OFDM Based Superchannel Transmission Technology

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(Invited Paper)

***Abstract*—This paper reviews recent advances in the generation, detection and transmission of orthogonal-frequency-division-multiplexing (OFDM) based superchannels, enabled by efficient and powerful digital signal processors. The use of OFDM to form a superchannel can be (1) at the modulation stage by naturally realizing a square-like signal spectral shape to allow close packing of multiple modulated signals, and/or (2) at the optical multiplexing stage by seamlessly multiplexing these modulated signals. This paper reviews recent advances in this field. Several OFDM-based superchannel architectures are described and compared.**

***Index Terms*—Coherent optical orthogonal frequency-division multiplexing (CO-OFDM), superchannel, wavelength-division multiplexing (WDM).**

I. Introduction

OPTICAL fiber transmission technologies with per-channel data rates beyond 100 Gb/s and up to 1 Tb/s are being actively researched worldwide for next generation transport systems to meet ever increasing capacity demands [1]–[4]. To increase the overall network capacity of wavelength-division multiplexed (WDM) systems, high spectral efficiency (SE) modulation formats coupled with high per-channel bit rates are being pursued as potential solutions. Two approaches are available today to implement such solutions. Following traditional methods, the modulation rate (or equivalently the symbol rate) of a single carrier has been progressively increased up to 80-Gbaud [5], [6] with both quadrature phase-shift keying (QPSK) and 16-level quadrature amplitude modulation (16-QAM) to achieve net information rates in excess of 300-Gb/s. This approach relies on ultra high speed analog-to-digital converters (ADCs) with very high sampling rates to achieve the desired performance. A second approach draws its strength from the power of parallel processing. In this approach, multiple optical carriers are modulated individually at relatively lower symbol rates, and then combined to result in a multi-carrier system delivering the desired net data rate. Net information rates from 400-Gb/s to 10-Tb/s have been demonstrated using multi-carrier schemes [7]–[23], [28], [31], [35]–[39]. This method exploits the benefits of mature technologies at lower speeds and uses optical parallelization in the frequency domain to achieve high aggregate data rates beyond the limits of the electronics. In addition to addressing the needs for high data rate generation and detection, multi-carrier formats have also been transmitted over long distances [9], [23] as well as multiple reconfigurable optical add/drop multiplexers (ROADMs) [10]. The need to pack modulated carriers close together to achieve high SE has also spawned the concept of "flexible" bandwidth allocation for maximizing network capacities with minimal wasted optical spectrum. These closely packed carriers that travel from the same origin to the same destination in a WDM system collectively form a *superchannel* [9]. Of particular interest are orthogonal frequency-division multiplexing (OFDM) based superchannels. The use of OFDM to form a superchannel appears into two categories: (1) OFDM-based modulation, which naturally realizes a square-like signal spectral shape to allow close packing of multiple modulated signals, and (2) coherent optical (CO)-OFDM-based carrier multiplexing, which enables *seamless* multiplexing of modulated signals. This paper will elaborate on these salient features of OFDM based superchannel transmission technology.

The paper is organized as follows. In Section II, we introduce various classes of WDM systems. We then introduce superchannel terminology and the associated conditions defining it. In Section III, we describe various methods by which one can generate terabit/s superchannels and compare the performance characteristics among the different approaches at a high level. In the following Section IV, we describe two detection methods typically applicable to such terabit/s class superchannels. Having set the fundamentals in these sections, we explore the role of digital signal processors (DSPs) in the synthesis as well as reception of superchannels in Section V. We then review the transmission performances of superchannels reported in literature in Section VI. Finally, we summarize the paper in Section VII with some perspectives on the future of such OFDM-based superchannel technology.

II. Classes of WDM

Over the last several decades, the field of WDM transmission has evolved from sparsely populated channels, as in coarse WDM (CWDM), to very high density WDM, as in the case of superchannel transmission. It is therefore instructive to classify WDM systems based on the channel bandwidth allocation (or channel spacing) Δf relative to the modulation symbol rate of the channel B. In Table I, different classes of WDM systems

Manuscript received May 22, 2012; revised July 17, 2012; accepted July 21, 2012. Date of publication August 13, 2012; date of current version December 12, 2012.

