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<td><strong>Citation</strong></td>
<td>Yao, S., Fu, S., Li, J., Tang, M., Shum, P., &amp; Liu, D. (2013). Phase noise tolerant inter-carrier-interference cancellation for WDM superchannels with sub-Nyquist channel spacing. Optics express, 21(18), 21569-21578.</td>
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<td><strong>Date</strong></td>
<td>2013</td>
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Phase noise tolerant inter-carrier-interference cancellation for WDM superchannels with sub-Nyquist channel spacing

Shuchang Yao,1 Songnian Fu,1,2,* Jianqiang Li,3 Ming Tang,1,2 Perry Shum,1,4 and Deming Liu2

1Wuhan National Laboratory for Optoelectronics, Huazhong University of Science & Technology, Wuhan, 430074 China
2National Engineering Laboratory for Next Generation Internet Access System, School of Optics and Electronic Information, Huazhong University of Science and Technology, Wuhan, 430074 China
3State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing, 100876, China
4School of Electrical and Electronic Engineering, Nanyang Technological University, 637553 Singapore
* songnian@mail.hust.edu.cn

Abstract: We propose and demonstrate a novel multi-input multi-output (MIMO) equalization based inter-carrier-interference (ICI) cancellation approach employing constant modulus algorithm (CMA) for superchannels with sub-Nyquist channel spacing, where optical combs are used as optical sources. Compared with the least mean square (LMS) algorithm based ICI canceller, the proposed approach has comparable capability to accomplish the ICI mitigation for 56 Gbaud dual-polarization quadrature phase shift keying (DP-QPSK) signals with tight channel spacing till 50 GHz. In particular, compared with the LMS-MIMO based ICI canceller, the optical linewidth tolerance of 6 MHz is relaxed to 20 MHz given a 1dB required optical signal-to-noise ratio (OSNR) penalty for the CMA-MIMO based ICI canceller. Meanwhile, the CMA-MIMO based ICI canceller is ideal for real-time processing, since the number of parallel processing pipelines can be greater than 240 even in the presence of large linewidth.

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OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (060.4510) Optical communications.

References and links

Towards terabit fiber-optic transmission systems, it is preferred to use the multi-carrier schemes to ease the ever-increasing requirements of both symbol rate and the number of bits per symbol. 1-Tbit/s dual-carrier transmission over 320-km standard single-mode fiber (SSMF) was demonstrated using dual polarization 64-ary quadrature amplitude modulation (DP-64QAM) at 64 Gbaud [1]. However, complex modulation formats are generally implemented at the expense of limited transmission distance, due to higher OSNR requirement. Terabit superchannels with a set of multi-carriers were implemented with the DP-QPSK and DP-16QAM signals in order to improve both transmission distance and system spectral efficiency (SE) [2]. Therefore, the multi-carriers are tightly spaced, separated by baud rate and even smaller than baud rate spacing. As a result, inter-carrier-interference (ICI) occurs due to the severe spectrum overlapping. Orthogonal frequency division multiplexing (OFDM) [3,4], Nyquist wavelength-division multiplexing (WDM) [5,6], and sub-Nyquist WDM [7–9] are promising approaches for terabit multi-carrier superchannels by using maximally dense channel spectra while retaining both spectral and temporal orthogonality. The ICI can be successfully suppressed if proper filtering and pulse shaping are performed. However, the OFDM transmission system is complicated and costly because of the computation complexity of fast-Fourier transform and inverse fast-Fourier transform (FFT/IFFT). Meanwhile, Nyquist WDM and Sub-Nyquist WDM also have stringent requirements on spectral shaping and optical filters which suffer from high complexity in reality [3–8]. Due to the likelihood of high capacity terabit superchannels experiencing ICI
impairments and the increasing capabilities of digital signal processing (DSP), the concept of joint ICI cancellation among multiple adjacent carriers using MIMO equalization was proposed recently [10]. Using commercial optical filters, ICI cancellation with the help of LMS algorithm based MIMO equalization was proved effectively in Nyquist WDM or conventional WDM systems whenever ICI exists. Furthermore, the ICI elimination technique was verified to function well in either the linear or nonlinear transmission region [11–13].

