Unified direct and coherent orthogonal frequency division multiplexing optical transmission scheme

Presnetation By Itay Yahav

Stanley Johnson and Milorad Cvijetic

College of Optical Sciences, University of Arizona

Published on December 14, 2015

Outline

Direct Detection

Direct detection acts as square law detector. The photodiode takes the square of the optical field on the incoming signal and results in an electrical signal whose current variations are proportional to the square of such optical field.

$$i_d(t) = |E(t)|^2 = E(t) \cdot E^*(t) \tag{1}$$

In frequency domain

$$i_d(\omega) = E(\omega) * E^*(-\omega) \tag{2}$$

Where $*$ is convolution operator.

Coherent Detection

Coherent detection use local oscillator (LO), which is in-phase with optical carrier, to recover both amplitude and phase of the signal in contrast to direct detection receiver.

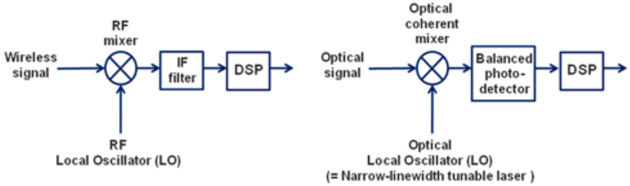


Figure: https://www.neophotonics.com/merits-coherent-detection-optical-transmission/ [4]

A Self-coherent detector does not need LO. For example:

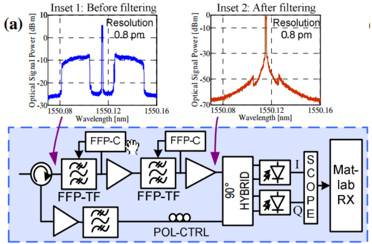


Figure: Self- Coherent Optical OFDM: An Interesting Alternative to Direct or Coherent Detection [5]

OFDM - Orthogonal Frequency Division Multiplexing

Multi-Carrier Modulation (MCM) is a principle of transmitting by dividing the stream into several bit streams, each of which has a much lower bit rate, and by using these substreams to modulate several carriers. OFDM is a special class of Multi-Carrier Modulation [1].

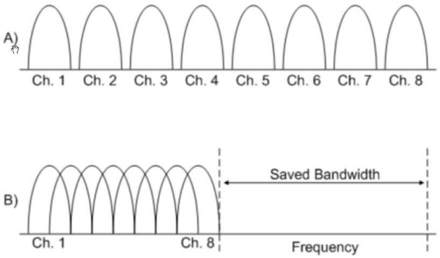


Figure: Optical Orthogonal Frequency Division Systems with Direct Detection Receivers,Juan Miguel Prez Rosas, University 2013

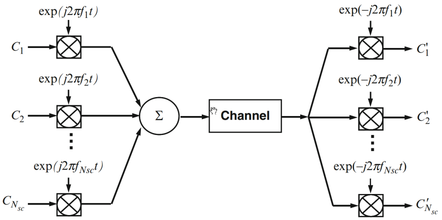


Figure: S. Kumar (ed.), Impact of Nonlinearities on Fiber Optic Communications, Chapter 2

MCM signal $s(t)$ is:

$$s(t) = \sum_{i=-\inf}^{+inf} \sum_{k=1}^{N_{SC}} c_{ki} s_k(t - iT_s) \tag{3}$$

$$s_k(t) = \Pi(t) e^{j2\pi f_k t} \tag{4}$$

OFDM signal is where MCM signals are orthogonal:

$$\begin{aligned} \delta_{kl} &= \frac{1}{T_s} \int_0^{T_s} s_k s_l^* dt = \frac{1}{T_s} \int_0^{T_s} e^{j2\pi(f_k - f_l)t} dt \\ &= e^{j2\pi(f_k - f_l)T_s} \frac{sin(\pi(f_k - f_l)T_s)}{\pi(f_k - f_l)T_s} \end{aligned} \tag{5}$$

When $f_k - f_l = m\frac{1}{T_s}$, two subcarriers are orthogonal.
These orthogonal subcarriers can be recovered with matched filter without intercarrier interference (ICI).

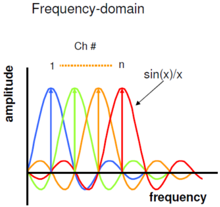


Figure: Optical Orthogonal Frequency Division Systems with Direct Detection Receivers,Juan Miguel Prez Rosas, University 2013

Example of Coherent OFDM (CO-OFDM) transmission system:

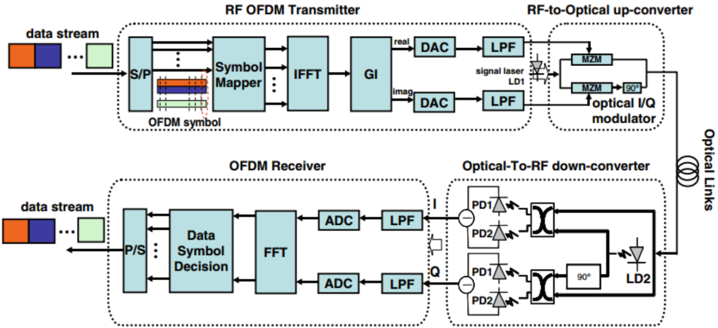


Figure: S. Kumar (ed.), Impact of Nonlinearities on Fiber Optic Communications, Chapter 2