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Digital Object Identifier 10.1109/JLT.2012.2210861

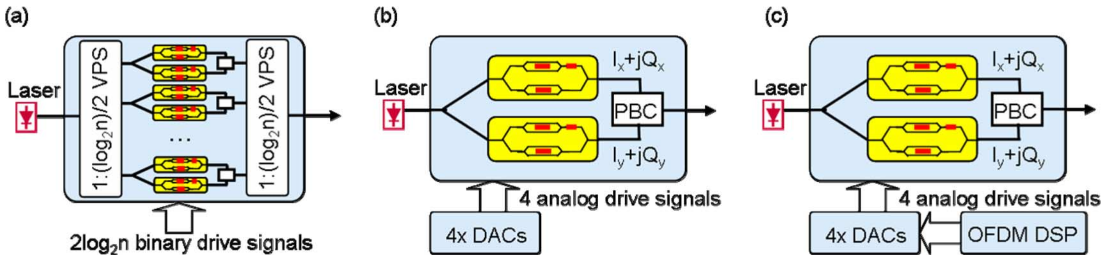

Fig. 1. Three common types of single-band transmitters (SB-TX). VPS: variable power splitter. (a) PDM-n-QAM Transmitter w/o DAC, (b) PDM-n-QAM Transmitter w/DAC, (c) PDM-OFDM/QAM Transmitter.

TABLE I
DEFINITIONS OF VARIOUS CLASSES OF WDM. Δf IS THE ALLOCATED CHANNEL BANDWIDTH AND B IS THE CHANNEL SYMBOL RATE

Condition Δf/B	Definition	Example
> 50	Coarse WDM	10 Gb/s on 20nm
> 5	WDM	10 Gb/s on 100 GHz
1.2 <Δf/B≤5.0	DWDM	28 Gbaud PDM-QPSK on 50 GHz
1.0 <Δf/B≤1.2	"quasi-Nyquist" WDM	28 Gbaud PDM-QPSK on 33 GHz
Δf/B = 1	"Nyquist" WDM	28 Gbaud PDM-QPSK on 28 GHz
Δf/B < 1	"super-Nyquist" WDM	28 Gbaud PDM-QPSK on 25 GHz

are thus defined. One can clearly see that the recent progress in high spectral efficiency systems using advanced modulation formats with coherent detection has opened new regimes, identified as "quasi-Nyquist" WDM (for $1 \leq \Delta f/B \leq 1.2$), "Nyquist" WDM (for $\Delta f/B = 1$) and "super-Nyquist" WDM (for $\Delta f/B < 1$), respectively. The definition makes no assumptions on how a channel is modulated, or any physical impairment associated with placing channels close together, such as crosstalk from overlapping spectral content. As an example, optical prefiltering has been employed to mitigate crosstalk in the demonstration of "quasi-Nyquist" WDM [14] and "super-Nyquist" WDM [15]. Alternatively, electronic pre-filtering has also been employed for similar demonstrations [16], [17]. A special case of "Nyquist" WDM is the one that additionally satisfies the OFDM conditions, as described below, allowing for crosstalk-free reception of symbol-rate spaced channels without using optical or electrical pre-filtering [18]–[23].

The OFDM conditions that must be met for multiplexing multiple modulated carriers to form a superchannel can be enumerated [20] as follows:

1) The carrier spacing must equal the symbol rate with sufficient accuracy (inversely proportional to the duration of each processing block at the receiver). This implies that the carriers on which the modulation is imprinted need to be frequency locked.
2) The modulated symbols on the carriers need to be time aligned at the point of de-multiplexing. (This follows from Fig. 2 of [20]. When the symbols are not exactly aligned, the transitions within a symbol time window from the interferer results in large crosstalk penalty and destroys the orthogonality condition. It is also important that this alignment is at the point of demultiplexing, when decisions are made of the received symbol. In back-to-back case, the point of demultiplexing is the same as the point of multiplexing. However, in transmission, after fiber chromatic dispersion, the symbols of neighboring carriers are displaced due to wavelength dependent dispersion. So it is important that at the point of detection/demultiplexing, this displacement be removed via dispersion compensation, so that one re-constructs the orthogonality condition that existed at generation, and thus detect the channel without any crosstalk penalty).
3) Typically, the frequency-domain response of the modulated symbols is a sinc function. This implies that sufficient bandwidth is needed at the transmitter and the receiver to modulate each subcarrier. At the receiver, there must also be sufficient oversampling speed to capture most of the sinc function for each of the modulated subcarriers. (Oversampling and banded detection are discussed in Section IV).

III. GENERATION OF TERABIT/S SUPERCHANNELS

The synthesis of Terabit/s superchannels is a two-step process. In the first step, one needs to pick a modulation format with the appropriate optical and electronic hardware to generate what we term as a single-band transmitter (SB-TX), generating a lower data rate channel. Here SB means there is no optical frequency domain parallelization. In the second step, multiples of the SB-TXs are combined in parallel optically to generate the total desired data rate superchannel. This we term multi-band transmitter (MB-TX).

