Digital Resolution Enhancer Employing Clipping for High-Speed Optical Transmission

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Abstract—Driven by the exponentially increasing demand for Internet traffic, single channel capacity in optical transmission systems continues to grow. Therefore, optical transmitter impairments such as low analog bandwidth, nonlinearities and digital-to-analog conversion with low resolution place a considerable burden on the system design. Methods aimed at compensating for the low transmitter bandwidth and transmitter nonlinearities have been introduced and recently, a digital resolution enhancer (DRE) which reduces the quantization noise added by a digital-to-analog converter (DAC) has been proposed. In this work, the interplay between DRE and clipping is introduced and studied. Experimental validation is performed by transmitting single channel 600 Gb/s 64-quadrature amplitude modulation (QAM) and wavelength-division multiplexing 460 Gb/s 128-QAM over 75 km of standard single-mode fiber. The combination of DRE and clipping allows the reduction of the DAC’s physical number of bits to 3, while still maintaining performance above the forward error correction (FEC) limit. Low resolution DACs will play an important role in the implementation of low-power transmitters generating high-cardinality modulation formats.

Index Terms—Amplitude clipping, digital resolution enhancer, digital to analog conversion, optical coherent transmission.

I. INTRODUCTION

In order to cater for the ever exponentially increasing Internet traffic demand [1], the optical transmission capacity has been increased by exploiting higher order modulation formats and novel constellation designs such as geometric shaping (GS) or probabilistic shaping (PS) [2], [3], as well as increasing the signal’s baud rate. This continues to place a considerable burden on the design of high speed electronics and the digital signal processing (DSP) techniques [4]. In the required digital-to-analog converters (DACs), radio frequency (RF) components, dual-polarization IQ-modulator (DP-IQM), and analog-to-digital converters (ADCs), limited analog bandwidth, distortions and non-linear performance adversely impacts the overall performance of the transmission system.

Particularly as 64-ary quadrature amplitude modulation (QAM) and higher order modulation formats emerge in transponder and transceiver products, digital pre-compensation (DPC) techniques have been proposed to enable low-end, low cost opto-electronics to be employed. In [5], a precompensation method to address the low electrical bandwidth of the transmitter components has been demonstrated. Digital precompensation for low analog bandwidth typically results in large peak-to-average power ratios (PAPRs), which places more stringent requirements on the DAC resolution. In [6]–[8] predistortion methods are introduced to compensate for the nonlinear responses of the transmitter components such as the RF amplifiers and DP-IQM.

In [9], [10], a digital pre-compensation technique which includes a dynamic quantisation approach, named digital resolution enhancer (DRE), was proposed. In that work, the effective DAC resolution is increased by shaping the DAC quantization noise. In other words, with a low physical number of bits (PNOB), higher order constellations can be generated in a regime where quantisation noise is the main contribution to the transmitter side noise [11]. In addition to the reduction of quantization noise using DRE, the quantization noise may be minimized by amplitude clipping of the transmitted signal. Clipping reduces the PAPR, resulting in lower quantization noise. While clipping results in lower quantization noise, it adds clipping noise to the signal and thus an optimum between quantization noise and clipping noise has to be found.

As for coherent transmission of polarization-division multiplexing (PDM) 16-QAM, digital-to-analog conversion is expected to consume already about 20% of the application-specific integrated circuit (ASIC) power [12] and is expected to increase when scaling to higher order modulation formats and higher baud rates. Reducing the required resolution of the DAC using DRE and clipping might contribute to low-power transceivers.

In this paper, we investigate the influence of clipping and the interplay between clipping noise and quantisation noise for enhancing normalized generalized mutual information (NGMI) while using DRE. Simulations of clipping combined with DRE are presented for DRE schemes with different complexities.
Experimental validation of this technique is carried out for single channel 64-QAM at 64 Gbd, which is used in commercial 600 Gb/s applications [13], [14], and for wavelength-division multiplexing (WDM) 128-QAM at 41.79 Gbd to show the performance of the technique in a 50 GHz spaced WDM system. The experiments are carried out over a typical data center interconnect (DCI) link of 75 km.

