Blind symbol synchronisation in direct-detection optical OFDM using virtual subcarriers

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Abstract: We investigate the performance of a novel blind symbol synchronisation technique using a 30.65Gb/s real-time 16-QAM OFDM transmitter with direct detection. The proposed scheme exhibits low complexity and does not have any bandwidth overhead.

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1. Introduction

Direct-detection optical orthogonal frequency division multiplexing (OFDM) has been suggested as one of the potential technologies for future passive optical networks (PON), data centres, and backhaul links [1,2]. In addition to its spectral efficiency and efficient dispersion compensation, OFDM and orthogonal frequency division multiple access (OFDMA) offer flexible and efficient frequency-domain allocation of bandwidth resources by allowing multiple users to share the bandwidth with fine granularity [1]. Moreover, the highly-digital implementation of OFDM transceivers makes it a promising high performance and cost-effective solution.

Symbol synchronisation, which is the process of aligning the receiver fast Fourier transform (FFT) with the transmitter inverse FFT (IFFT), is a key component in the OFDM transceiver design. Any misalignment between the two would cause the FFT to process samples from adjacent symbols leading to inter-symbol interference and BER degradation. Amongst the several methods that have been proposed for symbol synchronisation in wireless systems is the well-known Schmidl and Cox (S&C) algorithm [3], however, direct implementation of this method in high speed optical communications is very complicated because these systems usually have DSP clock frequency much lower than the sampling rate. In addition, S&C and most OFDM synchronisation methods use training symbols for symbol synchronisation; this side information leads to a reduction in the system capacity.

Recently, synchronisation techniques targeting optical OFDM have been developed [4-9]. Giddings et al [4] proposed a DC offset to be added to the signal with different levels to differentiate between the symbols. Bouziane et al. presented a method using training symbols and frequency-domain cross-correlation in [6] and another technique based on the standard deviation of the FFT output symbols in [7]. Most recently, we proposed a non-data aided algorithm that offers even lower complexity by constraining the computation to the virtual subcarriers (VSC) which constitute a small fraction of the FFT output [8]. The proposed method uses the power of VSC (P_vsc) as an indicator of symbol offset. Assuming the system is noise-free, P_vsc should be zero if symbol synchronisation is maintained; otherwise, energy from adjacent subcarriers will leak to VSC. Based on this, one can detect the timing offset by tracking P_vsc and determining its minimum. The accuracy of the method can be improved if the calculated power is averaged over multiple symbols. The resulting reduction in DSP complexity and bandwidth overhead makes this technique a practical approach in optical OFDM systems.

In this paper, we assess the performance of the method using real-time-generated signals and compare its performance with that of S&C. The real-time transmitter is implemented with an FPGA and generates direct-detection 16-QAM OFDM signals with a bit rate of 30.65Gb/s.

2. Experimental set up

Figure 1 shows the block diagram of the OFDM transmitter digital signal processing (DSP). At each clock cycle, a sequence of 200 bits from a 2^{15} DeBruijn pattern was sent to 16-level quadrature amplitude modulation (16-QAM) encoders generating 50 complex symbols. These symbols and their complex conjugates were fed to a 128-point inverse fast Fourier transform (IFFT) using the Hermitian symmetry so that the output of the IFFT was real, thus following the discrete multi-tone (DMT) configuration. The symbol mapping and the IFFT both had 12 bits of resolution. To design the IFFT block, we utilized Spiral, a tool that can automatically generate hardware and software cores for DSP transforms [9]. Subcarriers located at the higher frequencies (26 of them) were used as virtual subcarriers (set to zero) because they had low signal-to-noise ratio (SNR) due to the roll-off in the system frequency response and used for the proposed VSC synchronisation scheme. The output of the IFFT was then clipped and scaled to reduce the peak-to-average power ratio of the signal and match the resolution of the DAC (6 bits). These DSP blocks were implemented on a Xilinx Virtex-5 FPGA board (XC5VFX200T) running at a clock frequency of 156.25MHz. The transmitter employed 50 data subcarriers all encoded with 16-QAM resulting in a raw data rate of 31.25Gb/s. An overhead of 1.9% was allocated for training symbols; therefore, the data rate was 30.65Gb/s.

The output of the FPGA is passed to a DAC (Micram VEGA DAC II) with a sampling frequency of 20 GS/s and a nominal resolution of 6 bits. The output of the DAC was used to drive a Mach-Zehnder modulator to generate the intensity-modulated signal waveform. An external cavity laser (ECL) provided the continuous wave (CW) optical carrier signal to the modulator at 1550nm. In the optical back-to-back configuration, the output of the modulator was amplified using an erbium-doped fibre amplifier (EDFA) and then attenuated before being received by a Discovery photo-detector (DSC10) followed by an SHF amplifier (SHF806P) and a Tektronix digital sampling scope with 50GS/s sampling frequency and 8 bits of resolution (ENOB of 4.5). The captured waveforms were then processed offline using Matlab. The receiver offline DSP included the following blocks: symbol synchronisation, FFT, channel equalisation, symbol de-mapping, and bit error ratio (BER) calculation. The channel frequency response estimation was performed using 10 training symbols in every 512 OFDM symbols, therefore the training symbols overhead was approximately 1.9%. Figures 1 b,c show example constellations of the received signals at 2dBm received power (all subcarriers are plotted together in figure 1.b and only one subcarrier- subcarrier number 10- is plotted in figure 1.c).