A. Modulation

There are three common schemes used to construct a SB-TX for high-level constellations, as shown in Fig. 1. The first scheme (a) uses an array of polarization division multiplexed (PDM) I/Q modulators (PDM-IQMs) that are driven by binary drive signals. To generate a PDM-n-QAM signal, $\log_2(n)/2$ PDM-IQMs are needed, together with two $1 : \log_2(n)/2$ variable power splitters (VPSs) [24]. The second scheme (b) uses a single PD-IQM that is driven by four analog electronic drive signals, corresponding to the I and Q components of two polarization states of the signal. Four digital-to-analog converters (DACs) are needed. DSPs may be used for pre-equalization and pulse shaping at the transmitter. The third scheme (c) is based on OFDM with QAM subcarrier modulation, which requires both DACs and OFDM DSPs.

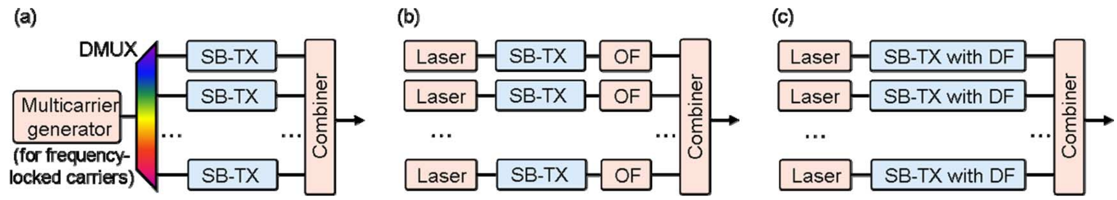

Fig. 2. Three common types of multi-band transmitters (MB-TX). DMUX: wavelength de-multiplexer. (a) OFDM-based multiband transmitter, (b) Nyquist WDM using optical filtering, (c) Nyquist WDM using digital filtering.

TABLE II
COMPARISON AMONG MODULATION SCHEMES

Single-band transmitter type	Number of MZMs needed	DAC needed? (sampling rate)	DSP needed?	Spectral width[1]	PAPR
(a) PDM-n-QAM w/o DAC	$2\log_2 n$ (8 for 16QAM)	No	No	~2B	Low
(b) PDM-n-QAM w/ DAC	4	Yes (2B preferred)	Optional	~2B w/o DF ~B w/ DF	Low
(c) OFDM	4	Yes (1.2~1.5B)	Yes	~B	High[2]

1: The spectral width is measured as null-to-null bandwidth.
2: The high PAPR of OFDM can be reduced by more DSP, e.g., via DFT-spread-OFDM. TX: transmitter; B: signal baud; DF: digital filter..

TABLE III
COMPARISON AMONG MULTIPLEXING SCHEMES

Multiplexing	CO-OFDM		Quasi-Nyquist-WDM	
Carrier modulation	SC	OFDM	SC w/ OF	SC w/ DF
Frequency locking	Needed	Needed	Not needed	Not needed
TX bandwidth	>~2B*	~B	~B	~B
ADC speed	>~4B*	1.2~1.5B	~2B	~2B
Extra components	No	DAC, TX-DSP	Optical filters	DAC, TX-DSP

SC: single-carrier modulation; TX-DSP: transmitter digital signal processor.

B. Multiplexing

There are three common schemes for constructing a MB-TX that consists of multiple SB-TXs, as shown in Fig. 2. The first scheme (a) is based on optical OFDM, which requires a set of frequency-locked carriers [7]–[12], [18]–[23], a carrier separation filter and an array of SB-TX, one for each carrier, and a passive combiner. The second scheme (b) is based on independent lasers feeding a SB-TX followed by tight optical filters (OFs) with sharp roll-offs to minimize the crosstalk-induced optical signal-to-noise ratio (OSNR) penalty among the modulated bands when the carrier spacing is approaching the Nyquist condition, i.e., the carrier spacing being equal to the symbol rate of each band. The third scheme (c) is similar to (b) with the use of a digital filter (DF), instead of an OF, to perform the filtering needed to support the different flavors of Nyquist-WDM. In this scheme, DSPs and DACs are both needed. The implementation of the DF can be a root-raised-cosine (RRC) filter. In a more general sense, the inverse fast Fourier transform (IFFT) used in OFDM modulation can also be regarded as a DF that naturally produces a well-confined square-like signal spectrum with a sharp roll-off.

C. Performance Comparison Among the Designs

It is of value to compare the above high-SE generation schemes. Table II compares the three SB-TX schemes. SB-(a) has benefits of (1) not requiring a DAC, (2) not requiring DSP, and (3) generating signals with low peak-to-average-power ratio (PAPR) and with low optical loss. However, it requires more than one PD-IQM for $n > 4$, so photonic integration of multiple PD-IQMs would make this scheme more attractive. SB-(b) and SB-(c) have the advantage of needing only one PD-IQM, but they require high-speed DACs. Compared to SB-(c), SB-(b) offers lower PAPR but prefers a slightly higher DAC sampling speed. The high PAPR in SB-(c) can be reduced by the DFT-spread technique [25]. Hybrid options are possible as well to trade DAC complexity with parallel-optics complexity.

