OFDM for Optical Communications

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dispersion compensated map as shown in Figure 1.6, which has been so deeply ingrained in the optical communications field for decades. The work ushered in an era of electronic DSP enabled optical transmission followed by the subsequent dramatic revival of the coherent optical communications.[11,12,62–66]

Although rapid advances were made in single-carrier transmission systems based on electronic digital signal processing, multicarrier modulation started to emerge as the competitive alternative. In 2006, three groups independently proposed two types of optical OFDM for long-haul application that were also aimed at eliminating the need for dispersion management in optical transmission systems: direct-detection optical OFDM (DDO-OFDM)[14,15] and CO-OFDM.[13] CO-OFDM holds the promise of delivering superior performance in spectral efficiency, receiver sensitivity, and polarization-dispersion resilience,[67,68] but implementation is much more complex than for DDO-OFDM.[14,15] The transmission experiments of CO-OFDM produced in research laboratories have achieved 100 Gb/s transmission over 1000 km SSMF.[16–18] Because both the single-carrier coherent system and CO-OFDM are attractive candidates for 100 GbE transport, the intriguing question naturally arises regarding which one is superior. This is addressed in the next section.

1.4 Single-Carrier or Multicarrier Transmission: An Optical Debate

Although OFDM has gained popularity in the past decade and has widely been implemented in numerous communication standards, there has been ongoing debate regarding whether OFDM or single-carrier frequency domain equalizer (SCFDE) is superior.[19,20] OFDM has two fundamental problems: (1) large PAPR and (2) sensitivity to frequency and phase noise. The debate has not produced a clear-cut answer but, rather, resulted in a split decision even in some standards; for instance, the United States has chosen single-carrier 8-level vestigial sideband modulation (8-VSB) as the digital TV standard, whereas Europe, Japan, and most other countries have elected OFDM. It may be premature to conclude that the debate of single-carrier and multicarrier transmission in the optical domain will emerge in the same manner as in the RF domain. Given the fact that the communication channel, devices, and systems are quite distinct between these two domains, it is imperative that we thoroughly understand the problems at hand and clarify the context in which the debate is being conducted.

The debate regarding single-carrier versus multicarrier transmission may have different meaning in the optical domain. Figure 1.7 shows the transmitter architectures for single-carrier systems and CO-OFDM systems. There are two conspicuous differences:

1. Single-carrier systems employ a relatively “conventional” and simpler architecture, in which discrete digital-level modulation is fed into the two arms of the QPSK modulator. With regard to generating the I and Q component, the QPSK modulation resembles that

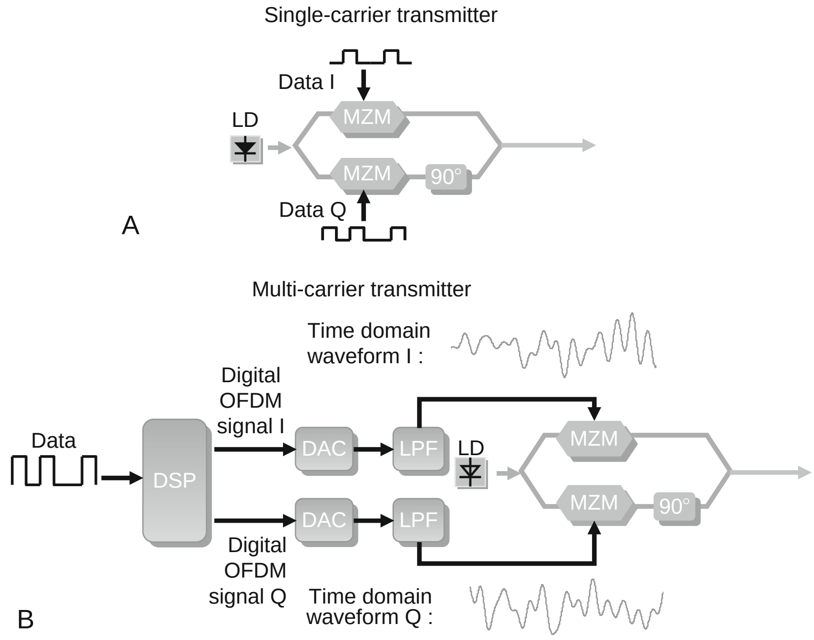

Figure 1.7: Transmitter architecture for (a) single-carrier systems and (b) multicarrier systems.

of conventional BPSK or DPSK modulation. In contrast, the CO-OFDM architecture includes drastic modification from the conventional single-carrier system, in which the electronic DSP module and DAC are required for complex OFDM signal generation at the transmit end. The OFDM transmitter strictly enforces linearity in each component associated with the CO-OFDM transmitter.

