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ORIGINAL RESEARCH

Point-to-point intensity modulation and direct detection flexible transceivers incorporating cascaded inverse fast fourier transform/fast fourier transform-based multi-channel aggregation/de-aggregation techniques

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Abstract
Point-to-point (P2P) flexible transceivers are the key technical enabler to cost-effectively offer fast, dynamic, and 'just-the-right-size' ultra-dense P2P connectivity for various applications including remote equipment control and distributed fibre networks. However, existing flexible transceivers originally designed for hub-and-spoke traffic patterns are sub-optimal. To effectively address such technical issue, a P2P flexible transceiver incorporating a cascaded inverse fast fourier transform/fast fourier transform-based multi-channel aggregation/de-aggregation technique and analogue in-phase and quadrature (IQ) mixers is proposed and numerically evaluated in a 56Gbps@20 km intensity modulation and direct detection transmission system. The proposed P2P flexible transceivers not only support adaptive and flexible variations in both channel count and channel line rate but also offer additional physical layer network security.

KEYWORDS
optical transceivers, optical fibre communication

1 | INTRODUCTION

Intensity Modulation and Direct Detection (IMDD) optical transceivers are the key elements in constructing present optical access networks and mobile access networks [1, 2]. The conventional IMDD transceivers can only operate at predefined speeds and provide static and fixed-grid connections [3]. They thus cannot cost-effectively meet the stringent requirements of the next generation of optical access networks and mobile access networks in terms of flexibility, elasticity, scalability, and upgradability [4–6].

To effectively solve this technical challenge, an IMDD point-to-multipoint (P2MP) flexible transceiver has recently been proposed and experimentally demonstrated in an upstream 55.3Gbps@25km IMDD passive optical network [7]. In the transceiver DSPs, cascaded inverse fast fourier transform/fast fourier transform (IFFT/FFT) operations are implemented to flexibly and adaptively aggregate and de-aggregate an arbitrary number of independent channels of various line rates. By activating and/or de-activating the corresponding IFFT/FFT function blocks, the P2MP flexible transceivers can potentially operate in an 'add-as-you-grow' mode. In addition, in the transmitter DSPs, after multi-channel aggregations, orthogonal digital filtering is also used to not only locate produced signals at the desirable radio frequency spectral regions but also considerably reduce out-of-band radiations. Using the P2MP flexible transceivers, guard band-free upstream signal transmissions in the conventional IMDD PONs are demonstrated experimentally without using extra optical/electrical components compared to their conventional counterparts. The results verify that this transceiver is promising for optical networks with hub-and-spoke traffic patterns.

However, for application scenarios such as P2P remote equipment control/configuration and distributed fibre networks with P2P fibre deployments [8–10] which may only require fast and dynamic P2P connections, the above P2MP transceiver is sub-optimal. To effectively address the above issue, in this paper, by modifying the P2MP flexible transceivers, a novel P2P flexible transceiver is proposed and numerically explored in a 56Gbps@20 km IMDD transmission system by numerical simulations. In the transceiver DSPs, cascaded IFFT/FFT operations are utilised for aggregating/de-aggregating multiple independent channels of various line rates. Analogue IQ mixers are used to realise the frequency up/down-conversions [11, 12]. The proposed P2P flexible transceivers maintain the salient features of the previous P2MP flexible transceivers, including (1) adaptive channel count variations, (2) flexible channel line rate variations, (3) additional physical layer network security, and (4) great potential for operating in an 'add-as-you-grow' model. More importantly, the proposed P2P flexible transceivers outperform the P2MP flexible transceivers in terms of transceiver digital signal processing (DSP) complexity due to the elimination of digital filtering [13, 14]. In addition, due to the use of low-cost IQ mixers, low-speed DACs/ADCs are applicable for the transceivers [15]. Apart from the transceiver design differences, in exploring the performances of the proposed P2P transceivers, in this paper, special attention is also given to the impacts of channel count variations on minimum SNR requirements and the feasibility of using small IFFT size to reduce the transceiver DSP complexity, which is not considered in Ref. [7].