Although the CMA algorithm has the advantages of fast convergence and good performance for QPSK signals, it is not recommended to be applied in the joint ICI canceller system [10]. That is because an ICI canceller based on MIMO processing requires a strict frequency alignment among the involved carriers. In the case of phase insensitive CMA algorithm, when different frequency offsets occur among the carriers after optical coherent detection, the equivalent frequency spacing is varied, which degrades the performance of the ICI canceller. As for the LMS algorithm based ICI canceller, it is placed after the modules of frequency offset compensation and carrier phase recovery. Therefore, the frequency offset problem imposes negligible impact on the LMS-based ICI canceller. However, such DSP flow forces the carrier phase recovery to suffer from strong ICI, which reduce the optical linewidth tolerance. Fortunately, a number of frequency-locked optical comb generation methods have been proposed and demonstrated [14–18], and optical combs with stable frequency spacing can be considered as a promising approach to implement high-performance superchannels. Until now, optical combs can be generated with excellent spectral flatness and equal frequency spacing using mode-locked lasers [14], external optical modulators [15], monolithic microresonators [16], and amplified fiber loops [17]. It was shown that sub-Hz deviation from the symmetry of optical combs can be secured, while the optical linewidth of each carrier may vary from several hundred kHz to several tens of MHz [14–17]. For the optical-comb-based superchannels, the frequency offset for each carrier after coherent detection is identical. Hence the frequency spacing among the carriers is maintained. Therefore the ICI canceller can be placed before the modules of frequency offset compensation and carrier phase recovery. As a result, the MIMO processing can be done together with the adaptive channel equalization just prior to the carrier phase recovery. Considering the insensitivity of CMA algorithm to the carrier phase, we propose a novel CMA-based ICI cancellation algorithm for optical comb based superchannel systems and compare it in details with the LMS-based one that was proposed in the prior art [11–13]. The use of CMA instead of decision-directed LMS has comparable performance but a potential complexity reduction in real-time implementations.

2. System configuration and operation principle

As shown in Fig. 1(a), optical combs are employed as the multi-carrier source for terabit superchannels. The wavelength spacing of multi-carriers is optimized to reach sub-Nyquist spacing. After a wavelength demultiplexer, the carriers are respectively injected to multiple parallel DP-QPSK modulators which are driven by pseudo-random bit sequences (PRBS) with a length of 2^{17}-1 at 56 Gbaud. Differential coding is used to solve the phase ambiguity problem. To achieve a trade-off between inter-symbol-interference (ISI) and ICI, each carrier is filtered by a 4th order Gaussian optical filter whose response is available in commercial wavelength multiplexers. All carriers are then launched to the N × 80 km EDFA-only SSMF link with a total launch power controlled by a variable optical attenuator (VOA). At the receiver side, another optical comb is adopted as the local oscillator. Meanwhile, the output of an independent amplified spontaneous emission (ASE) source with variable power levels is combined with the transmission signal so that the OSNR can be adjusted. After the polarization-diverse and phase-diverse coherent receiver, an electronic 5th order Bessel low-pass filter (LPF) with a bandwidth of 0.75 times baud rate is applied. Supposing that the synchronized information across the carriers can be effectively captured, the joint DSP is enabled subsequently.
Since the ICI of a specific carrier usually comes from its neighboring carriers in the high frequency band for WDM superchannels, as shown in Fig. 1(a), the ICI canceller for a specific carrier generally involves 3 carriers, while the ICI canceller for one edge carrier only involves 2 carriers. As shown in Fig. 1(b) and 1(c), we describe the joint DSP flow using LMS-MIMO and CMA-MIMO based ICI cancellers respectively in a typical scenario of 3 carriers, where the signal recovery of carrier 2 is executed as an example. The baseband complex signals for the three carriers are first sampled at 2 samplers per symbol independently but synchronously. Then, the in-phase/quadrature (I-Q) imbalance compensation [19], static dispersion compensation, CMA-based polarization de-multiplexing, frequency offset compensation [20] and carrier phase recovery [21] are implemented sequentially for each carrier, similar to the conventional digital optical coherent detection. As
shown in Fig. 1(c), our proposed ICI canceller module is composed of two parts, a frequency shifter and a MIMO equalizer. The neighboring carriers (carrier 1 and carrier 3) are firstly shifted, in the frequency domain from the baseband to the high frequency band, by the amount of carrier frequency spacing to retrieve the ICI located at the high frequency band. Then the retrieved carriers are subsequently fed into the MIMO equalizers to recover the desired signal of carrier 2. The major difference between our proposed ICI canceller and the previously proposed LMS-MIMO based ICI canceller can be clearly seen from Fig. 1(b) and 1(c). The CMA-MIMO based ICI canceller, placed before the carrier phase estimation, is implemented with the ICI cancellation equalizer and the conventional polarization demultiplexing equalizer, while the LMS-MIMO based ICI canceller with two LMS-MIMO equalizers is concatenated with the conventional polarization demultiplexing equalizer and functioned behind the carrier phase estimation to mitigate the ICI for both X and Y polarizations, respectively. It is assumed that both LMS-MIMO and CMA-MIMO based ICI canceller have a similar ICI mitigation performance due to the effectiveness of CMA algorithm to the QPSK signals. However, for the viterbi-viterbi carrier phase estimation before the LMS-MIMO based ICI canceller, each polarization demultiplexed signal with severe ICI distortion is introduced to the carrier phase recovery module. Thus the OSNR is severely degraded due to the existence of unavoidable cycle slips and poor phase noise estimation results. As for the CMA-MIMO based ICI canceller, it is expected to be substantially improved due to the successful ICI removal before the carrier recovery. Note that, to cancel the residual ISI and solve the timing skew among carriers, the tap number of the equalizers is set over 10 in order to cover at least 5 symbols. Importantly, for both ICI cancellers, the equalizer coefficients \( W_{ij} \) and \( C_{ij} \), which are adaptively updated using LMS or CMA algorithm, can effectively represent the weighted interference from the ith polarized wavelength channel to the jth polarized wavelength channel.