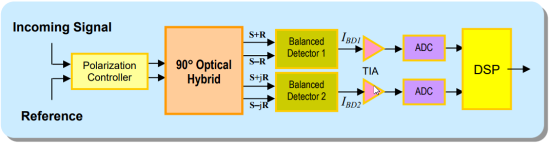


Figure: http://www.optoplex.com/download/coherent_detection_and_optical_hybrid.pdf

Balanced detection is used in order to suppress the DC component and maximize the signal photocurrent [6].

Unified Tx System
Concept

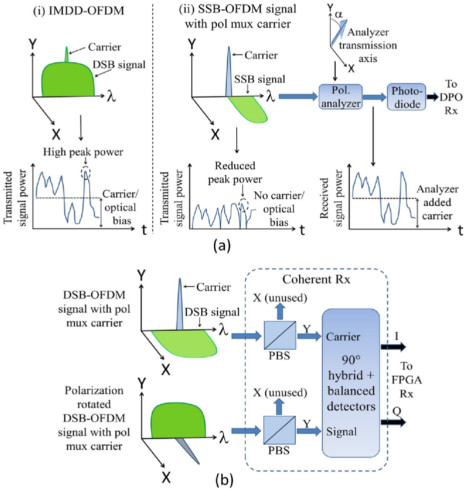
- The idea is to unified direct and coherent OFDM transmitter that is able to communicate simultaneously with both simple direct detection receiver and coherent receiver.

- It provides scalability, flexibility, and higher efficiency since the detection scheme can be readily interchanged.

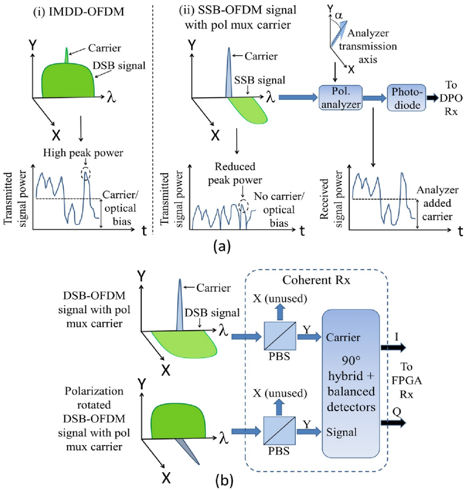
Unified Tx System

Concept - Carrier Signals

- Two sidebands can be around the optical carrier frequency OFDM signal. Each sideband can be turned on/off independently.
- Turning on a single sideband (SSB) can work with both direct and coherent receivers.
- Turning on dual sidebands (DSB) works only with coherent detection receiver.
- The optical signal is transmitted with two orthogonal polarizations. One for the carrier and the other for signal to reduce peak-to-average power ratio (PAPR) and for self-coherent detection.



- Direct receivers can detect only SSB-OFDM. They consists Polarization Analyzer (PA), photodiode and Digital Phosphor Scope (DPO).
- Direct receivers are relatively low cost and simple, although they can receive only half bit rate.
- The optimum value of α ,α_{opt}, is determine according to SNR limits.



Optimum PA Angle

The optical signal incident the photodiode is:

$$\begin{aligned}&[E_{carr}e^{j\omega_{carr}t}\cos(\alpha)+E_{sig}e^{j\omega_{sig}t}\sin(\alpha)]^2 \\ &= E_{carr}^2\cos^2\alpha+E_{sig}^2\sin^2\alpha+2E_{carr}E_{sig}\cos[(\omega_{carr}-\omega_{sig})t]\cos\alpha\sin\alpha\end{aligned} \tag{6}$$

The desire signal is

$$S_{sig-carr}=2E_{carr}E_{sig}\cos[(\omega_{carr}-\omega_{sig})t]\cos\alpha\sin\alpha \tag{7}$$

The noise is

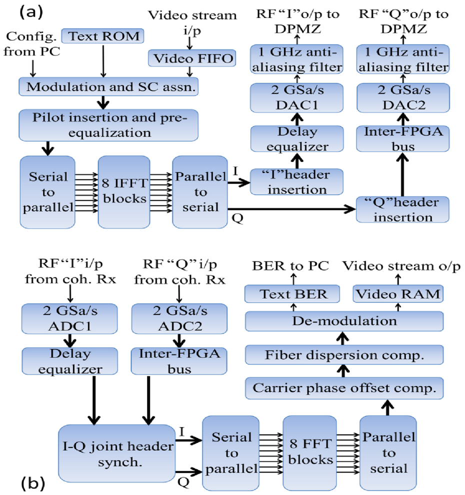
$$N_{sig-sig}=E_{sig}^2\sin^2\alpha \tag{8}$$