2 | OPERATING PRINCIPLE OF PROPOSED FLEXIBLE TRANSCEIVERS

The proposed P2P flexible transceiver is illustrated in Figure 1. The cascaded IFFT/FFT-based multi-channel aggregation/de-aggregation techniques utilised are outlined in Figure 2.

2.1 | Cascaded IFFT-based multi-channel aggregation

The cascaded IFFT-based multi-channel aggregation operation can generate a complex-valued baseband signal containing an arbitrary number of independent channels. As seen in Figure 2a, the aggregation of R independent channels requires $(R-1)$ IFFT operations. To aggregate the r-th channel, the $(r-1)$-th IFFT operation size is given by

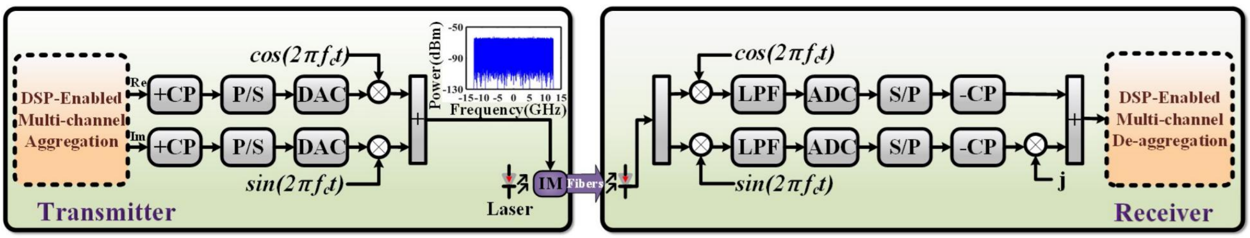

FIGURE 1 Operating principle of the proposed P2P flexible transceiver incorporating cascaded IFFT/FFT-based multi-channel aggregation/de-aggregation techniques for intensity modulation and direct detection transmission system. CP, cyclic prefix; DAC/ADC, digital-to-analogue/analogue-to-digital convertor; IFFT/FFT, inverse fast fourier transform/fast fourier transform; IM, intensity modulator; LPF, low pass filter; P/S, parallel-to-serial conversion; S/P, serial-to-parallel conversion.

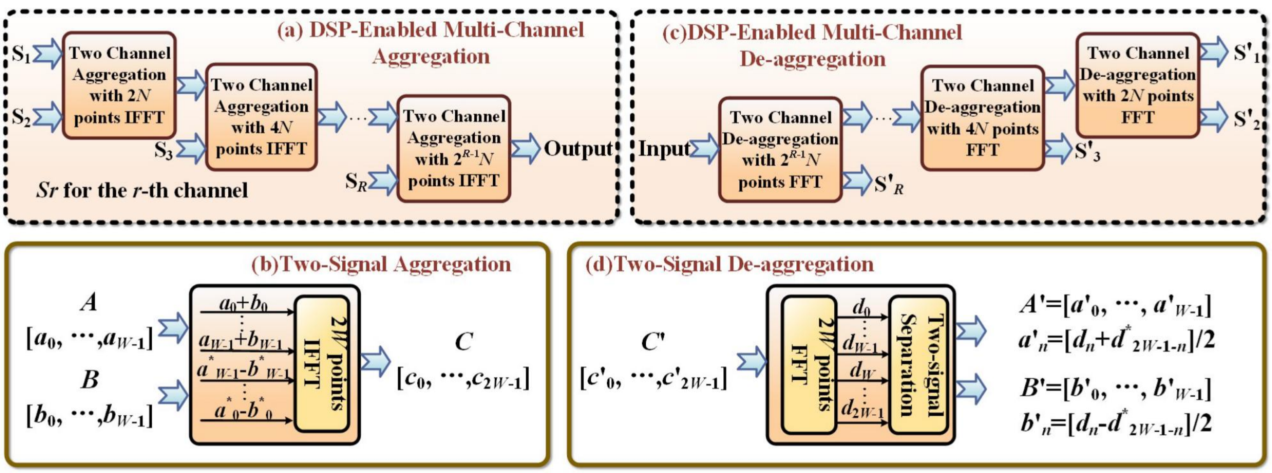

FIGURE 2 (a) DSP-enabled multi-channel aggregation, (b) Two-signal aggregation, (c) DSP-enabled multi-channel de-aggregation, and (d) Two-signal de-aggregation. DSP, digital signal processing.