This work is an extension to the work presented during the European Conference on Optical Communications (ECOC) 2019 [15] and provides a more extended description of the employed DRE algorithm and provides additional simulation results to provide more insight into the clipping effects and the employed DRE schemes.

II. DIGITAL-TO-ANALOG CONVERSION

The DAC in an optical transmission setup converts a signal from the digital to the analog domain by quantizing the digital input samples to a limited set of analog output levels. The possible DAC output levels are usually uniformly spaced and the number of possible output levels is indicated by the number of bits the DAC uses. The number of output levels translates to the number of bits by taking the base two logarithm of the number of output levels.

Due to the limited number of output levels, the DAC adds quantization noise to the output signal. This quantization noise is usually modelled as uniformly distributed white noise [16] and the power of the quantization noise is given by

$$\sigma_q^2 = \frac{\Delta^2}{12}, \hspace{1cm} (1)$$

where $\Delta$ is the DAC output step size, defined as the maximum peak-to-peak amplitude of the input signal divided by the number of output levels. As can be seen from Eq. (1), increasing the number of bits of the DAC reduces the DAC output step size and thus the quantization noise power, resulting in a higher signal-to-noise ratio (SNR).

The number of bits of a DAC can be described by two parameters, namely by the PNOB and by the effective number of bits (ENOB). The PNOB indicates the nominal number of bits a DAC uses to reproduce the input signal, but is reduced to the ENOB due to other effects in addition to quantization, such as clock jitter and sampling effects inside the DAC [4]. The ENOB describes the number of bits an ideal DAC would have to get the same performance as the DAC which is impaired by effects like clock jitter [17]. In Fig. 1, the ENOB versus frequency of the Micram DACs used in this paper, which have a PNOB of 6 and a sample rate of 100 GSa/s, is depicted. As can be seen, the ENOB is reduced to about 5 and the ENOB is a function of frequency. More details on the DAC employed for this study can be found in [19].

III. DIGITAL RESOLUTION ENHANCER COMBINED WITH CLIPPING

This section presents a DRE combined with clipping which enhances the resolution of the DAC in the transmission setup.

First, the system model is introduced after which a DRE implementation based on [9], [10] is described and next, an extended version of the DRE employing clipping is presented.

A. Transmission System Model

A diagram of the transmission system model is given in Fig. 2. A DRE block is placed after the conventional transmitter DSP, which consists of mapping input bits to QAM symbols, pulse shaping, and pre-compensation for the linear bandwidth limitations of the transmitter components. The DRE quantizes the output samples coming from the transmitter DSP, denoted by $x(n)$, to $x_q(n)$. The quantized samples are converted from digital to analog by a DAC, the output of the DAC is amplified by RF amplifiers and is used to modulate a carrier wave using a DP-IQM. At the receiver, the optical signal is mixed with an local oscillator (LO) in a coherent receiver. Finally, after analog to digital conversion, matched filtering is performed to produce samples $y_q(n)$ which are used to recover the transmitted symbols.

When referring to the channel, the combination of the DACs, RF amplifiers, DP-IQM and coherent receiver is meant. Combining the response of the channel with the matched filter (MF) at the receiver forms the combined impulse response (CIR) $h(n)$.

B. Digital Resolution Enhancer

The DRE proposed in [10] shapes the spectrum of the quantization noise of the DACs inversely to the combined frequency response of the channel and the MF at the receiver. As a result, the quantization noise at low frequencies will be reduced, since the MF and channel have a low pass response due to the low analog bandwidth of the channel’s components. This occurs at the cost of increased quantization noise at high frequencies, where the channel and MF response is low. Then, after digital-to-analog conversion, the low-pass response of the channel and MF suppresses the increased quantization noise at high frequencies, resulting in a net decrease of quantization noise at the receiver.