Table III compares several common multiplexing schemes. The columns under CO-OFDM cover MB-TX (a) while the columns under Quasi-Nyquist-WDM cover MB-TX (b) and MB-TX(c). Single-carrier modulation in conjunction with the orthogonality conditions described earlier, as used in [9], does not require DAC and transmitter DSP, but requires the sampling speed of the receive-side ADC to be much larger than the modulation speed of each modulated carrier. On the other hand, OFDM modulation on each optical carrier, combined with seamless band multiplexing, as used in [7], [8], [10]–[12], has the benefits of (1) not requiring the tight OFs and (2) lower requirements on transmitter bandwidth and ADC speed. Quasi-Nyquist multiplexing has the advantage of not requiring frequency-locked carriers, so independent lasers can be used. Confinement of the signal spectrum using DF has the advantage of not requiring bulky optical filters, although additional DSP is needed to implement the DF at the transmitter. Also, DF usually produces sharper spectrum roll-offs than OF, thereby allowing the modulated carriers to be packed closer with minimal crosstalk penalties.

IV. Detection of Superchannels

In conventional WDM systems, wavelength channels are first de-multiplexed before being received. For superchannels, however, the modulated carriers inside each superchannel are typically too closely spaced to be separated by WDM filters without incurring a filtering penalty. As sharp filtering functions can be readily generated in the digital domain, digital coherent detection enables banded-detection of a superchannel [26]–[28], which consists of the following steps.

1) Splitting the superchannel into M copies;
2) Mixing these M copies in M polarization-diversity optical hybrids with M different optical local oscillators (OLOs);
3) Performing digital coherent detection of each of the M copies, with an RF bandwidth that is slightly larger than half of the occupied optical spectral bandwidth of the modulated subcarrier(s) intended for detection;
4) Digitally filtering each modulated subcarrier and recovering the data carried by the subcarrier.

Note that the tight confinement of the spectral content of each modulated subcarrier in a superchannel, e.g., through transmitter DF, is very beneficial as it reduces the oversampling ratio requirement at the receiver, leading to relaxed ADC sampling speed requirement and more efficient digital signal processing for channel recovery.

It is possible to simultaneously detect more than one carrier per digital sampling at the receiver. At 112 Gb/s, a 2-carrier signal was shown to be detected with low sampling rate ADC to reduce both hardware complexity and receiver DSP load [26]. It was also shown that an oversampling factor, defined as the ratio between the sampling rate and the symbol rate of the carrier modulation, as small as 1.4 is sufficient [27]. In [9] the simultaneous detection of 2 subcarriers, in the presence of all 24 subcarriers, with 50-GS/s ADC, was demonstrated. In this experiment, the oversampling ratio was 2. More recently, simultaneous detection of three 50-Gb/s carriers with a low oversampling factor of 1.33 was demonstrated [28].

V. DSP-Enabled Transmitters and Receivers

Digital-to-analog converters at the transmitter and analog-to-digital converters at the receiver, coupled with digital signal processing, have enabled the exploitation of the full E-field of light to encode and decode information using advanced multi-level modulation formats, achieving high data rate and high spectral efficiencies. Such software-defined transponders have enabled demonstrations of intelligent optical transport and networking with superchannels.

A. DSP at the Transmitter

We examine three techniques that have been extensively researched recently, expanding on the entries in Tables II and III.

1) Reduced-Guard-Interval (RGI) OFDM: In conventional CO-OFDM, a guard interval (GI), e.g., in the form of a cyclic prefix (CP) [29] is inserted in the time domain between adjacent OFDM symbols to accommodate for fiber chromatic dispersion (CD) induced inter-symbol interference (ISI). The larger the chromatic dispersion, the longer the GI needed, leading to an increased overhead and a reduced spectral efficiency. In the proposed RGI-CO-OFDM scheme [10], a reduced GI or CP between adjacent OFDM symbols is used to accommodate ISI with short memory, such as that induced by transmitter bandwidth limitations or fiber polarization-mode dispersion (PMD), while fiber CD-induced ISI having long memory and well-defined characteristics is compensated prior to OFDM signal processing at the receiver, as is done in single-carrier frequency-domain equalization (SC-FDE) systems. This approach enables the reduction of the GI from $>20\%$ for conventional OFDM to only $\sim 2\%$ for RGI-OFDM in a typical long-haul 100-Gb/s OFDM system [10]. Multiple RGI-CO-OFDM signals, when their symbols are time-aligned, can be seamlessly multiplexed to form an OFDM-based superchannel without crosstalk among the subcarriers, as seen before in Table III under MB-TX(a).