$$L_{\mathrm{IFFT}_{r-1}} = 2W = 2^{r-1}N, r = [2, \ldots, R] \tag{1}$$

where N is the number of data-bearing subcarriers in the first or second channels. W is the size of two signals to be aggregated by the $(r-1)$-th IFFT operation. The rth IFFT operation is twice the size of the $(r-1)$-th IFFT operation.

For the $(r-1)$-th IFFT operation, as seen in Figure 2b, two independent signals, $A = [a_0, a_1, \ldots, a_{W-1}]$ and $B = [b_0, b_1, \ldots, b_{W-1}]$, are aggregated, where A is the output of the $(r-2)$-th IFFT operation and B is the signal aggregated by the $(r-1)$-th IFFT operation. The input of the $(r-1)$-th IFFT operation can thus be achieved by

$$S_{\mathrm{IFFT}_{r-1}}(n) = \begin{cases} a_n + b_n, n = 0, 1, \ldots, W-1 \\ a^*_{2W-1-n} - b^*_{2W-1-n}, n = W, W+1, \ldots, 2W-1 \end{cases} \tag{2}$$

where * represents the conjugate operation. a_n is the nth sample of the aggregated signal output by the $(r-2)$-th IFFT operation. b_n is the n-th sample of the rth channel transmission signal to be aggregated. a_n and b_n can be M-ary quadrature amplitude modulation/phase-shift keying (m-QAM/PSK)-coded complex data samples or M-ary pulse amplitude modulation (m-PAM) real data samples. Such cascaded IFFT-based multi-channel aggregation technique is transparent to signal modulation formats [7].

After multi-channel aggregation, cyclic prefix (CP) insertion and parallel-to-serial conversion (P/S), an analogue IQ mixer is used to convert the produced complex baseband signal to a real-valued radio frequency signal. Finally, intensity modulation is performed to generate an optical signal. The produced optical signal $S(t)$ can be expressed as follows:

$$S(t) = \sqrt{1 + m\{I(t)\cos(2\pi f_c t) + Q(t)\sin(2\pi f_c t)\}} \tag{3}$$

where m is the intensity modulation index. $I(t)$ and $Q(t)$ are the real and imaginary parts of the produced complex-valued baseband signal containing multiple channels. $\cos(2\pi f_c t)$ and $\sin(2\pi f_c t)$ are the electrical sinusoidal carriers with the central frequencies of f_c.

In the simulations, an ideal intensity modulation with an intensity modulation index of 0.99 is used to reduce the resulting optical signal's carrier-to-signal ratios for achieving the best transmission performance. In practical implementations, the optimum modulation depth should be identified by adjusting the modulator's driving signal voltages.

Due to the nature of the IFFT/FFT operations, for the proposed technique, multiple channels are aggregated in both the time domain and the frequency domain, thus offering additional physical layer network security by preventing eavesdroppers from illegally de-aggregating channels without the knowledge of the transceiver DSP configurations. Detailed explorations of such additional physical layer network security features associated with the cascaded IFFT/FFT-based multi-channel aggregation/de-aggregation techniques can be found in Ref. [7].

2.2 | Cascaded FFT-based multi-channel de-aggregation

As seen in Figure 1, after I/Q down-conversion and low pass filtering, two ADCs digitise the received complex baseband signal. In the receiver DSP, following serial-to-parallel conversion and CP removal, the cascaded FFT-based multi-channel de-aggregation operation is then performed. It can be seen in Figure 2c that the de-aggregation of R independent channels requires $(R-1)$ two-signal de-aggregation operations each involving an FFT operation.

