing (FDD) technique. FDD is a method for establishing full-duplex transmission at the wireless domain. When FDD is used, we assume both RAU and the wireless user employ equipment that transmits at two different frequencies, one dedicated for the downlink wireless traffic from the RAU to the User and the other for the uplink traffic (User to the RAU).

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When two RAUs are signaled to exchange packets using the NC unit, they simultaneously transmit a packet and start receiving the coded packet after a delay equal to the Round Trip Time (RTT), at the downlink wavelength $\lambda_3$. It must be noted that an extra wavelength is required for inter-RAU communication, denoted as $\lambda_2$. A tunable laser is assumed at each RAU, which allows it to tune to $\lambda_1$ to transmit to the OLT and to either $\lambda_1$ or $\lambda_2$ to transmit to another ONU. Moreover the control plane of the OLT, that typically runs the DBA algorithm, is responsible for orchestrating the operation of the OLT and NC unit and the allocation of $\lambda_3$ to OLT or NC for downlink traffic, so as to avoid collisions in the optical downlink. Specifically, when a pair of RAUs exchange inter-ONU traffic, $\lambda_3$ is assigned to the NC. On the other hand, when the OLT forwards traffic from the backhaul network to one RAU, the NC unit should remain silent. To guarantee this, the NC module should turn on its laser only during inter-ONU communication, which can be signalled by the OLT.

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We evaluate the performance of the proposed OPNC scheme, in a scenario where 4 RAUs need to communicate. To this end, the Status Reporting (SR)-DBA algorithm was employed to schedule transmission [26]. This algorithm runs at the OLT, and in each polling cycle collects bandwidth requests (Status Reports), from all RAUs. Then, each RAU or pair of RAUs is assigned a dynamic time slot based on these
Status Reports, following the max-min fair sharing technique. Poisson traffic is assumed, and the aggregate throughput is measured as the traffic load is varied. Both the throughput and the traffic load are normalized as a percentage of wavelength capacity. Two scenarios that employ all-optical NC and one using electrical NC are evaluated. In the half-duplex scenario, denoted as "optical NC-HD", two half-duplex constrained RAUs exchange packets. In the full-duplex scenario, denoted as "optical NC-FD", the half-duplex constraint is lifted such that a maximum of 2 Gb/s full-duplex capacity can be achieved. For reference, a baseline TDMA scheme for inter-ONU communication is evaluated, where the OLT is employed to forward the packets to their destination RAU. A conventional electrical digital NC scheme for PON networks was implemented [13]. As opposed to our OPNC scheme, in this scenario packets are transmitted sequentially to the CO, which performs a digital XOR operation of their contents in the electrical domain and broadcasts the coded packet.

Fig. 12 shows that NC can significantly enhance the performance of inter-ONU traffic. Electrical NC only increases the efficiency of the broadcast phase of inter-ONU communication, while in the upstream the RAUs still have to transmit their packets sequentially. This leads to a 25% performance gain. "Optical NC-HD" on the other hand can be almost twice as fast, as it also optimizes the upstream phase, where RAUs transmit their packets simultaneously. Finally, it can be seen that in scenarios of "optical NC-FD", all-optical NC can effectively double the available capacity.

VI. CONCLUSION

We have reported a novel Optical Physical-layer Network Coding scheme located at the CO of RoF based PONs. This scheme is capable of handling two SCM On/Off Keyed signals up to 2.5 Gb/s, assuming wireless-to-optical conversion at the RAU. A 10 GHz SC was used for the experimental demonstration and a 60 GHz SC for the PHY-layer simulations, while a SOA-MZI was employed as an all-optical XOR gate in order to perform the digital encoding process. For evaluation of the overall quality degradation of the optical infrastructure, a second XOR gate was employed as a decoder for retrieving the original data. The data were successfully decoded, achieving error-free operation at 10^{-9}. Finally, a network-layer analysis was presented, revealing network throughput enhancement by using the OPNC scenario in PON based network. The simulations were accompanied by a power budgets study, showing how an OPNC-enabled PON architecture can be scaled in terms of RAUs.

REFERENCES