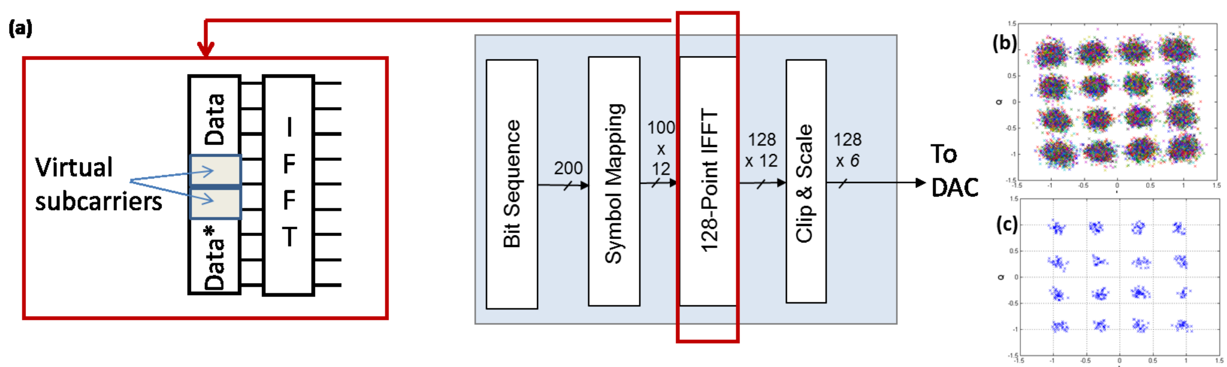

Figure 1. (a) Block diagram of the transmitter DSP, (b) constellation diagram of the optical-back-to-back signal at 2dBm (c) constellation diagram showing the 10th subcarrier only.

3. Performance comparison between S&C and the proposed synchronisation method

The received power was varied from -11dBm to +3dBm and BER was calculated in each case. Figure 2.a shows the BER of the system as a function of the received power using the Schmidl and Cox algorithm in one case and using the proposed virtual subcarrier-based synchronisation method with different numbers of averaging symbols (symbols over which the power calculation was averaged) in the other cases. The forward error correction (FEC) limit of 3.8×10^{-3} is indicated in the figure as well. BER is below the FEC limit for received powers greater than or equal to -1 dBm.

Using 100 symbols, the performance of the proposed method is similar to that of S&C. However, reducing the number of symbols degrades the performance at low received powers. With 10 symbols, the performance of the two methods is the same down to a received power of -7dBm. Figure 2.b shows the minimum received power at which the performance of the proposed method matches that of S&C as a function of the number of symbols over which the metric is averaged. For best performance, 100 symbols need to be used. It is worth noting that although the synchronisation rate (the rate at which synchronisation is achieved) increases in the case of 100 symbols (10 times than that of 10 symbols), the complexity remains the same. Figure 2.b shows this trade-off between robustness and synchronisation rate.

In terms of complexity, the proposed method operates in the frequency domain at the output of the FFT and calculates the power of virtual subcarriers only requiring 26 complex multipliers and 25 real adders (a small amount of operations relative to the rest of the processing). If S&C is implemented in parallel over S=128 channels, it would require S=128 complex multipliers and S^2=16384 real adders, although simpler implementations have been suggested e.g. [10], but with other limitations.

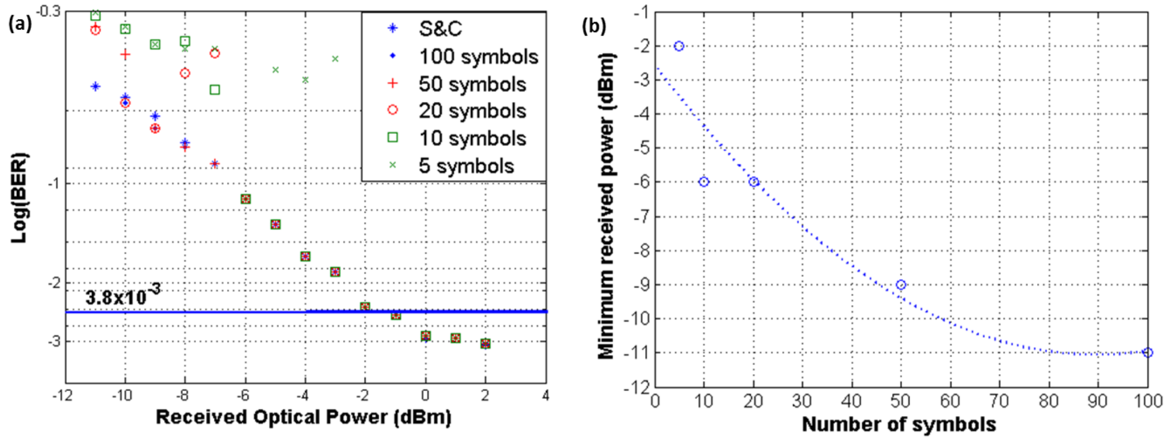

Figure 2. (a) Performance comparison between Schmidl and Cox algorithm (S&C) and the non-data aided synchronisation method using different numbers of symbols (b) Minimum received power to match the performance of S&C vs. number of averaging symbols.

4. Conclusion

The paper assessed and quantified the performance of a novel synchronisation techniques based on virtual subcarriers. The experimental set up included an FPGA-based real-time optical OFDM transmitter operating at a bit rate of 30.65Gb/s in a direct-detection configuration. The proposed symbol synchronisation scheme exhibits low complexity and does not have any bandwidth overhead. There is a trade-off between accuracy and synchronisation rate.

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6. References

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