In order to decrease the quantization noise, first a metric for the quantization noise is defined. The quantization noise for each

Fig. 1. The ENOB versus frequency of a Micram DAC 4 with a PNOB of 6 operating at a sample frequency of 100 GSa/s with an output swing of 500 mV. Reproduced from [18].
digital sample is given by
\[ q(n) = x_q(n) - x(n), \]
where \( x_q(n) \) is the quantized version of the digital input signal \( x(n) \), which has to be converted to analog. \( x_q(n) \) is transmitted over the channel and the signal at the receiver after MF is denoted as \( y_q(n) \). The effective quantization error is then given by
\[ q_{\text{eff}}(n) = y_q(n) - y(n), \]
where \( y(n) \) is the received value if there would be no quantization noise. It is this effective quantization error that has to be minimized by the DRE, since this is the quantization noise as seen at the receiver. In the case of a linear channel the effective quantization noise can be calculated as
\[ q_{\text{eff}}(n) = y_q(n) - y(n) = x_q(n) \ast h(n) - x(n) \ast h(n) = q(n) \ast h(n) = \sum_{i=0}^{L-1} h(l)q(n-l), \]
with \( L \) the number of taps of the CIR and \( \ast \) denoting the convolution operator. From Eq. (4) it is seen that \( x_q(n) \) should be chosen such that when \( q(n) \) is convoluted with \( h(n) \), the result is minimized.

The quantization noise is shaped by not selecting the DAC output with the smallest Euclidean distance to the input sample (so rounding off), but by dynamically quantizing the DAC output. This is visually represented in Fig. 3. An input sample is quantized to one of \( M \) soft quantization possibilities, which are the \( M \) closest DAC outputs to the input sample. Mathematically, this is described as [10]
\[ q_{\text{dq}}(n) = q_{ro}(n) + u(n) \cdot \Delta, \]
where \( q_{ro}(n) \) is the error if a standard round-off quantizer would be used, \( u(n) \) is an integer control sequence which changes the selected DAC output, and \( \Delta \) is the DAC output step size.

The optimum DAC outputs, and thus \( u(n) \), are determined by finding the outputs which minimize the mean squared error (MSE) given by
\[ \text{MSE} = \frac{1}{N} \sum_{n=0}^{N-1} |q_{\text{eff}}(n)|^2, \]
with \( N \) the number of samples in the input signal. Since the number of quantization combinations scales exponentially with \( N \), finding the optimum \( u(n) \) by evaluating Eq. (6) for all combinations would not be possible. Instead, the optimum \( u(n) \) is determined by using the Viterbi algorithm [20], resulting in a linear complexity dependence on the sequence length. The required number of calculations is proportional to the number of states in the Viterbi trellis, given by \( M^{L-1} \cdot N \). Hence, also the number of soft quantization possibilities \( M \) and the length of the CIR are minimized to reduce the complexity. The CIR is shortened by designing a new filter with a small amount of taps which best matches the frequency response of the CIR in the least-square sense according to [21].

In Figs. 4 and 5, the effect of DRE on the quantized samples and on the spectrum of the quantization noise is visualized. Fig. 4 depicts the soft quantization possibilities corresponding to the input signal for \( M = 3 \), together with the DRE quantized signal. It can be observed that the quantized sample does not always correspond to a trivial round-off quantization of the input sample. In Fig. 5, simulated spectra of the quantization noise with and without DRE are shown. As can be seen, when
DRE is employed, the quantization noise power increases at high frequencies and reduces for frequencies inside the signal band. The DRE algorithm can be tuned by choosing $L$ and $M$. Increasing the number of taps $L$ of combined impulse response $h(n)$ results in a filter which better matches the real channel and MF response, and increasing the amount of soft quantization possibilities $M$ results in a better match of the spectrum of the quantization noise to the inverse of the reduced CIR. Increasing $L$ and $M$ results in higher complexity, but is expected to result in better performance since the quantization noise will be better shaped.

C. Clipping the Transmit Sequence

According to Eq. (1), the power of the quantization noise added by the DAC scales with the DAC output step size. For signals with a large PAPR, such as digitally pre-compensated signals, the DAC output step size becomes large, resulting in a large quantization noise power. Since the output samples of pre-compensated signals are Gaussian-like distributed, high value output samples occur rarely, while the low valued output samples occur more often, as can be seen in the histogram in Fig. 6(a).