3. Simulation results and discussions

As shown in Fig. 1, VPI Transmission Maker 9.0 simulations are carried out with a 3-carrier setup, and the central carrier is chosen under investigation. Three carriers out of the 5 generated optical combs based on complementary frequency shifters technique [22] are chosen as optical sources. The linewidths of the optical combs are characterized to be 100 kHz. Both the LMS-MIMO based ICI canceller and CMA-MIMO based ICI canceller are implemented with 15-tap \( T/2 \)-spaced fractional equalizers. The block size for viterbi-viterbi carrier phase estimation is optimized in each case.

3.1 Back-to-Back (B2B) performance

In order to investigate how close two adjacent carriers can be packed, we first examine the effect of the 4th order Gaussian filter located at the transmitter side. As shown in Fig. 2(a), Nyquist WDM with channel spacing equal to 56 GHz is considered. For conventional DSP without ICI cancellation function, the narrow filter bandwidth causes severe ISI while broad bandwidth over channel spacing introduces a large amount of ICI. The optimum bandwidth appears at around 54 GHz because of the compromise between ICI and ISI. However, using either the LMS-MIMO based ICI canceller or CMA-MIMO based ICI canceller, severe ICI due to the broad bandwidth and tight carrier spacing can be effectively mitigated, and there is no obvious performance penalty with the increase of optical filter bandwidth. Importantly, in both cases, the optimum bandwidths seem to be located around 62 GHz. Therefore, we can conclude that both ICI cancellers have comparable robustness over a broad range of optical filter bandwidths. Next, we choose the optical filter bandwidth of 62 GHz to examine how the two ICI cancellers operate with respect to the reduced channel spacing. In Fig. 2(b), it is clearly shown that for channel spacing from 48 to 70 GHz, the CMA-MIMO based ICI canceller yields no more than 0.2 dB required-OSNR penalty compared with the LMS-MIMO based ICI canceller, indicating that both have comparable performance in sub-Nyquist WDM
systems. Meanwhile, both ICI cancellers are capable to achieve substantial performance improvements for the sub-Nyquist channel spacing. Specifically, both ICI cancellers gain more than 7 dB improvement at 50 GHz channel spacing and maintain less than 2.5 dB penalty as compared to the case of large channel spacing.

![Graph showing performance improvement](image)

Fig. 2. (a) Required OSNR at BER = 10^{-3} as a function of optical filter bandwidth, channel spacing = 56 GHz; (b) Required OSNR at BER = 10^{-3} versus channel spacing, optical filter bandwidth = 62 GHz.

3.2 Linewidth tolerance

![Graph showing linewidth tolerance](image)

Fig. 3. (a) Linewidth tolerance for Nyquist-spaced and sub-Nyquist-spaced superchannels; (b) Required OSNR as a function of the Viterbi-Viterbi block size for 50 GHz spacing and linewidth = 1 MHz.

