RF-pilot aided modulation format identification for hitless coherent transceiver

MENG XIANG,1,2 QUNBI ZHUGE,2,3 MENG QIU,2 XINYU ZHOU,2 MING TANG,1 DEMING LIU,1 SONGNIAN FU,1,* AND DAVID V. PLANT2

1Wuhan National Laboratory for Optoelectronics, and School of Optics and Electronic Information, Huazhong University of Science & Technology, Wuhan, 430074, China
2Department of Electrical and Computer Engineering, McGill University, Montreal, QC, H3A 2A7, Canada
3Ciena Corporation, Ottawa, Ontario, K2H 8E9, Canada
*songnian@mail.hust.edu.cn

Abstract: We propose a RF-pilot aided modulation format identification (MFI) technique to enable a hitless flexible coherent transceiver with fast format switching. For the MFI, modulation format information is encoded to the amplitude of the RF-pilot, which can be simultaneously used for the compensation of both laser phase noise and fiber nonlinearity. The proposed MFI technique is able to identify arbitrary modulation formats including multidimensional formats and hybrid QAM formats. The high accuracy of the proposed MFI scheme is experimentally demonstrated without sacrificing the tolerance of both laser phase noise and fiber nonlinearity for various modulation formats up to dual-polarization (DP) 64QAM. Finally, over 2240 km standard single mode fiber (SSMF) link, we experimentally demonstrate a hitless coherent transceiver with a fast block-by-block modulation format switching enabled by the proposed MFI.

© 2017 Optical Society of America

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (060.4080) Modulation.

References and links

1. Introduction

Due to the emergence of bandwidth-consuming services such as high-definition video streaming, cloud and 5G, optical network is evolving from a conventional fixed architecture to an agile and intelligent network [1–3]. Recently, hitless flexible transceiver has gained increasing attentions owing to its ability to adapt transceiver configurations such as bit-rate and modulation format according to instantaneous link margin without interrupting network traffic [4–6]. Such hitless flexible transceivers further exploit potential network capacity in a dynamic environment. A key building block of hitless flexible transceiver is modulation format identification (MFI), which is used to reconfigure the digital signal processing (DSP) flow at the receiver-side (Rx) when the format of received signals is changed. Recently, several MFI techniques based on the properties of specific standard QAM formats have been proposed [7–13]. For example, MFI can be realized in the Stokes space by identifying either the number of clusters or the higher order statistics [7–10]. It can also be implemented by identifying the power distributions of received signals [11–13]. However, those techniques cannot be easily extended to more complex modulation formats, such as hybrid QAM formats or multi-dimensional formats [3,14]. Ref [15] proposed a MFI method for Hybrid QAM by examining the statistical radius distribution of received signal. However, it does not work for higher order hybrid QAM such as hybrid 8QAM/16QAM. Moreover, all those MFI techniques are unable to track a fast block-by-block change of modulation format because of the long averaging length or the high computation complexity to realize single accurate MFI.

Recently, we have proposed a MFI scheme and demonstrated hitless flexible coherent transmissions [5]. In that MFI, the information of modulation format is encoded onto pilot symbols, which are simultaneously used for superscalar phase locked loop (PLL) based carrier phase recovery [16].

In this paper, we propose and experimentally demonstrate a RF-pilot aided MFI scheme for hitless flexible coherent transceivers. The RF-pilot has been proposed for compensation of both laser phase noise and fiber nonlinearities by extracting the pilot phase information at Rx [17–20]. In those systems, the amplitude information of the RF-pilot is not utilized. Here, we propose to encode arbitrary modulation format information onto the amplitude of the RF-pilot for the purpose of MFI. Comprehensive simulations and experiments are conducted to evaluate the performance of the proposed MFI method. Particularly, in the experiment with
34.94 Gbaud signals and various modulation formats up to dual-polarization (DP) 64QAM (419.28 Gb/s), the RF-pilot aided MFI is able to achieve a very high identification accuracy without sacrificing the transmission performance. Moreover, fast hitless modulation format switching between DP-8QAM, set-partitioning (SP) 128QAM and DP-16QAM enabled by the proposed MFI over a 2240 km standard single mode fiber (SSMF) link is demonstrated.