As illustrated in Figure 2d, assuming that the input to the corresponding two-signal de-aggregation operation is $D = [d_0, \ldots, d_{W-1}, d_W, \ldots, d_{2W-1}]$, after the $2W$-point FFT operation, the separation of the r-th channel is obtained by

$$\begin{cases} a'_n = \frac{1}{2}\left[d_n + d^*_{2W-1-n}\right] \\ b'_n = \frac{1}{2}\left[d_n - d^*_{2W-1-n}\right] \end{cases}, n = 0, \ldots, W-1 \tag{4}$$

where $B' = [b'_0, \ldots, b'_{W-1}]$ is the separated rth signal/channel, and the signal $A' = [a'_0, \ldots, a'_{W-1}]$ is the input signal of the following two-signal de-aggregation operation. Detailed descriptions of the cascaded IFFT/FFT-based multi-channel aggregation/de-aggregation technique can be found in Ref. [7].

For practical implementations of the proposed technique, the bandwidths of the intensity modulators and photodetectors can be slightly larger than the maximum bandwidth of the produced up-converted radio frequency signals for reducing signal distortions.

In addition, in practical implementations, to achieve the best transmission performances, the bandwidths of the IQ mixers for down-conversion should be larger than the input radio frequency signal bandwidth, and the bandwidths of the analogue low pass filters should be slightly larger than the down-converted baseband signal bandwidth. In the simulations, for simplicity, ideal IQ mixers are used and the low pass filters have bandwidths of 6.25 GHz.

2.3 | Transceiver DSP complexity

For the proposed P2P flexible transceiver, the transceiver DSP complexity mainly arises from the cascaded IFFT/FFT operations, and more importantly, the transmitter and receiver have a similar DSP complexity. To simplify the transceiver DSP complexity calculation, the transceiver DSP complexity per sample is considered, which is defined as the total number of multiplication operations required for producing each individual sample.

For the proposed P2P flexible transceiver, assuming R independent channels are aggregated, the transceiver DSP complexity per sample can be calculated as follows:

$$O_{\text{persample}} = \frac{\sum_{v=1}^{R-1} (2^{v-1}N)\log_2(2^{v}N)}{2^{R-1}N} \tag{5}$$

where $(2^{v}N)$ is the size of the v-th IFFT operation, and $(2^{R-1}N)$ represents the symbol length. It is worth mentioning that the transceiver DSP complexity per sample is only related to the subcarrier size of the first channel and the number of independent channels transmitted.

3 | P2P FLEXIBLE TRANSCEIVER PERFORMANCES

In this section, comprehensive numerical simulations are undertaken to evaluate the performances of the proposed flexible transceiver over standard single-mode fibre (SSMF) IMDD transmission systems. The major transceiver and transmission system parameters adopted in this paper are presented in Table 1. Using the multi-channel aggregation/de-aggregation procedures illustrated in Figure 2, three IFFT operations with their IFFT sizes of 256/512/1024 are performed for aggregating four independent channels. Unless stated explicitly in the corresponding sections, these parameters are adopted throughout this paper.

TABLE 1 Transceiver and transmission system parameters.

Parameter	Value
Subcarrier count of 1st channel	128
IFFT/FFT points	256/512/1024
Clipping ratio	14 dB
Cyclic prefix	12.5%
DAC&ADC resolution	10 bits
DAC&ADC sample rate	12.5 GS/s
Centre frequency of RF signals for up/down-conversion	6.25 GHz
PIN detector sensitivity	−19 dBm
PIN responsivity	0.8 A/W
SSMF dispersion parameter at 1550 nm	16 ps/(nm km)
SSMF dispersion slope at 1550 nm	0.07 ps/nm/nm/km
Linear fibre attenuation	0.2 dB/km
Kerr coefficient	2.35×10^{-20} m^2/W

Abbreviations: DAC/ADC, digital-to-analogue/analogue-to-digital convertor; GS, giga sample; IFFT/FFT, inverse fast fourier transform/fast fourier transform; PIN, positive intrinsic negative; RF, radio frequency; SSMF, standard single-mode fibre.