2) Nyquist and Quasi-Nyquist Pre-Filtered Signaling: High SE requires modulated channels need to be spaced as closely as possible with minimal crosstalk. One solution would be to pre-filter the channels, either digitally or optically, at the transmitter in order to avoid crosstalk, but this, in turn, causes inter-symbol-interference (ISI). Fortunately, ISI can in principle be removed through digital equalization at the receiver as long as the equalizer used has a tap length that is longer than the maximum time spread resulting from the ISI. Preferably, a matched filter is needed prior to the equalization at the receiver to maximize the signal-to-noise ratio. One example is to have an ideally rectangular spectrum in the frequency domain with a bandwidth equal to the symbol rate and a sinc-like pulse shape in the time domain. (This would come under the classes of "quasi-Nyquist" WDM, "Nyquist" WDM, and "super-Nyquist" WDM, as described before). Modulated channels may have some overlap in the spectral domain, giving rise to some amount of linear crosstalk. Most commonly, this scheme is implemented with some margin for easier implementation by allowing the modulated channels to be spaced more than 1.1B, where B is the symbol rate.

3) DFT-Spread-OFDM: Conventional OFDM typically has a large PAPR, leading to high fiber nonlinear impairments in links with small chromatic dispersion, e.g., dispersion-managed links. Discrete Fourier Transform (DFT)-Spread-OFDM is a technique used in wireless uplink applications and offers lower PAPR than OFDM. It has recently been adopted in optical transmission, and higher nonlinear tolerance of DFT-Spread-OFDM over conventional OFDM has been demonstrated [25], [30], [31]. The DSP expense paid for the lower PAPR of DFT-Spread-OFDM is one more pair of DFT and inverse DFT (IDFT), with the DFT implemented at the transmitter and the IDFT at the receiver. Note that the PAPR of a DFT-spread-OFDM signal is still higher than unfiltered single-carrier signal for the same

TABLE IV
EXPERIMENTAL DEMONSTRATIONS OF SUPERCHANNELS BASED ON SINGLE-CARRIER MODULATION AND CO-OFDM MULTIPLEXING

Ref.	Modulation Format	Superchannel data rate (Gb/s)	Composition	Intrachannel SE (b/s/Hz)	Reach (km)	ISEDP (km×b/s/Hz)
18	NRZ-OOK (DD)	288	7 x 41.3-Gb/s	0.93	1200	1116
33	DQPSK (DD)	100	2 x 25-Gb/s	1.87	1300	2431
34	Duobinary (DD)	100	4 x 25-Gb/s	0.93	100	93
26	PDM-QPSK	112	2 x 56-Gb/s	3.74	10093	37748
9	PDM-QPSK	1200	24 x 50-Gb/s	3.74	7200	26928
22	PDM-QPSK	11200	112 x 100-Gb/s	3.57	640	2285
23	PDM-QPSK	1150	23 x 50-Gb/s	3.33	10000	33300
21	PDM-8QAM	1200	16 x 100-Gb/s	4.71	1600	7536
39	PDM-16QAM	1500	15 x 100-Gb/s	7.00	1200	8400

modulation format, but it is similar to that of Nyquist-filtered single-carrier signal. This modest PAPR of DFT-spread-OFDM or Nyquist-filtered single-carrier signal may be the price that one has to pay in order to achieve the well-confined signal spectrum, as compared to the unfiltered single-carrier signals. Nevertheless, the impact of initial PAPR on transmission performance decreases with the increase of dispersion, especially for high-speed optical transmission.

B. DSP at the Receiver

In the case of OFDM-based superchannel transmission systems, the DSP at the receiver is strongly linked to the DSP at the transmitter, particularly with the frame structure, training symbols, and pilot subcarriers. Concepts such as correlated dual-polarization (CDP) training symbols and intra-symbol frequency-domain averaging (ISFA) [32] have enabled reliable and efficient reception of OFDM signals after long distance transmission. OFDM-based superchannels are well suited for banded detection for the following reasons. First, when OFDM modulation is used, a square-like optical spectrum with sharp roll-off is naturally obtained, reducing the needed guard band if quasi-Nyquist WDM with independent lasers is used as the multiplexing scheme. Second, when CO-OFDM multiplexing is used, the orthogonality among the modulated carriers can be exploited to achieve crosstalk-free demultiplexing of these carriers. Alternatively, multiple modulated carriers can be simultaneously detected to reduce hardware complexity. An OFDM-superchannel with a spectral extent of 65 GHz has been detected with a single-band detection, recovering 606 Gb/s of data using a single optical frontend and four ADCs [11].