2. Principle of RF-pilot aided MFI

In the system utilizing a RF-pilot for laser phase noise and fiber nonlinearity compensation, the amplitude of the pilot is a constant, which leaves a free dimension for slow information transmission. The proposed MFI scheme encodes the modulation format information of the co-propagating signal onto the amplitude of the RF-pilot. At the Rx, the RF-pilot is extracted using a digital filter. Then the RF-pilot amplitude is decoded for the purpose of MFI, while the RF-pilot phase is used for the compensation of phase noise on signals. In this work, we apply a 2-level amplitude modulation (AM) on the RF-pilot with low level and high level amplitude equal to 1 and \( R_{AM} > 1 \), respectively. The symbol rate of the RF-pilot amplitude modulation is set to \( R_s / M \), where \( R_s \) denotes data symbol rate. In the following investigations, we choose \( M = 512 \). In addition, we conduct MFI for every 2048 data symbols where 4-bit modulation format information can be obtained during each MFI frame. Therefore, \( 2^4 = 16 \) different modulation formats can be identified. Table 1 shows an example of the encoding table with 4-bit information. Apparently, the proposed method is able to identify arbitrary modulation formats. This is very important since the modulation formats in coherent optical transmissions are becoming more complex. Moreover, other system configurations such as symbol rate and FEC settings can also be identified by simply modifying the encoding table.

<table>
<thead>
<tr>
<th>0000: BPSK</th>
<th>0001: QPSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>0010: 8QAM</td>
<td>0011: 16QAM</td>
</tr>
<tr>
<td>0100–0111: High level QAM</td>
<td></td>
</tr>
<tr>
<td>1000–1011: Time-domain hybrid QAM</td>
<td></td>
</tr>
<tr>
<td>1100–1111: Multi-dimensional modulation formats</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 illustrates the phase and amplitude of the received RF-pilot over 8192 data symbols. We can see that the RF-pilot phase tracks the laser phase noise, while the RF-pilot amplitude contains the information for MFI. For example, the decoded sequences ‘0001’, ‘0010’ and ‘0011’ represent QPSK, 8QAM and 16QAM for each MFI frame, respectively.
When additive white Gaussian noise (AWGN) is assumed due to the transmission impairments arising in optical channel, the probability of false identification for the proposed MFI is a function of the SNR of the RF-pilot amplitude symbols, and given by

$$P_{MFI} = 1 - (1 - P_M)^M, \quad P_M = 0.5 \text{erfc} \left( \frac{R_{AM} - 1}{\sqrt{2(1 + R_{AM}^2)}} \right)$$  \hspace{1cm} (1)$$

where $M$ symbols are averaged to magnify the effective SNR by a factor of $M$. $P_{MFI}$ is the probability of false identification, which will be investigated in the next section. Note that the SNR of the RF-pilot amplitude symbols is determined by the SNR of transmitted signal and pilot-to-signal ratio (PSR).

3. Setup, results and discussions

Figure 2 depicts the experimental setup. We generate a digital subcarrier-multiplexing (SCM) signal with 2 subcarriers and the RF-pilot is inserted in-between [17,21]. Identical coding and mapping are first applied to both subcarriers at $R_c = 17.47$ Gbaud with the modulation format assigned by a rate change controller, leading to an aggregate baud rate of 34.94 Gbaud. Although we can assign different modulation formats to each subcarrier, we choose the same modulation format for two subcarriers, for the ease of implementation. Then, root-raised cosine (RRC) pulse shaping with a roll-off factor of 0.1 is implemented before digital subcarrier division multiplexing block. The gap between the two subcarriers for the RF-pilot insertion is set to 1 GHz, leading to a 2.6% bandwidth overhead. The pilot tone is placed at the frequency of 250 MHz to avoid DC blocking. Afterwards, the generated waveforms are loaded to a Ciena WaveLogic 3 transmitter, which incorporates a low-linewidth external-cavity laser (ECL), four high-speed digital-to-analog converters (DACs) and a DP IQ modulator. The wavelength of the laser is set to 1554.54 nm. The output of the transmitter is boosted by an Erbium-doped fiber amplifier (EDFA). A variable optical attenuator (VOA) is used to manage the launch power before the signal enters the re-circulating fiber loop. The fiber loop contains 4 spans of 80 km SSMF, and four EDFAs with a noise figure of 5 dB. After fiber loop transmission, the signal is filtered, pre-amplified and filtered again. After the coherent detection using another ECL, a four-channel real time oscilloscope with a sampling rate of 80 GSa/s per channel is employed to digitize the waveform. Finally, the captured waveforms are processed offline in MATLAB. For the Rx offline DSP, chromatic dispersion (CD) compensation is first performed followed by a coarse frequency offset (FO) correction. Then, the RF-pilot is extracted using a digital third order Gaussian filter with a 3 dB bandwidth of 150 MHz. The phase of the RF-pilot is used to compensate for phase noise and the amplitude of RF-pilot is decoded for MFI with $M = 512$. After subcarrier de-multiplexing and matched filtering, adaptive equalization is implemented with four butterfly 25-tap T/2-
spaced finite impulse-response (FIR) filter. This filter is first adapted by the standard constant modulus algorithm (CMA) algorithm for the purpose of pre-convergence. Then, equalization is done by switching the CMA to decision-directed least-mean-square (DD-LMS) algorithm. Within the DD-LMS loop, carrier phase recovery with a maximum likelihood (ML) algorithm is performed [22]. Finally, signal de-mapping and decoding is applied.