We further investigate the linewidth tolerance of the ICI canceller, when different linewidths of optical combs are taken into consideration. Both the optical combs at the transmitter side and the receiver side are assumed to have the same linewidth. In Fig. 3(a), we show the required OSNR for BER = 10^{-3} as a function of the linewidth of the optical combs. All the points are obtained under the condition that optimum viterbi-viterbi block size is used for carrier recovery, while the sub-Nyquist WDM with 50 GHz channel spacing is chosen in comparison of the Nyquist WDM. For the CMA-MIMO based ICI canceller, the maximum tolerable linewidth can reach 40 MHz within the 1 dB required-OSNR penalty for the Nyquist WDM. Furthermore, it is reduced to about 20 MHz in the case of sub-Nyquist WDM. However, using the LMS-MIMO based ICI canceller, the tolerable linewidth is reduced to 10 MHz for the Nyquist-WDM scenario, while the required OSNR quickly increases by several dB with a growing linewidth above 10 MHz. For the sub-Nyquist WDM, the tolerable
linewidth is further reduced to 6 MHz, where more severe ICI is suffered and cycle slip has a high probability of occurrence. Figure 3(b) further presents the required OSNR as a function of viterbi-viterbi block size, taking 1 MHz linewidth into account. It shows that, the optimum block size for the CMA-MIMO based ICI canceller is 80, while the optimum block size for the LMS-MIMO based ICI canceller is 110. Moreover, within the 1 dB required-OSNR penalty, the block size for the CMA-MIMO based ICI canceller can be reduced to 20, while it is 50 for the LMS-MIMO based ICI canceller. Thus, in terms of computational complexity of Viterbi-Viterbi carrier phase recovery, the CMA-MIMO based ICI canceller is much simpler than the LMS-MIMO based ICI canceller.

![Graph showing coefficient magnitude versus iteration number for different block sizes.](image)

Fig. 4. The central tap coefficients magnitude versus iteration number for (a) LMS-MIMO based ICI canceller (Y-polarization) with viterbi-viterbi block size = 20; (b) LMS-MIMO based ICI canceller (Y-polarization) with viterbi-viterbi block size = 30; (c) LMS-MIMO based ICI canceller (Y-polarization) with viterbi-viterbi block size = 50; (d) CMA-MIMO based ICI canceller (Y-polarization);

In order to obtain a clear understanding of distortion induced by poor carrier phase recovery of the LMS-MIMO based ICI cancellation, we present the magnitude of the central tap coefficients of the equalizer for the ICI cancellers of the Y-polarization tributary ($W_{45}$, $W_{55}$, $W_{65}$ and $C_{15}$, ..., $C_{65}$) versus the iteration number, as shown in Fig. 4. For X-polarization, it behaves similarly to that of Y-polarization. In the following discussion, the linewidth is set to be 1 MHz for a 50 GHz sub-Nyquist spacing WDM. We complete the carrier recovery in the case of the LMS-MIMO based ICI canceller with the viterbi-viterbi block size equals to 20, 30 and 50. In Fig. 4(b), it is clearly seen that in the presence of severe ICI, there are many glitches of the equalizer coefficients during the process of convergence. The glitches are most likely induced by cycle slips, and they are more likely to happen with a reduced viterbi-viterbi block size, as shown in Fig. 4(a). Note that for the LMS-MIMO based ICI canceller, the symbol error caused by cycle slips no longer occurs only between two
slipped symbols, while a re-convergence of equalizer coefficients is undergoing. It means that, even though the differential coding can correct the phase ambiguity due to the cycle slips, the re-convergence of the coefficients for the LMS-MIMO equalizer will cause equalization distortion which can't be ignored. Alternatively, it is possible to avoid the cycle slips for the LMS-MIMO based ICI canceller, if the block size is large enough, as shown in Fig. 4(c), where the block size is 50 and almost no glitches occur. However, the LMS-MIMO based ICI canceller is unable to achieve this for a linewidth over 6 MHz, because too large block size violates the premise that the symbols captured by the Viterbi-Viterbi block experience the same phase offset. That’s the reason why a sudden increase of the required OSNR appears with linewidth greater than 6 MHz for the sub-Nyquist WDM system with the LMS-MIMO based ICI canceller. For the purpose of comparison, in Fig. 4(d), the equalizer coefficients of the CMA-MIMO based ICI canceller are more stable without any glitches due to its intrinsic insensitivity to the phase ambiguity of the CMA algorithm.