3.1 | Minimum SNR requirements

For the proposed P2P flexible transceivers capable of transmitting/receiving multiple independent channels, multichannel aggregation and/or channel count variations may influence the minimum signal-to-noise ratio (SNR) requirements for achieving a specific bit error rate (BER) performance for each channel.

To explore the transceiver SNR requirements, an electrical back-to-back (B2B) transmission system with only an additive white gaussian noise (AWGN) channel is considered. For different SNRs, the BER performances of the considered four channels are plotted in Figure 3a. Here, each channel adopts 16-QAM. The theoretical SNR versus BER curve for the conventional 16QAM signals is added in Figure 3a. It can be found that the theoretical 16QAM SNR versus BER performances are similar to the simulated performances of the proposed techniques conveying four independent 16QAM channels. The results also show that for a specific SNR, the aggregated channels have similar BER performances when adopting similar modulation formats.

When the channel count is varying, the minimum SNRs for achieving a BER of 1.0×10^{-3} for each channel are explored, and the results are shown in Figure 3b. As seen in Figure 3b, when the aggregated channel count is > 2, the minimum required SNRs for each channel to achieve a BER of 1.0×10^{-3} is increased by < 0.5 dB only because of the channel count increase-induced enhancements in channel interferences. When the aggregated channel count is ≤ 2, the increase in the channel count has negligible impacts on the minimum required SNRs for achieving BERs of 1.0×10^{-3}. This implies that for transmission systems with an AWGN channel, the channel count variations can be made flexibly without considerably influencing BER performances of each channel.

3.2 | 20 km SSMF transmission performances

Utilising the transceiver and transmission system parameters given in Table 1, the performances of the proposed flexible transceivers transmitting four independent channels over 20 km SSMF IMDD transmission systems are presented in Figure 4a. The optical back-to-back transmission performances of the considered four channels are also presented in the same figure. In obtaining Figure 4a, adaptive bit-loading is used to maximise each channel transmission performance, and the resulting channel bitrates are listed in Table 2, which give rise to a total bitrate of 56Gb/s over a 12.5 GHz radio frequency spectral region. As seen in Figure 4a, after 20 km SSMF transmissions, due to the adaptive bit-loading, all the channels have similar transmission performances. The fibre transmission-induced power penalties at a BER of 1.0×10^{-3} are <1.5 dB for all the considered channels. It can be found that the 3rd channel has the largest power penalty, this is due to the inter-play between the channel fading effect (as shown in Figure 4b) and the cascaded IFFT/FFT operations [7].

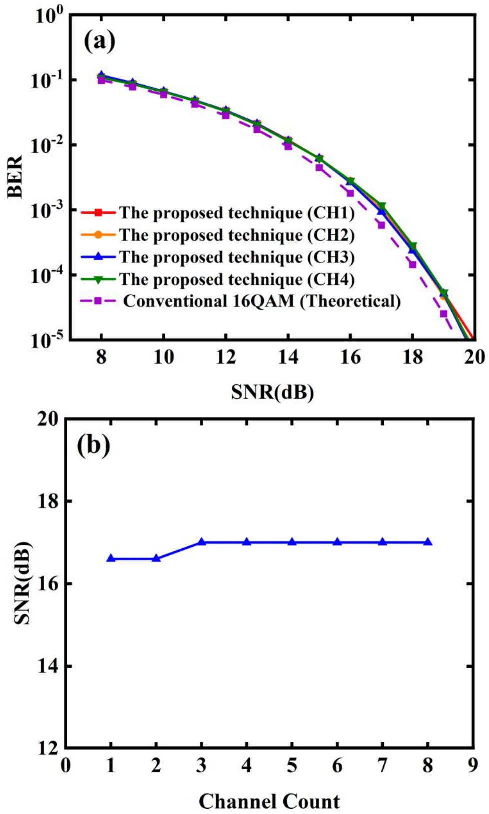

FIGURE 3 (a) BER versus SNR of considered four channels using 16-QAM. (b) Impacts of channel count variations on minimum SNR requirements for achieving BERs at 1.0×10^{-3} for each channel. BER, bit error rate; SNR, signal-to-noise ratio.

