# Is there a role for frequency combs in long-haul fiber transmission?

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# Is There a Role for Frequency Combs in Long-haul Fiber Transmission?

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**Abstract:** We present and discuss the unique benefits with respect to joint signal processing, of using frequency combs instead of independent lasers in long-haul wavelength-division multiplexed systems.

## 1. Introduction

Optical frequency combs are mainly characterized by their spectrum, which consists of a number of narrow lines, separated a frequency $f_r$ (the *repetition frequency* and located at an (in our case optical) *center frequency* $f_c$ in the 192 THz regime (corresponding to the standard telecom wavelength of 1550 nm). For data transmission purposes at high spectral efficiencies one wants $f_r$ to be close to the channel bandwidth $B$, and usually one adds guard bands between channels so that $B < f_r$.

Already in the early days of wavelength-division multiplexing filtering of short pulses, so called supercontinuum sources, from mode-locked lasers were demonstrated [1], which were later developed in to *electro-optic (EO)* combs [2] where a 1000 channels were demonstrated. A schematic of such a comb source is shown in Fig 1(a). More recent examples of comb sources used in WDM is parametric combs [3], and microresonator combs as, e.g., [4] and [5]. The latter have the potential of being integrated and can thus potentially be low cost.

However, in WDM research the bulkier EO-combs are beneficial thanks to their flexibility and stability. An EO-comb consists of a continuous-wave-operated laser source followed by a cascade of phase and amplitude modulators modulated at $f_r$, and by judicious selection of the modulation amplitude and phase to each modulator, a wide and flat comb such as the one shown in Fig 1(b) can be realized. The critical parameters for comb sources when used in WDM transmission is the phase stability (linewidth) $\Delta\nu_k$ of the k:th line (numbered from the original laser line), and the optical signal to noise ratio (OSNR) of each line [6]. For EO-combs, if $\Delta f_c$ and $\Delta f_r$ are the respective RMS spectral widths of the laser and the RF source, the resulting comb lines scale their linewidth according to $\Delta f_k^2 = \Delta f_c^2 + k^2 \Delta f_r^2$, so that the outer lines are more susceptible to instability of the RF source. This holds also for parametric comb sources, but the linewidth scaling with comb line number for microresonator-based sources is still an issues under research. Traditionally, the main arguments for using combs in WDM transmission has been that they can replace huge banks of independent laser sources, thus simplifying systems and reducing the need for e.g. laser cooling at each channel. In addition, the correlated nature between the lines enable the use of reduced guard bands between channels (approximately a factor of 10), resulting in denser channel packing and improved spectral efficiency. However, the purpose of our work is to investigate other unique benefits of comb-based links. These are based on the correlated phase nature between the lines in a comb, and can be taken advantage of when using combs in both the transmitter and receiver (as local oscillator). In such systems it is crucial that *both* $f_c$ and $f_r$ are well matched so that all channels will deviate as little as possible from each other, as discussed in e.g. [6].

This might be difficult when using microresonator combs, unless the repetition rate $f_r$ can be tuned between the comb sources, so for this purpose various schemes of *comb regeneration* have been studied, for example based on co-transmission of two [7] or one [8] unmodulated comb lines. However, independent electro-optic combs can also be used, as e.g. demonstrated in [9–11], and probably originally for characterization purposes by Fontaine in [12]. The benefit of this is that a number of unique benefits of combs, enabling *joint phase tracking* can be demonstrated, as will be described next.

## 2. Joint phase estimation

When independent data signals are perturbed by the same, or correlated, distortions, one will benefit from processing them *jointly*. The reason is simply that one is in possession of more information of the distortions which then can be more efficiently mitigated. This is particularly efficient in the case of joint phase tracking when using transmitter and receiver combs to detect WDM data. It can be shown that the resulting phase wander between two such detected WDM channels will be very well correlated, provided that the comb lines in the individual combs are correlated with each other in the same way [9, 12]. Two examples of how this can be used are shown in figure 2. The upper figure (a) shows fully joint phase estimation, when the detected phases from several WDM lines are used to predict the joint phase of all channels. This will increase the performance of the phase tracking by using more data than in an individual channel. The lower figure (b) shows master-slave detection, where a single phase tracker (the master) is used to phase track the other channels (slaves). This idea was originally proposed for spatial (multicore) channels [13], but the use of frequency combs enable it to be applied also to WDM channels.