3.3 Parallel procession comparison

![Fig. 5. Q factor as a function of parallel pipeline number for (a) linewidth = 100 kHz. (b) linewidth = 6 MHz](image)

We further evaluate the parallel processing capability for both ICI cancelling, since such feature is indispensable for the real-time implementation. For a certain count of parallel processing pipelines, the convergence speed of the equalizer coefficients for both the CMA-MIMO and the LMS-MIMO based ICI cancellers is reduced, since they can only be updated once over multiple symbols due to parallelism. Figure 5 shows the Q factor as a function of parallel pipeline number for a 50 GHz spaced sub-Nyquist WDM, when the linewidth is characterized to be 100 kHz and 6 MHz, respectively. When the linewidth is small, the degradation of the Q factor with the lower updating speed is quite small for both ICI cancellers. Even when the parallel pipeline number reaches 240, the Q factor penalty remains no more than 1dB. However, for the case of large linewidth of 6 MHz, the Q factor of the LMS-MIMO based ICI canceller is quickly reduced to 4dB, which is even worse than that of the conventional processing technique due to its inability to maintain convergence in the presence of frequent cycle slips. On the other hand, considering the CMA-MIMO based ICI canceller, the tolerance for parallel pipeline number of 240 is still secured within the 1dB required-OSNR penalty.
3.4 Fiber transmission performance

In order to investigate the transmission performance, three carriers with total optical power of 12 dBm are launched into the SSMF link, indicating that the fiber nonlinearity definitely occurs. Through our investigation, we find that the results of phase noise tolerance and real-time processing capability, after 640 km SSMF transmission, have no apparent difference with that of B2B situation. In order to present the effect of nonlinearity more clearly, we also investigate the superchannels transmission at different distances. In Fig. 6, a series of simulations for superchannels at different transmission distances are carried out. It can be seen that the nonlinearity induced OSNR penalty becomes obvious for both two joint signal processing methods and conventional processing method, when the fiber transmission distance is longer than 640 km. However, the joint signal processing methods always require less OSNR for BER at $10^{-3}$ than that of conventional processing method. Thus we can conclude that in our joint signal processing based superchannel systems, linear ICI can be removed even in the occurrence of nonlinearity and the maximum transmission distance is mainly limited by the launch power of optical carriers.

3.5 Optical comb synchronization

Since the precise synchronization of the two comb sources needs to pay substantial effort in real experiments, we here investigate the case of two independent combs without synchronization. Through a careful adjustment of the combs, it is possible to control the frequency offset between the two independent combs within the range of 0-4 GHz [23].
Moreover, due to the uniform carrier spacing of the frequency-locked optical comb lines, the frequency offsets of all carriers in the WDM superchannel systems are consistent. In Fig. 7, the effect of frequency offset as much as 4GHz is considered. It can be seen that with the increase of frequency offset, there are no additional BER performance penalties for our proposed CMA-MIMO ICI cancellation method while distinct performance improvements are maintained. That is because when all the carriers are suffering from the same frequency offset, the high frequency band interference can still be exactly retrieved. Therefore, the CMA-MIMO equalizer can still work effectively to eliminate the ICI.

4. Conclusion

We have proposed a new CMA-MIMO based ICI canceller for the sub-Nyquist WDM superchannels, when optical combs are selected as optical sources. Through a comprehensive investigation, our proposed CMA-MIMO based ICI canceller has almost the same performance as that of the LMS-MIMO based ICI canceller. The enabled carrier spacing is reduced to 50 GHz for the 3 × 56 Gbaud DP-QPSK sub-Nyquist WDM system with no more than 2.5 dB required-OSNR penalty for BER = 10^{-3}. In addition, the CMA-MIMO based ICI canceller is verified to be more tolerant of phase noise than that of the LMS-MIMO based ICI canceller. A linewidth over 20 MHz is permitted for a 50 GHz spacing sub-Nyquist WDM supperchannel using the proposed ICI canceller. Moreover, the CMA-MIMO based ICI canceller is robust in parallel processing allowing 240 parallel processing pipelines within a 1 dB required-OSNR penalty. Thus, it is ideal for the CMA-MIMO based ICI canceller to be applied in high-speed real-time processing systems, regardless of linewidth restrictions.

Acknowledgments

This work was supported by the National Basic Research Program of China (973 Program: 2010CB328302), the 863 High Technology Plan (2012AA011301, 2013AA014203), National Natural Science Foundation of China (61275069), and Open Fund of State Key Laboratory of Information Photonics and Optical Communications (Beijing University of Posts and Telecommunications).