3.3 | Transmission capacity

For different channel counts, the transmission capacities for fibre lengths varying from 0 to 50 km are illustrated in Figure 5. The optical launch power is fixed at 8 dBm, and the received optical power is fixed at−3 dBm.

As shown in Figure 5, when the fibre transmission distance is<20 km, the impacts of fibre transmission on the maximum achievable aggregated transmission capacity is relatively small. If fibre transmission distances are increased to 30 km, the channel fading effect becomes significant, thus resulting in a relatively large transmission capacity degradation. When the fibre transmission distances are ≥30 km, further prolonging the fibre length does not considerably degrade the transmission capacity.

In addition, it can also be found in Figure 5 that for a specific transmission distance, the case of transmitting two channels has relatively large transmission capacities in comparison with all other cases, and this agrees with the results reported in Ref. [7]. This is because the channel interferences become slightly pronounced when the channel count is > 2 [7]. However, as seen from the figure, such channel count variation-induced capacity changes are just <4 Gbps. This reveals that for the proposed P2P flexible transceivers, the channel count can be changed adaptively and dynamically without considerably compromising the transmission capacity.

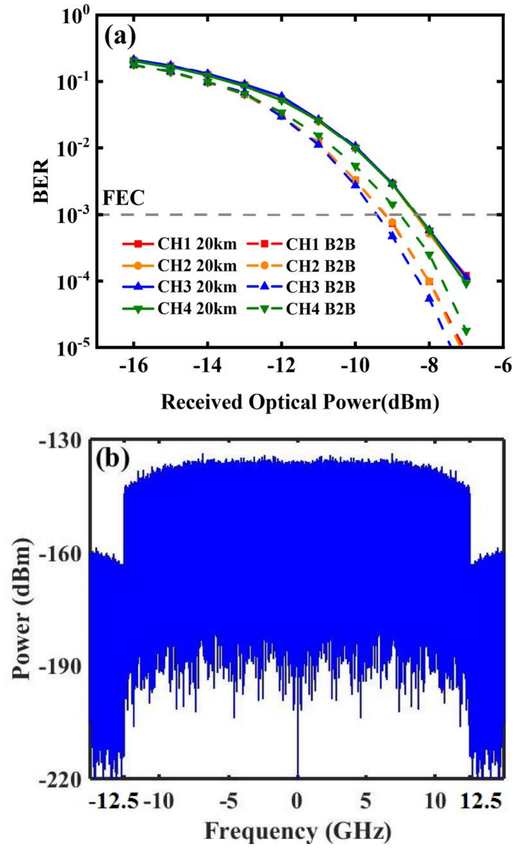

FIGURE 4 (a) BER performance of considered four channels over B2B and 20 km SSMF intensity modulation and direct detection transmission systems. (b) Received electrical signal spectrum after 20 km SSMF. In obtaining (a) and (b), the optical launch power is fixed at 8 dBm. BER, bit error rate; SSMF, standard single-mode fibre.

TABLE 2 Channel bitrate (Gbps).

CH1	CH2	CH3	CH4
7.0	7.0	13.9	28.1

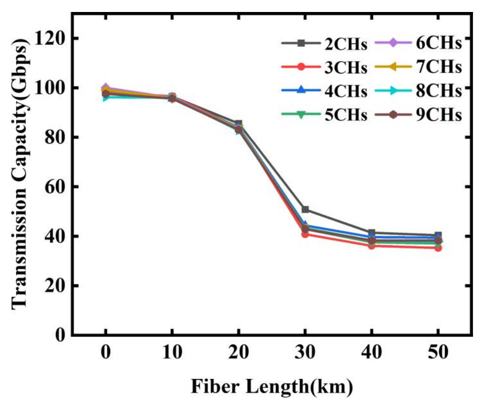

FIGURE 5 Impacts of fibre transmission distance on maximum achievable transmission capacity for various channel counts.