3.1 Simulations results

Before experimental verification, we first provide numerical evaluations of the proposed MFI method for various modulation formats using MATLAB and OptiSystem. The laser linewidth $\Delta \nu$ is 100 kHz and the frequency offset is 1 GHz. Differential coding is not required due to the use of RF-pilot. We first investigate the laser linewidth tolerance under the scenario of back-to-back (B2B) transmissions. Figure 3(a) shows the OSNR penalty to achieve a BER $= 2 \times 10^{-2}$ as a function of $\Delta \nu \cdot T_s$, with respect to the case of $\Delta \nu \cdot T_s = 0$ for the following formats: 1) DP-8QAM, 2) DP-16QAM, 3) set-partitioning (SP)-512-QAM, and 4) DP-64QAM. The encoded bits for the corresponding modulation formats on the RF-pilot can be referred from Table 1. The “Reference” in the figure is the system only using a constant-amplitude RF-pilot [17]. As shown in Fig. 3(a), the performance penalty due to the integration of the MFI function compared with the “Reference” is negligible. Considering 1 dB OSNR penalty, the linewidth tolerances for DP-8QAM, DP-16QAM, SP-512-QAM and DP-64QAM signals are $6.9 \times 10^{-4}$, $3.15 \times 10^{-4}$, $2.3 \times 10^{-4}$ and $9.4 \times 10^{-5}$, respectively. Then, we investigate the transmission performance for various modulation formats. Figure 3(b) depicts the relationship between launch power and BER for DP-8QAM, DP-16QAM, SP-512-QAM and DP-64QAM signals after 5760 km, 2880 km, 1920 km and 640 km SSMF transmission, respectively. Again, almost identical performance is obtained with and without MFI, even under conditions of strong fiber nonlinearities due to the high launch power. These results indicate that the proposed MFI method does not deteriorate system performance. This is somewhat expected since the amplitude modulation of RF-pilot is very slow.

Fig. 3. (a) Laser linewidth tolerance under B2B transmissions. (b) BER versus launch power for DP-8QAM, DP-16QAM, SP-512-QAM and DP-64QAM after 5760km, 2880 km, 1920 km and 640 km SSMF transmission, respectively. PSR = 15 dB.
3.2 Experimental results

Fig. 4. BER as a function of PSR for DP-16QAM signals after 1920 km SSMF transmissions.