In order to reduce the PAPR, the amplitude of the transmitted signal may be clipped, as is also done for orthogonal frequency division multiplexing (OFDM) transmission [22]. By clipping the tails of the Gaussian distribution, as visually represented in Fig. 6(a) for a clipping probability of 0.01, the PAPR is reduced, resulting in less quantization noise. Here, the clipping probability is defined as the probability that an output sample is clipped to a lower value. Fig. 6(b) depicts the DAC output occurrence for a 3 bits DAC. It can be seen that without clipping, the lower and upper two DAC outputs have a very low occurrence. After clipping, those DAC outputs occur more often. Since the clipping is performed before DRE, the introduced clipping noise is also taken into account by the DRE.

By clipping the output samples, clipping noise is added to the signal since the output values above the clipping level are now quantized to the clipping level. By tuning the amount of clipping, an optimum between quantization noise and clipping noise can be found, resulting in better performance. Fig. 7 shows the NGMI versus clipping probability for simulated transmission of 128-QAM. As can be seen, there exists an optimum between quantization noise and clipping noise. Also, the largest performance gain due to clipping is observed for a DAC which has a low resolution compared with the cardinality of the transmitted constellation. For 128-QAM, the largest gain is expected for a 3 bits DAC.

IV. SIMULATION OF DRE COMBINED WITH CLIPPING

Based on the results from Section III-C, single channel transmission for a 3 bits DAC employing DRE and clipping was simulated for 64-QAM and 128-QAM at 64 GBd and 42 GBd, respectively. Please note that a 128-QAM constellation has 12 amplitude levels, which is less than the 8 output levels of a 3 bits DAC. Different DRE schemes were evaluated, which are given in Table I. The schemes differ in terms of the number of taps of the reduced CIRs and the number of soft quantisation possibilities, allowing to evaluate different DRE complexities. Also a scheme without DRE was tested as a reference. In Fig. 8, the frequency responses of the used reduced CIRs are depicted.
Table I: The Different Transmission Schemes Used in Simulations and Experimental Validation in Increasing Order of Complexity

<table>
<thead>
<tr>
<th>Scheme</th>
<th>DRB</th>
<th>Nr. of reduced CIR taps $L$</th>
<th>Nr. of soft quantization possibilities $M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>Yes</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>Yes</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>Yes</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 8. Frequency responses of the reduced channel impulse response (CIR) with 3 and with 7 taps for transmission at 42 Gbd (a) and at 64 Gbd (b). Also, the frequency spectrum of the RRC-shaped transmit signal is depicted.

Fig. 9. Simulation results for a DAC with a PNOB of 3, showing the NGMI versus clipping probability for single channel 64-QAM at 64 Gbd transmission for different DRE transmission schemes and a reference scheme without DRE. See Table I for the scheme definitions.

for a filter with 3 and 7 taps, together with the spectrum of the corresponding transmit signal. Note that different reduced CIRs were used for transmission at 54 Gbd and 42 Gbd.

The simulation consists of pulse shaping using a root-raised-cosine (RRC) filter with $\beta = 0.01$, DPC for the transmitter band-width limitations as given in [5], clipping the amplitude of the samples, DRE, digital-to-analog conversion, channel simulation consisting of the transmitter low-pass response and addition of additive white Gaussian noise (AWGN), equalisation, and calculation of the normalized generalised mutual information (NGMI) as given in [23].

Fig. 9 shows the NGMI versus clipping probability for 64-QAM at 64 Gbd for a DAC with a PNOB of 3. As can be seen, the NGMI of scheme A without DRE at the optimum clipping probability does not achieve the FEC limit of 0.85. The assumed 25.5% overhead FEC is based on a spatially-coupled low-density parity-check (LDPC) code [24] and the corresponding NGMI limit of 0.85 is derived in [25]. Looking at the NGMI for schemes B and C without clipping, indicated by the dashed horizontal lines, the NGMI increases compared to scheme A, but remains below FEC limit. After also enabling clipping, the NGMI increases for both schemes B and C, and the NGMI of the more complex scheme C increases to above FEC. Observing the NGMI for scheme D, it is significantly lower than for scheme B and C. This may be explained by comparing the responses of the used reduced CIRs in Fig. 8(b). The frequency response of the CIR for scheme D (7 taps) has a higher attenuation inside the frequency band of the transmit signal, compared to scheme B and C (3 taps). This has as result that the quantization noise is shaped such that it also increases inside the signal band, degrading the signal quality.