2. In the single-carrier systems, the information is coded in the time domain, whereas in CO-OFDM, the information is encoded in the frequency domain, more precisely onto each individual subcarrier.

Based on these two differences, we now make some detailed comparisons of some key properties:

Ease of signal processing: CO-OFDM places the signal processing capability in the transmitter and enables the aforementioned SDOT that brings all the benefit of transmitter adaptability. In particular, we first discuss the two important signal processing procedures for coherent communications: channel estimation and phase estimation. In CO-OFDM-based systems, by using pilot symbols or pilot subcarriers, the channel estimation and phase estimation are made relatively straightforward. In the single-carrier coherent systems as shown in Figure 1.7, the channel estimation has to rely on blind equalization—for instance, using the CMA algorithm—or decision feedback, both of which are prone to error propagation. The phase estimation usually adopts the Viterbi algorithm, which is most effective for the pure phase modulation and less effective for other constellation modulation. Furthermore, differential-phase coding needs to be employed to resolve the intrinsic phase ambiguity for the *m*th-power law algorithm, resulting in approximately a factor of 2 BER increase.[69]

Higher order modulation: For the commonly used QPSK modulation, the transmitter complexity of CO-OFDM is higher, as shown in Figure 1.7, but once the modulation goes beyond 2 bits per symbol, such as 8-PSK or 8-QAM, the CO-OFDM has lower complexity than the single-carrier system, which subsequently reduces the system cost. The reason is that CO-OFDM can be gracefully scalable to the higher order modulation without optical hardware alternation. The only change from 4-QPSK to 8-QAM modulation is enabled via the software to reconfigure the DSP and DAC. In contrast, the higher order single-carrier optical system requires more complicated optical modulator configuration either in a serial or in a parallel manner,[30] which inevitably increases the system complexity and cost. The drive toward more complex constellation for high-spectral efficiency transmission is certainly turning the tide in favor of CO-OFDM.

Tight bounding of spectral components: Because the OFDM spectral shape is tightly bounded, it is more tolerant to the filter narrowing effect. As long as the filter is wider than the OFDM rectangular-like spectrum, the OFDM signal practically suffers no penalty. Even if the edge subcarriers are attenuated by the narrowing filtering, some form of bit and power loading scheme can be employed to mitigate the effect. In contrast, for the single-carrier system, because of the difficulty in reducing the timing jitter at the high clock rate, it is necessary to maintain some additional excess bandwidth for the pulse shaping such that a sufficient margin is allocated for timing accuracy. The filtering narrowing effect not only causes the pulse distortion but also makes single-carrier signal susceptible to the timing jitter. The resilience to the filter narrowing effect makes CO-OFDM particularly fit for the systems employing long cascades of ROADMs.

Bandwidth scalability: Because CO-OFDM spectrum is inherently tighter than the single-carrier one and the CO-OFDM signal is generated in the frequency domain, it is relatively simple to partition the entire OFDM spectrum into multiple bands and process each band separately.[16,18] In particular, if the orthogonality is maintained between adjacent bands, there is no need for the frequency guard band; that is, there is no sacrifice in spectral efficiency for the sub-banding of OFDM spectrum.[16] In doing so, the OFDM transceiver is not limited to the bandwidth constraint of the DAC/ADC. In contrast, the single-carrier encodes the information across the entire spectrum, making it impossible to scale down the bandwidth. It is foreseeable that single-carrier coherent systems solely relying on the timing domain information encoding will hit the brick wall of the electronic DSP speed much sooner than the CO-OFDM-based systems.

Sub-wavelength bandwidth access for performance monitoring and multiaccess/multicast networks: It is a great advantage to place the DSP in the transmitter for CO-OFDM systems. The ability and flexibility to allocate a certain number of subcarriers for channel estimation and performance monitoring will prove to be an attractive feature for CO-OFDM. For instance, this leaves the option of grouping a band of subcarriers for monitoring, which can be easily detected without processing the entire spectrum. Similarly, sub-banding of OFDM allows for the dynamic bandwidth allocation for multiaccess networks using the orthogonal frequency domain multiple-access scheme.[70] All these are difficult to achieve with the single-carrier system.