VI. TRANSMISSION PERFORMANCE

A useful parameter that specifies the spectral efficiency of the superchannel is the intrachannel SE (ISE). For a superchannel whose carriers are multiplexed by PDM n-point quadrature-amplitude modulation (n-QAM), the maximum ISE that can be achieved without a coherent crosstalk penalty is

$$\mathrm{ISE}_{\max} = 2\log_2(n) \tag{1}$$

where the factor of 2 on the right hand side accounts for PDM. The actual ISE for an OFDM-based superchannel can be expressed as

$$\mathrm{ISE} = \mathrm{ISE}_{\max}/(1+O_{\mathrm{FEC}})/(1+O_{\mathrm{GI}}) \tag{2}$$

where $\mathrm{O}_{\mathrm{FEC}}$ is the overhead used for forward error correction (FEC) and O_{GI} is the OFDM signal processing related overhead, used for guard intervals, training symbols, and/or pilot subcarriers.

A. Performance of Superchannels Based on Single-Carrier Modulation and CO-OFDM Multiplexing

Table IV shows the transmission performance reported for various superchannels in experimental demonstrations. An early demonstration [18], called coherent wavelength division multiplexing (CoWDM), was based on non-return-to-zero (NRZ) signaling, with 42.66-GHz carrier spacing and 42.66-Gb/s on-off keyed (OOK) data modulation on the carriers, with appropriate phase control applied to minimize crosstalk. Subsequently, a two-carrier optical OFDM was demonstrated [33] where differential quadrature phase shift keying (DQPSK) was used to generate a 100-Gb/s superchannel, with the two carriers spaced 25-GHz apart, and each modulated at 25 Gbaud. A variant of this approach with four carriers, each modulated using the duobinary format was also reported [34]. All three of the above demonstrations used direct detection (DD) to recover information from each carrier. All subsequent demonstrations have used coherent detection. Coherent optical (CO) OFDM using two carriers, each modulated with single-carrier PDM-QPSK, was demonstrated for 100-Gb/s long-haul transmission [26]. The underlying CO-OFDM principles elucidated in [20] were used to demonstrate 1.2-Tb/s 24-carrier superchannel generation, detection and transmission [9]. This was also the first time ultra-large area fiber (ULAF) was used for terabit/s superchannel transmission. The ULAF had an average fiber loss, dispersion, and dispersion slope at 1550 nm of 0.185 dB/km, 19.9 ps/nm/km, 0.06 ps/nm^2/km, respectively. The effective area was 120 μm^2, which allowed for high signal launch powers without suffering very much from fiber nonlinearities. As can be seen in Table IV, several multi-level modulation formats (QPSK, 8-QAM and 16-QAM) have been used to synthesize superchannels, and a wide range of ISEs have been demonstrated.

In Table IV, we also compare another figure of merit, namely, the intrachannel spectral efficiency and distance product (ISEDP). Large ISEDP values reflect the superior transmission characteristics of high SE superchannels. As the complexity of a modulation format increases, the ISEDP are correspondingly reduced due to higher OSNR requirements. Record ISEDP values have been achieved by using PDM-QPSK modulation with ISEs ranging from 3.33 to 3.74 b/s/Hz [9], [23].

TABLE V
EXPERIMENTAL DEMONSTRATIONS OF SUPERCHANNELS BASED ON OFDM MODULATION AND CO-OFDM MULTIPLEXING, AS WELL AS QUASI-NYQUIST-WDM

Ref.	Format (subcarrier modulation)	Superchannel raw data rate	Composition	Intrachannel SE (b/s/Hz)	Reach (km)	ISEDP (km×b/s/Hz)
10	RGI-OFDM (PDM-16QAM)	448 Gb/s	10 x 45-Gb/s (2-band detection)	7.00	2000	14000
35	RGI-OFDM (PDM-16QAM)	485 Gb/s	10 x 48.5-Gb/s (single detection)	6.20	4800	29760
11	RGI-OFDM (PDM-32QAM)	606 Gb/s	10 x 60.6-Gb/s (single detection)	7.76	1600	12416
12	RGI-OFDM (PDM-64QAM)	728 Gb/s	10 x 72.8-Gb/s (single detection)	8.00	800	6400
36	Quasi-Nyquist-WDM PDM-32/64QAM	504 Gb/s	5 x 100-Gb/s	8.40	1200	10080
37	Quasi-Nyquist-WDM PDM-64QAM	538 Gb/s	8 x 67-Gb/s	8.96	1200	10752
38	Quasi-Nyquist-WDM PDM-64QAM	12.64 Tb/s	100 x 128.4-Gb/s	7.90	320	2528
31	DFT-Spread-OFDM (PDM-16QAM)	1630	16 x2 x 34-Gb/s	5.50	2500	13750