Fig. 10 shows the simulation results of 128-QAM at 41.79 Gbd using a DAC with a PNOB of 3. Note that the simulation results without DRE are not shown, since the equaliser did not converge for those simulations. From Fig. 10 observe that schemes B, C and D do not achieve FEC without clipping. When clipping is applied, all DRE schemes achieve FEC at the optimum clipping probability. Additionally, it is seen that high complexity scheme D outperforms the lower complexity schemes B and C.

In order to compare the performance of the simulated 3 bits DAC employing clipping and DRE with a conventional DAC, the 64-QAM and 128-QAM scenario were simulated for DACs with PNOBs ranging from 3 to 6 bits without DRE and clipping. The results are tabulated in Table II. In the case of the 3 bit DAC enhanced with clipping and DRE, the clipping probability is chosen such that the NGMI is maximized. Comparing the performance of the 3 bit DRE and clipping enhanced DAC with the conventional DACs, it can be seen that for this case the performance of the enhanced DAC corresponds to that of a conventional DAC with 5 bits, indicating a gain of 2 bits by using clipping and DRE.
V. EXPERIMENTAL VALIDATION

Based on the simulation results found in the previous section, for the 64-QAM at 64 GBd scenario, schemes A, B and C were experimentally evaluated. For 128-QAM at 41.79 GBd schemes B and D were experimentally tested.

A. Experimental Setup

The simulated schemes were experimentally validated using the setup shown in Fig. 11. Pseudorandom bit sequences containing $2^{16}$ containing symbols are RRC shaped with roll-off $\beta = 0.01$ and digitally pre-compensated for transmitter bandwidth limitations as in [5]. Subsequently, the samples are uploaded to a Micram DAC4 system operating at 100 GSa/s. The positive differential DAC outputs are connected to an optical-multi-format transmitter (OMFT) which contains RF amplifiers, a DP-IQM, an automatic bias controller and an external cavity laser (ECL). The OMFT is used to provide the channel under test (CUT), while 10 loading channels are generated by amplifying the negative differential DAC outputs using RF amplifiers and modulating 10 optical carriers provided by external cavity lasers (ECLs) using a DP-IQM. The loading channels are subsequently amplified and decorrelated by splitting them, delaying them using fibres of 50 m and 200 m, and multiplexing them with the channel under test (CUT) on a 50 GHz grid using an optical tunable filter (OTF) which is configured such that from the 50 m path only the even channels pass, and from the 200 m path only the odd channels pass. The output of the OTF is amplified and launched into a span of standard single-mode fiber (SSMF) with a length of 75 km, which corresponds to typical DCI distances. At the receiver side, the optical signal is amplified using an erbium-doped fiber amplifier (EDFA), filtered by a wavelength selective switch (WSS), and received by a coherent receiver consisting of a LO, a 90-degree hybrid, and 4 balanced photo-diode. The resulting electrical signal is subsequently digitized by an 80 GSa/s ADC. Offline DSP is performed, consisting of front-end correction, frequency-offset compensation, chromatic dispersion compensation, multiple-input multiple-output (MIMO) equalisation with in-loop blind phase search, and NGMI evaluation.

For single channel experiments, the WDM setup described above was used, but without the loading channels enabled. The PNOB of the DACs was chosen by only using a reduced number of the maximum PNOB of the DAC.

B. Experimental Results

Fig. 12 shows the experimental results for single channel, 600 Gb/s DP-64-QAM 64 GBd transmission with a DAC with PNOB of 3. First, a sweep of the clipping probability was performed, of which the results are shown in Fig. 12(a). The optimum clipping probability per scheme is determined and at this optimum, a launch power sweep is executed. From Fig. 12(b), a NGMI increase of 0.14 and 0.12 for scheme B and C, as defined in Table I, respectively.