Computation complexity: The computation complexity is an important factor that affects the chip design complexity and power consumption of the DSP chip. The single-carrier system using IFFT/FFT has the computation complexity scales as the channel length N_x:

$$C_{\mathrm{bit}} \propto \log_2(N_{\mathrm{sc}}),\ N_{\mathrm{sc}} = \alpha \cdot D \cdot B \tag{1.1}$$

where C_{bit} is the computation complexity defined as the number of multiplications required per bit, and N_{sc} is the number of subcarriers in CO-OFDM or number of points used in FFT/IFFT. The computation complexity of the single-carrier system involving DFT and IDFT is the same as that for CO-OFDM, but for the single-carrier time domain equation systems based on FIR equalization, the computation complexity scales as follows[43,71]:

$$C_{\mathrm{bit}} \propto D \cdot B^2 \tag{1.2}$$

It can be seen that CO-OFDM outperforms the FIR equalized single-carrier systems,[43,71] and the advantages are dependent on the detailed design.[71] On the other hand, the SCFDE uses block signal processing, and FFT/IFFT can have the computation complexity on par with CO-OFDM.[19,20,71] However, the block-based signal processing is more conveniently performed if the DSP is available in the transmitter, and if so, the advantage of transmitter simplicity for single-carrier systems as shown in Figure 1.7a disappears. More important, once the DSP and DAC are available at the transmitter and the signal processing is performed on a block basis, the distinction between the multicarrier and single-carrier systems is purely pedagogical.

Sampling rate: For single-carrier systems, it is best for the sampling rate to be twice the signal band rate because it is sensitive to sampling phase inaccuracy if lower.[10–12] Although resampling can reduce the oversample factor somewhat, the computation is intensive and thus impractical. For the CO-OFDM system, oversampling is done simply by not filling the edge subcarriers in order to tightly bound the signal spectrum[16,18]; therefore, approximately 10–20% oversampling is sufficient.[64,72] Reduction of the sampling rate of CO-OFDM from that of the single-carrier system will become more attractive when the high-speed ADC/DACs become more difficult to design.

Tolerance to the component imperfection: It is anticipated that transmitter components, including the RF amplifier, ADC/DAC, and optical IQ modulator, will deviate from their perfect form when operating at high speed for the bit rate of 100 Gb/s and beyond. CO-OFDM enforces linearity throughout every stage of the transmitter design; thus, the imperfections, when linear in nature, can be largely estimated and compensated through the transmitter and receiver signal processing. In contrast, the single-carrier system relies on the drive voltage operating at the saturation, making the component imperfection difficult to estimate and mitigate.

Bit and power loading: One of the major advantages of CO-OFDM is the ability to manipulate the frequency domain at the transmitter, which involves bit and power loading along the line of the "water-filling" algorithm.[73] This is a commonly emphasized advantage in the RF communications in which the channel can be in deep fading, or some part of the spectrum may be completely notched out due to the severe multipath interference. How this bit/power loading capability is to be exploited in the optical domain is of great research interest. Furthermore, the channel rate of a conventional optical transmission system is set at the required level throughout its lifetime, whereas the CO-OFDM offers the new functionality of the adaptive data rate according to the channel condition through bit or power loading. The benefits of the adaptive data rate are reduced transponder inventory because one transponder can be used for multiple data rates and the increased channel usage by delivering more data rate when the margin is plentiful.

Based on the previous comparisons, we conclude that CO-OFDM is advantageous, especially in areas that are key to future transmission systems, including scalability to the ever increasing data rate and transponder adaptability. Nevertheless, the CO-OFDM unavoidably inherits the two main problems intrinsic to OFDM: (1) high PAPR that suggests the CO-OFDM is more susceptible to nonlinearity, and (2) sensitivity to the frequency and phase noise. A proper understanding and treatment of these two important issues is critical to the implementation of CO-OFDM and is without doubt an area of rich research potential. It is also extremely meaningful to briefly discuss different circumstances in which the two problems are being investigated for RF and optical OFDM systems, which are addressed in the next section.

1.5 The Difference between RF OFDM and Optical OFDM Systems

It is a fallacy that because RF OFDM has been extensively studied during approximately the past 20 years, optical OFDM will be an effortless one-to-one translation from the wireless domain to the optical domain. As we shall see in what follows, a clear understanding of the uniqueness of the optical channel and the optical systems makes possible the most efficient