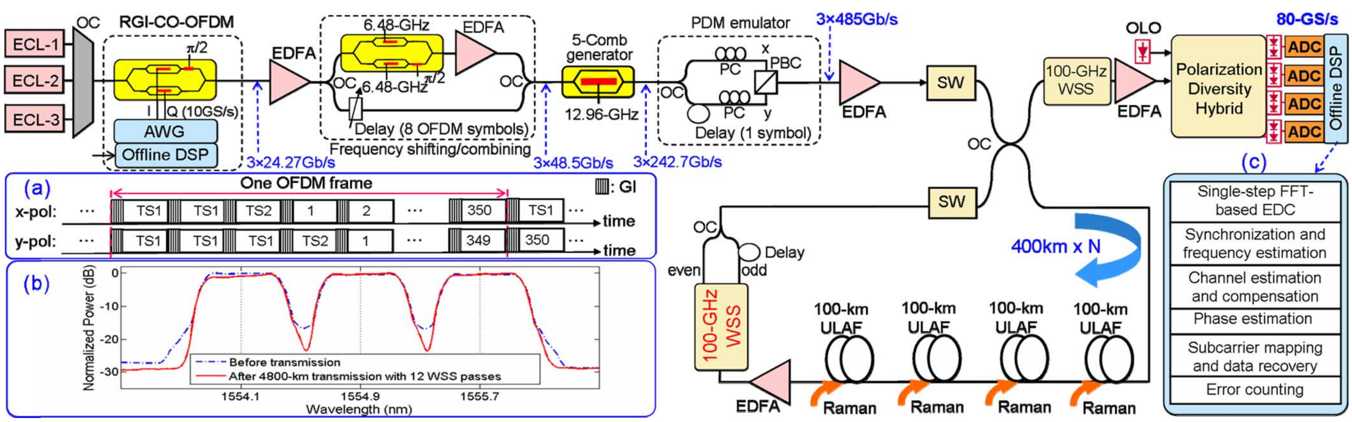

Fig. 3. Schematic of the experimental setup [35]. Insets: (a) OFDM frame structure; (b) Optical spectra of three 485-Gb/s WDM channels before and after 4800-km transmission; (c) Block diagram of the receiver offline DSP.

B. Performance of Superchannels Based on OFDM Modulation and CO-OFDM Multiplexing

In Table V we list experimental demonstrations of superchannels using RGI-CO-OFDM formats as well as quasi-Nyquist filtered single-carrier formats, using digital signal processing techniques at the transmitter as described earlier. It is evident that achieving ISEs beyond 5 b/s/Hz is generally easier using either RGI-CO-OFDM or the quasi-Nyquist-filtering based modulation as compared to unfiltered single-carrier modulation. In addition, the demonstrated ISEDP values in Table V are generally larger for approximately the same ISE as compared to the values demonstrated in Table IV. The reason for both these observations is related to the relative ease of generating high-quality crosstalk-free subcarriers that are multi-level modulated when DAC and transmitter-side signal processing are used. For quasi-Nyquist WDM, the intentionally allocated guard bands between channels alleviate crosstalk impairments, albeit at the expense of slightly reduced SE.

We illustrate the performance of RGI-CO-OFDM class of superchannels with the experiment reported in [35] and depicted in Fig. 3. The same setup was successfully used to demonstrate three different modulation formats, show optical parallelization concepts, demonstrate banded detection of the entire superchannel with one digital sampling, and evaluate the concatenation performance of reconfigurable add/drop multiplexers (ROADMs). A brief description follows.

At the transmitter, three 100-GHz-spaced 485-Gb/s superchannels based on RGI-OFDM modulation and CO-OFDM multiplexing were generated. The WDM channels were launched into a transmission loop consisting of four Raman-amplified 100-km ULAF spans To assess the signal performance in optically routed networks with ROADMs, we used a 100-GHz wavelength selective switch (WSS) in the loop to separate and recombine the even and odd channels. For each WSS passband, the 0.1-dB and 35-dB bandwidths were ~72 GHz and ~125 GHz, respectively. The optical spectra of the three WDM channels, measured by an optical spectrum analyzer with 0.1-nm resolution before and after 4800-km transmission are shown as inset (b) in Fig. 3. Evidently, no optical filtering induced spectral clipping is observed, even after 12 WSS passes. At the receiver, each WDM channel was sequentially filtered out by a second 100-GHz WSS for performance evaluation. An optical local oscillator (OLO) was tuned to the center frequency of the channel under test. With the use of four 80-GS/s ADCs with 32.5-GHz RF bandwidth, each 485-Gb/s signal with an optical

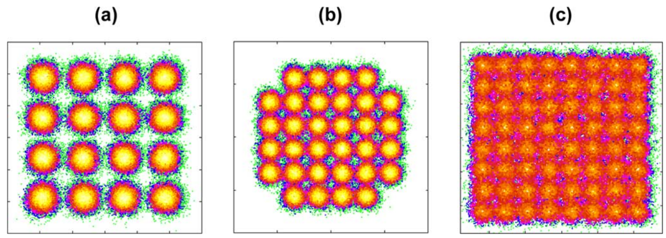

Fig. 4. Constellations of the OFDM subcarriers (recovered in the back-to-back configuration) when modulated by 16-QAM [35], 32-QAM [11], and 64-QAM [12], respectively, achieving superchannel data rates of 485 Gb/s, 606 Gb/s, and 728 Gb/s. (a) PDM-OFDM-16QAM (485 Gb/s), (b) PDM-OFDM-32QAM (606 Gb/s), (c) PDM-OFDM-64QAM (728 Gb/s).