As seen in Figure 5, for a specific transmission distance, the maximum available transmission capacity is almost independent of the channel count, when the channel count is ≤ 9, which agrees with the results published in Ref. [7]. Such a feature can be easily understood from an energy perspective that the fixed received optical powers make the transmission systems' SNRs remain the same, thus leading to similar maximum achievable transmission capacities for different channel counts. Of course, a higher received optical power may lead to a higher transmission capacity. It is also worth pointing out that the transmission capacity differences for different fibre lengths are mainly arising from chromatic dispersion, which can result in signal distortions and channel interferences.

3.4 | Transceiver DSP complexity

For the proposed transceivers, because the transmitter and receiver have similar DSP complexity, in this section, special attention is thus given only to the transmitter DSP complexity.

The transmitter DSP complexity per sample for accommodating four independent channels is calculated and presented in Figure 6, where the subcarrier count of the first channel varies from 4 to 2048. It can be found from Figure 6 that the transmitter DSP complexity is only related to the subcarrier count of the first channel when the channel count is fixed. As such, for practical applications, the first channel's subcarrier count should be sufficiently small to achieve relatively low transceiver DSP complexity.

For the proposed technique, the 1st channel's IFFT size determines all other channel's IFFT sizes. Different channels have different maximum data-bearing subcarrier counts, which further result in different maximum achievable bitrates. As such, for practical applications, flexible and dynamic channel count variations and channel allocations can be made adaptively according to actual service/application requirements in terms of connection count and bitrate.

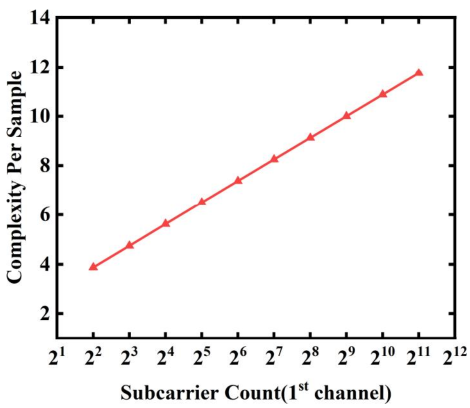

FIGURE 6 Transceiver DSP complexity per sample for accommodating four independent channels. DSP, digital signal processing.

4 | CONCLUSIONS

A novel P2P flexible transceiver based on cascaded IFFT/FFT-based multi-channel aggregation/de-aggregation technique and I/Q mixers has been proposed and numerically explored in a 56Gb/s@20 km IMDD transmission system. The proposed transceiver not only supports flexible and adaptive variations in both the channel count and channel line rate but also offers additional physical layer security and would potentially operate in an 'add-as-you-grow' mode.

In the considered 20 km IMDD transmission systems, it has shown that (1) the fibre transmission-induced power penalties are <1.5 dB, (2) when the fibre transmission distances are <20 km, the fibre transmission distance-induced variations in maximum achievable aggregated transmission capacity is negligible, (3) the impacts of the channel count variations on the maximum achievable aggregated transmission capacity are almost negligible, and (4) for practical applications, the first channel subcarrier count should be sufficiently small to achieve a relatively low transceiver DSP complexity when the channel count is fixed.

AUTHOR CONTRIBUTIONS

Conceptualisation, Lin Chen, Wei Jin and Xinyu Wang; Methodology, Jianming Tang; Software, Gang Yang and Mingyang Jiang; Validation, Lin Chen and Xinyu Wang; Formal analysis, Xinyu Wang; Investigation, Xinyu Wang; Data curation, Xiaoyu Huang; Writing-original draft, Xinyu Wang; Writing-review and editing, Lin Chen, Wei Jin and Xinyu Wang.

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CONFLICT OF INTEREST STATEMENT

The authors declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data are contained within the article.

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