<table>
<thead>
<tr>
<th>Bits</th>
<th>DRE</th>
<th>64-QAM at 64 GBd</th>
<th>128-QAM at 41.79 GBd</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Yes</td>
<td>0.86 (DRE scheme C)</td>
<td>0.86 (DRE scheme D)</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>0.55</td>
<td>0.57</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>0.78</td>
<td>0.77</td>
</tr>
<tr>
<td>6</td>
<td>No</td>
<td>0.89</td>
<td>0.83</td>
</tr>
</tbody>
</table>

**TABLE II**
SIMULATED PERFORMANCE COMPARISON OF A 3 BIT DAC EMPLOYING CLIPPING AND DRE VERSUS CONVENTIONAL DACS

**Fig. 11.** Experimental setup for single channel and WDM transmission. For single channel experiments, the WDM setup was used, but without the optional loading channels enabled. Used abbreviations: external cavity laser (ECL), dual-polarization IQ-modulator (DP-IQM), erbium-doped fiber amplifier (EDFA), standard single-mode fiber (SSMF), optical-multi-format transmitter (OMFT), channel under test (CUT), optical tunable filter (OTF), wavelength selective switch (WSS), local oscillator (LO).
clipping and DRE are applied, indicating the importance of clipping when implementing DRE. The results for scheme A without clipping are not shown in Fig. 12(b), since the equaliser did not converge.

The DRE pushes the DAC quantization noise to outside the signal band, which for WDM transmission might result in quantization noise impairing the adjacent WDM channels. Therefore, the loading channels are combined with the CUT using an OTF which filters each channel using a 50 GHz wide filter. The results for 460 Gb/s per channel WDM transmission for DP-128-QAM operating at 41.79 Gbd using a DAC with a PNOB of 3 are depicted in Fig. 13, where the center WDM channel is used as CUT. Firstly, the clipping probability was swept for schemes B and D, see Fig. 13(a), in order to determine the optimum clipping probabilities. Next, the obtained optima were used to perform a launch power sweep without clipping and a sweep at the optimum clipping level, as shown in Fig. 13(b). A NGMI increase of 0.10 is shown for scheme B and an increase of 0.064 for scheme D, resulting in performance above FEC for the more complex scheme D.

VI. CONCLUSION

Clipping combined with DRE is introduced and verified by simulations and experiments. By artificially reducing the PNOB of the digital-to-analog converter in an optical transmission system, the quantization noise becomes the dominant noise source of the transmission system enabling the study of the interplay between clipping and DRE. By jointly optimising the clipping probability and DRE, 600 Gb/s transmission of DP-64-QAM at 64 Gbd over 75 km of SSMF using a PNOB of merely 3 bits is shown. Also, 460 Gb/s per channel WDM transmission using DP-128-QAM at 41.79 Gbd is demonstrated. Moreover, in both scenarios, a normalized generalized mutual information gain of at least 0.1 over DRE without clipping is achieved, indicative of the importance of joint optimisation of DRE and clipping.

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REFERENCES


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Chigo Okonkwo (Senior Member, IEEE) was born in Wakefield, U.K., in 1979. He received the Ph.D. degree in optical signal processing from the University of Essex, Colchester, U.K., in 2010. Between 2003 and 2009, he was a Senior Researcher with the Photonic Networks Research Lab, University of Essex, U.K. After his Ph.D., he was appointed as a Senior Researcher with the Electro-optical communications group working on digital signal processing techniques and the development of space division multiplexed transmission (SDM) systems. He is currently an Assistant Professor and leads the High-capacity optical transmission laboratory within the Institute for Photonic Integration (former COBRA), Department of Electrical Engineering, Eindhoven University of Technology (TU/e), The Netherlands. He was instrumental to the delivery of the first major SDM project in the European Union—MODEGAP project. Since 2014, he has been tenured at the ECO group, where he has since built up a world-class laboratory collaborating with several industrial and academic partners. His general research interests are in the areas of optical and digital signal processing, space division multiplexing techniques, and long-haul transmission techniques. In 2018, he was TPC chair for subcommittee 3 on digital signal handling. Between 2015 and 2017, he served on the TPC for the OSA conference on signal processing in photonic communications (SPPCom). In 2017 and 2018, he was the Program Chair and the Conference Chair at SPPCom, respectively. Dr. Okonkwo recently served as an associate editor for special edition of the IEEE Journal on Lightwave Technology. For the next 3 years, he has been elected to serve as technical programme subcommittee on Fiber-optic and waveguide devices and sensors (subcommittee D5) at Optical fiber communications conference OFC 2020.