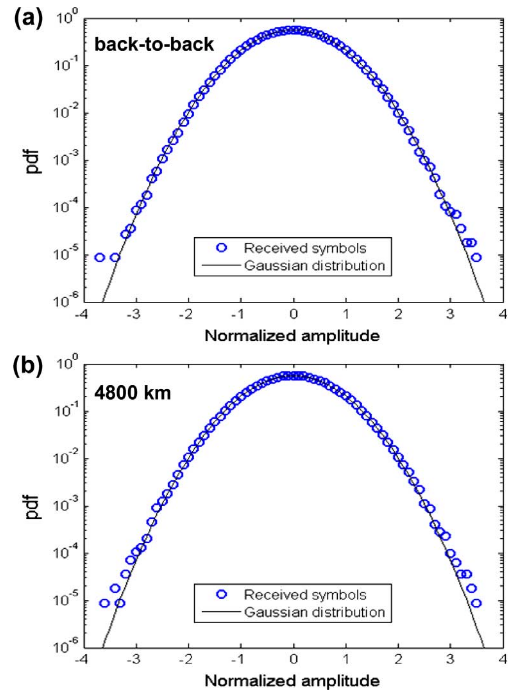

Fig. 5. (a) Probability density function (pdf) of the signal distortion in the back-to-back configuration; (b) pdf after 4800-km transmission at 1 dBm per superchannel.

bandwidth of 64.8 GHz can be completely sampled through a single coherent detection, without having to resort to individual sub-banded detection. The digitized waveforms were processed offline. The DSP blocks are shown in inset (c) of Fig. 3.

With the use of transmitter DSP, the modulation format used for subcarrier modulation in OFDM can be easily changed, leading to a so-called *software-defined* transmission link. Fig. 4 shows the recovered constellations of the OFDM subcarriers when modulated by 16-QAM [35], 32-QAM [11], and 64-QAM [12] achieving superchannel data rates of 485 Gb/s, 606 Gb/s, and 728 Gb/s, respectively. The distances transmitted over ULAF fiber with all-Raman amplification were 4800 km, 1600 km, and 800 km, respectively.

It is interesting to note that the three formats had a spectral occupancy of between 60 and 65 GHz, demonstrating the adaptive nature of multilevel formats to support high data rates without sacrificing optical spectrum.

With the prevalence of soft-decision based forward error correction (FEC) [40] in next generation transport systems, it is important to not just look at pre-FEC error rates (as is permissible for hard-decision FEC if errors are uncorrelated) but to also investigate the probability density function (pdf) of the signal after transmission to see if the noise distribution is, in fact, Gaussian, as the net coding gain (NCG) for the FEC is typically derived using the additive white Gaussian noise (AWGN) assumption [41].

Fig. 5(a) shows the pdf of the I and Q components of both polarizations of the center 485-Gb/s PDM-16QAM RGI-CO-OFDM superchannel in the back-to-back configuration, which closely follows the Gaussian distribution. Fig. 5(b) shows the pdf after 4800-km transmission at the optimal signal power, which also closely follows the Gaussian distribution. In addition, careful analysis of the pdf's for all 16 constellation points showed that all pdfs are identical and individually obey circularly symmetric complex Gaussian statistics. This indicates that soft-decision FEC can be effective, even in the nonlinear transmission regime, for OFDM-based superchannel transmission. One needs to confirm such a statistical distribution for other methods of modulation such as single-carrier based quasi-Nyquist filtered formats in order for soft-decision FEC to be effectively applied.

VII. SUMMARY

We have reviewed the field of OFDM-based superchannel generation, detection, and transmission. OFDM brings two key benefits to superchannel transmission, one at the modulation stage by naturally realizing square-like signal spectra with sharp roll-offs to allow close packing of multiple modulated signals, and the other at the optical multiplexing stage by enabling seamless multiplexing of these modulated signals. Several recently demonstrated OFDM-based superchannel architectures, together with a more general quasi-Nyqusit-WDM based superchannel architecture, have been described and compared. It is expected that OFDM-based superchannel transmission may play an important role in future high-capacity Tb/s-per-channel optical fiber networks.

ACKNOWLEDGMENT

The authors wish to thank P. J. Winzer, A. R. Chraplyvy, and R. W. Tkach for support.

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