First Demonstration of FPGA-based Hitless Flexible Receiver with Blind Modulation Format Identification

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Abstract: We present a FPGA-based flexible receiver with real-time DSP that adapts to the modulation format of the incoming signal automatically. Hitless switching between 1.024-μs long QPSK and 16-QAM frames has been experimentally demonstrated.

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1. Introduction

As the global IP traffic continues its explosive growth, optical networks are evolving from the conventional fixed grid structure toward a flexible, reconfigurable, and cognitive architecture [1]. By allocating variable bandwidth and modulation formats to each user according to the instantaneous link margin and traffic demands, the next generation flexible network has the potential to significantly increase the total traffic volume [1]. Flexible transceivers that can enable the transmission and reception of a plurality of modulation formats have received substantial research interest [2, 3]. A key building block of a flexible receiver is the modulation format identification (MFI) module, which tracks the format of the incoming signal and reconfigures the digital signal processing (DSP) circuit of the receiver accordingly. This automatic format recognition function removes the need for end-to-end handshaking between the transmitter (Tx) and receiver (Rx). Recently, various MFI techniques have been proposed, including the utilization of machine learning technique or the exploitation of statistics of the signal power distribution [4-6]. However, to the best of our knowledge, a real-time, blind MFI-aided flexible receiver has not been demonstrated yet.

In this paper, we experimentally demonstrate the first real-time, FPGA-based flexible coherent receiver, which supports 10 Gbd QPSK and 16-QAM signals. The unique hardware architecture of the proposed receiver allows dynamic reconfiguration between QPSK and 16-QAM after each clock cycle (312.5 MHz) of the FPGA based on the result of the MFI block. Back-to-back and 300-km transmission experiments are conducted to evaluate the performance of the proposed receiver.

![Diagram](image-url)

Fig. 1. (a) DSP chain of the proposed receiver. (b) Hardware implementation diagram of the MFI used in this work.

2. System architecture

Fig. 1(a) shows the DSP architecture of the proposed flexible receiver. The proposed receiver operates at 312.5 MHz with parallel blocks of 64/32 complex samples and 8-bit data width. Two-fold oversampling (20 GS/s) is utilized before the adaptive equalizer for the 10 Gbaud received signal. Static chromatic dispersion (CD) compensation and Godard-based clock recovery are performed at the beginning of the DSP chain, as they are transparent to different modulation formats. Sampling at twice the baud rate, a 23-tap, fractionally spaced equalizer (FSE) corrects the channel’s distortion and the residual timing error, as well as decimates the samples into 10 GS/s. The equalizer is adapted by the classic constant-modulus algorithm (CMA) by default regardless the modulation format of the incoming signal, but it can be switched to the radius-directed multi-modulus algorithm (RDE-MMA) for 16-QAM depending on the result of the subsequent MFI module. Fig. 1(b) presents the hardware implementation diagram of
the MFI block used in this work. The MFI module identifies QPSK and 16-QAM formats by counting the number of samples located within the inner circle of 16-QAM for a given block of symbols. To conserve the hardware resources, the amplitude of each complex sample can be obtained by using CORDIC softcore instead of multipliers and adders. For a block of 256 symbols, if there are over 32 samples whose amplitude is less than the decision threshold (0.724), the MFI counts this block as 16-QAM signal. Otherwise, the MFI decides that the signal is QPSK. Finally, the time-domain QPSK-partitioning based frequency offset estimation (FOE) and Viterbi-Viterbi carrier phase recovery (CPR) are applied to eliminate the wavelength mismatch and phase noise [7]. The output of the MFI module is feedforwarded to the FOE and CPR modules to control whether to bypass the partitioning block (in case of QPSK) or not (in case of 16-QAM). Both the FOE and the CPR modules operate in polar coordinates, and the average filter length is 256 for FOE and 16 for CPR. The demodulated samples are then transferred to an external workstation via the UART interface for symbol decoding and error counting. The proposed receiver uses 329,438 (76.04%) of slice look up tables (LUTs), 335,710 (38.74%) of slice registers, and 2,276 (63.22%) of DSP blocks.