Generally, for the systems aided by RF-pilot, the PSR needs to be optimized [18]. This is because at low PSR the ability of phase noise compensation is limited while at high PSR the SNR of data signal is reduced. Therefore, we first experimentally investigate the impact of PSR on system performance. Figure 4 shows the relationship between BER and PSR after 1920 km SSMF transmission for DP-16QAM. It can be seen that BER almost keeps unchanged with PSR varied from $-27$ dB to $-15$ dB. This wide range of optimal PSR is obtained because of the employed ML algorithm for further phase recovery [18]. When PSR is larger than $-15$ dB, there is a performance penalty due to the SNR degradation of data signal. On the other hand, the insets of Fig. 4 show the amplitude waveforms of the received RF-pilot, which is used to conduct MFI. As we can see, a larger PSR improves the accuracy of MFI as the two amplitude levels become more distinguishable. Therefore, a PSR of $-15$ dB is preferred and chosen in our experiments. Next, the B2B performance is evaluated in Fig. 5. The OSNR is swept by using receiver-side noise loading. The theoretical curves are also plotted as references. We can see that the system with MFI and the “Reference” system without MFI show almost the same performance under various OSNRs, which is consistent with the previous simulation results. Figure 6(a) plots the transmission performance as a function of launch power for DP-16QAM, SP-512-QAM and DP-64QAM signals after 1920 km, 640 km and 320 km SSMF transmission, respectively. The results show that both systems achieve almost the same performance under various launch powers, indicating that the applied modulation on the RF-pilot amplitude does not enhance the impact of fiber nonlinearities on the signal. With the optimal launch power, which is 1 dBm, we further evaluate the BER performance at different transmission distances in Fig. 6(b). Again, both systems achieve identical performance indicating that the proposed implementation does not degrade performance. Therefore, we conclude that the proposed MFI method result in no performance penalty in terms of both the laser phase noise and fiber nonlinearity tolerance.
Then, a fast hitless rate change enabled by the proposed MFI scheme is demonstrated by switching the modulation format block by block in a 2240 km SSMF transmission experiment, as shown in Fig. 7(a). The transmitted signal consists of interleaving blocks with DP-8QAM, DP-16QAM, and SP-128-QAM formats. Each block contains 2048 symbols per subcarrier and MFI is conducted for each block during a hitless rate change. Within each block, the SNR (obtained by measuring the noise variance on the received symbols) and the BER of the received data symbols are obtained. First, the SNR is quite stable when we switch the modulation format. The fluctuation is within 0.07 dB. In addition, the obtained BERs are similar for the same modulation format. Figure 7(b) shows the corresponding amplitude waveform of the received RF-pilot. It can be seen that the transmitted modulation formats can be easily identified by decoding the RF-pilot amplitude.
Finally, we evaluate the accuracy of the proposed MFI technique. As mentioned earlier, the proposed MFI scheme can support arbitrary modulation formats by provisioning the encoding table accordingly. The probability of false identification $P_{\text{MFI}}$ of the proposed RF-pilot aided MFI is calculated in the DP-16QAM experimental B2B transmissions. Given different OSNRs, we measure the SNR (from the noise variance) of the received RF-pilot amplitude symbols and estimate $P_{\text{MFI}}$ with different averaging factor $M$ according to Eq. (1).

As shown in Fig. 8(a), $P_{\text{MFI}}$ is determined by the OSNR and $M$. Specifically, at OSNR = 10 dB, which is lower than the required OSNR of QPSK at BER $= 2 \times 10^{-2}$, as $M$ increases from 1 to 12, $P_{\text{MFI}}$ decreases dramatically from the order of $10^{-1}$ to $10^{-10}$. In our implementations where $M = 512$, a very low probability of false identification is guaranteed. In order to further highlight the high accuracy of the proposed MFI method, the performance comparison with other two MFI methods, namely the k-means clustering based Stokes MFI method [7] and the feature-based MFI method [11], is conducted. Figure 8(b) shows the probability of correct MFI for each MFI method as a function of transmission distance with DP-16QAM signals. We carry out 1000 times independent MFI for each transmission distance, in order to calculate the probability. As we can see, no error is observed for our proposed MFI method because of its low probability of false identification as described above. On the contrary, the distances to assure 100% correct MFI for the Stokes MFI and feature-based MFI methods are limited to 1600 km and 2240 km, respectively. Compared with the MFI scheme where the modulation formats information is encoded on the training symbols for PLL initialization [5],
the proposed RF-pilot aided MFI has higher accuracy, because more symbols of 512 are averaged to magnify the effective SNR. To summarize, the proposed MFI method can achieve a superior MFI performance compared with other MFI methods.

4. Conclusions

We propose and experimentally demonstrate a RF-pilot aided modulation format identification (MFI) scheme to enable a hitless coherent transceiver. This MFI method is capable of supporting arbitrary modulation formats, achieving very high identification accuracy and tracking a fast switching of modulation formats. Experimental results show that the proposed MFI induces no performance degradation in terms of laser phase noise and fiber nonlinearities tolerance. Then, a hitless transmission with a fast block-by-block modulation format switching among DP-8QAM, SP-128-QAM and DP-16QAM is successfully demonstrated over 2240 km SSMF transmission. Finally, we show that the proposed MFI method achieves much higher accuracy than other two MFI methods.

Funding

The 863 High Technology Plan (2015AA015502); National Natural Science Foundation of China (61575071, 61331010); and Open Fund (2016OCTN-01) of State Key Laboratory of Optical Communication Technologies and Networks, Wuhan Research Institute of Posts & Telecommunications.