These schemes have also been demonstrated experimentally. The experimental setup consisted of 25 WDM channels of polarization-multiplexed 64-QAM data at 20 GBaud with 25 GHz separation. EO-combs were used in the transmitter and receiver, seeded with independent free-running lasers. The data was transmitted over one and two 80-km spans of SMF, and then received in either conventional intradyne (for benchmark), or master-slave, or joint schemes. Two synchronized 4-channel oscilloscopes were used to detect two channels simultaneously, and the data was then postprocessed off line. The results are shown in figure 3. The performance is quantified in terms of generalized mutual information (GMI) which indicates the net achievable spectral efficiency after ideal coding. Figure 3(a) shows the results from master-slave phase tracking (solid) compared to independent (dashed) phase detection, as a function of the separation between master and slave. One can see a slight penalty at the outer channels, but otherwise the master slave scheme works as well as independent processing.

In figure 3(b) we compare the fully joint with independent phase tracking for the center channel as function of the signal power. An improved performance, especially in the nonlinear regime can be clearly seen. Constellation diagrams for two cases are indicated. It is quite clear than an improvement in the nonlinear regime is clear.

These experimental results are a first indication of the potential of joint signal processing enabled by frequency combs, and thus answering affirmatively the question posed in the title of this paper. We believe these results can be improved further by using more advanced phase tracking algorithms, and also by combining it with spatial multiplexing.

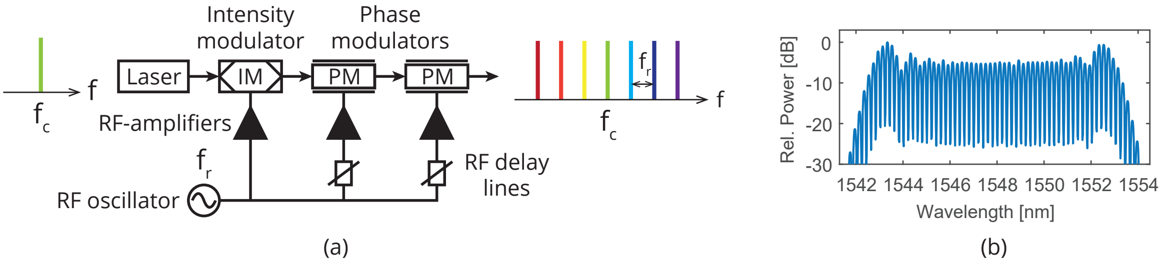

Fig. 1. (a) An electro-optic (EO) comb, realized by a cascade of phase and amplitide modulators. (b) Example of a resulting comb.

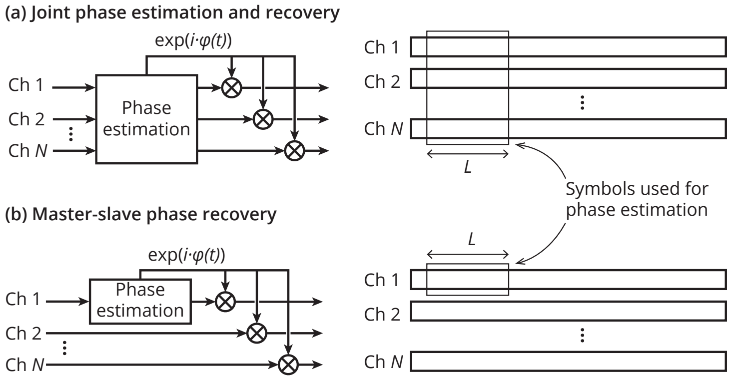

Fig. 2. (a) Joint phase estimation over several WDM channels shown schematically. (b) The master-slave scheme with channel 1 as master, providing phase tracking info to the other channels. The joint scheme uses more instances for estimation and can be expected to have better performance. The master-slave scheme is less complex than the use of independent estimation for every channel, ideally without loss of performance.

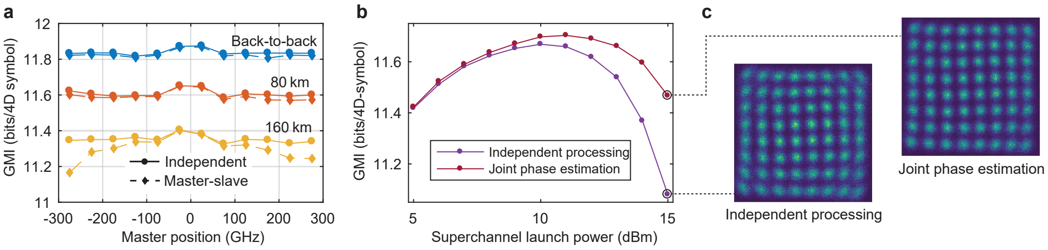

Fig. 3. Results of joint processing for the phase tracking. From [11].

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