3. Experimental setup and results

![Experimental setup](image)

Fig. 2. (a) Experimental setup. PC: polarization controller. VOA: variable optical attenuator. EDFA: erbium-doped fiber amplifier. BPF: bandpass filter. ADC: analog-to-digital converter. (b) FPGA placement view of the proposed flexible receiver. Pink: adaptive equalizer (CMA + MMA). Green: FOE. Blue: CPR. Yellow: Memory. IO interface and clock recovery.

Fig. 2(a) shows the experimental setup for the real-time flexible receiver characterization. A 30-kHz linewidth external cavity laser (ECL) is used as the Tx laser. The Tx laser is modulated with a 10 Gb/s QPSK or 16-QAM signal with a LiNbO3 I/Q modulator and an electrical arbitrary waveform generator (EAWG) with 12 GS/s sampling rate and ~ 4.5 effective number of bits (ENOB). The output of the I/Q modulator is fed to a noise loader or a 300-km fiber span. The fiber span consists of 150-km standard single mode fiber (SSMF) and 150-km dispersion shifted large-effective-area-fiber (LEAF). At the Rx, the optical signal is mixed with a 100-kHz linewidth local oscillator using a 90-degree optical hybrid and subsequently detected by two pairs of balanced detectors. The electrical signal is then sampled and fetched to a Virtex-7 FPGA board (xc7vx690t), which contains the DSP chain in Fig. 1(a). Fig. 1(b) depicts the floorplan of the FPGA chip with the implemented DSP algorithms.

Fig. 3(a) shows the back-to-back results for the 10 Gb/s QPSK and 16-QAM signals with noise loading. The optical signal to noise ratio (OSNR) is measured by an optical spectrum analyzer (OSA) with 0.1 nm resolution bandwidth. The back-to-back results show that the proposed receiver can achieve a BER of ~2×10^-3, which is less than the 7% HD-FEC threshold (3.8×10^-3), with 17 dB OSNR for 16-QAM. We attribute the measured error floor of 16-QAM signal to the limited ENOB of the EAWG, as the equivalent signal to noise ratio (SNR) per bit is around 6.02 dB/bit [7]. The insets in Fig. 3(a) present the constellations for QPSK and 16-QAM at OSNR values of 15 dB and 31 dB, respectively. Fig. 3(b) depicts the results from the 300-km transmission experiment for QPSK and 16-QAM by adjusting the launch power of the fiber span. The optimal Q-factor for QPSK and 16-QAM signals are 18.2 dB and 10.3 dB with -2 dBm and -7 dBm launched power, respectively.

To verify the dynamic modulation format tracking and switching functionality of the proposed receiver, we concatenated 10,240 QPSK and 10,240 16-QAM signals together without any guard time or training symbol, and loaded the corresponding waveform into the EAWG. Then, we conducted the second back-to-back experiment with
noise loading. First, we swept the OSNR and measured the successful recognition rate of the MFI module. The results in Fig. 3(c) show that the proposed flexible receiver can achieve very high identification accuracy (over 99%) between QPSK and 16-QAM when the OSNR is larger than 12 dB. Fig. 3(d) depicts the results of the modulation format switching experiment with 30 dB OSNR. Each data point is averaged over 128 samples to show the rapid modulation switching and plotted as a function of time (number of clock cycles). Due to the limited number of symbols for each block, we calculated the Q-factor instead of the BER. It shows the proposed receiver can achieve a Q-factor around 15 dB for QPSK and 8.9 dB for 16-QAM even if the modulation format of the incoming signal is rapidly switching for every 1024 ns. The constellation of the demodulated samples is shown in Fig. 3(e).

![Image]

Fig. 3. (a) Back-to-back experimental result (b) transmission result after 300-km (c) measured probability of correct recognition as a function of OSNR. Inset: loaded waveform on EAWG (d) Measured Q-factor as a function of time. (e) constellations for the dynamically switching QPSK/16-QAM formats.

4. Conclusion

For the first time to our knowledge, we demonstrate a FPGA-based real-time flexible coherent optical receiver that can track and adapt to the modulation format of the incoming signal. Blind and hitless reception of rapid switching (1,024 ns) 10 Gbd QPSK and 16-QAM signal with high signal quality is demonstrated. The proposed flexible receiver is suitable for the future elastic and flexible optical network where the modulation format between each link may be dynamically reconfigured.

5. References


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