The requirement for adequate reception is when $S_{sig-carr}/N_{sig-sig}>10$. With the condition $E_{sig}=E_{carr}$ and maximizing E_{sig} we get

$$\alpha_{opt}=10^\circ \tag{9}$$

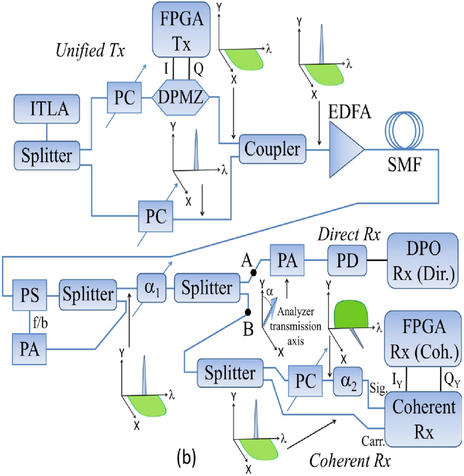
Modulation Setup

- FPGA system used to modulated and demodulate the data (text and video) on Tx and Rx respectively.
- 8 parallel 512 point inverse fast fourier transform (IFFT) blocks.
- Each block clocked at 250 MHz and produce complex value.
- Subcarrier are turned on/off to produce SSB or DSB OFDM signal.
- FPGA on Tx side outputs analog I-Q signals.



Experiment Setup - Tx

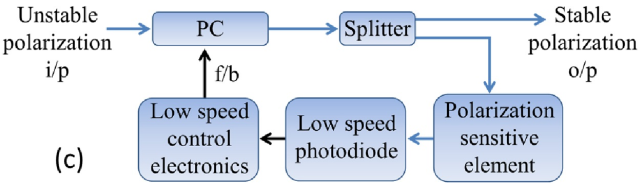
- The Integrable Tunable Laser Assembly (ITLA) (1550.12 nm) is carrier signal for FPGA Tx signals I and Q. The carrier and the signal are passed through Polarizer Controller (PC) with α_{opt}.
- dual-parallel Mach-Zehnder (DPMZ) is used to modulate the signal over the ITLA source.
- Erbium-Doped Fiber Amplifier (EDFA) set input power (10-17 dBm) into the 20 Km single mode fiber (SMF).



(b)

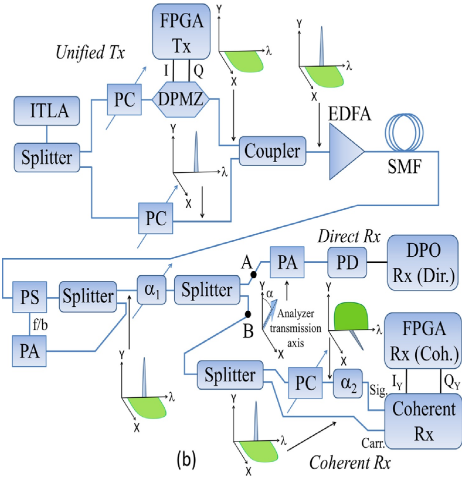
Polarization Tracking

- Polarization tracking system maintain constant polarization state at the output of the tracker using feedback control.
- The tracker stabilize the random changes of the polarization drift in the fiber.
- Polarization of light at the output of a fiber changes over time in the microsecond to millisecond range, the photodiode and control electronics needed in the feedback path are required to have only an electrical bandwidth in the MHz range and a sampling rate in the MSa/s range.

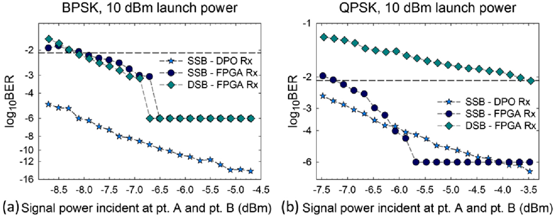


Experiment Setup - Rx

- Variable optical attenuator (VOA), α_1, control the input power to receivers.
- Direct detector consists of PA tuned to α_{opt} and PIN photodiode connected to DPO.
- Self-Coherent detector consist of PC, fixed optical attenuator α_2 to set the optical signal power to be 13 dB lower than the optical carrier power for proper coherent detection and standard coherent detector.



Experiment Result



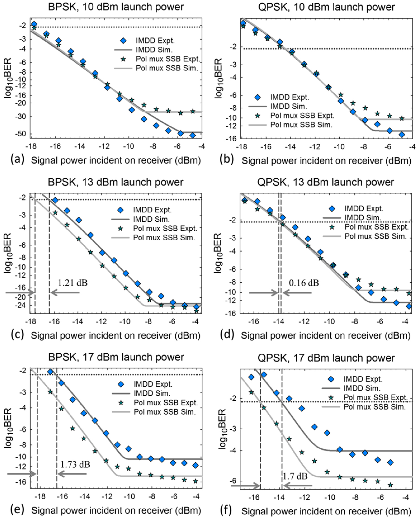
- Different BER measurement method for DPO and FPGA.
- BER measurement on FPGA-Rx is limited to 1E-6 due to hardware resource limitations.
- The differences between the direct and coherent receiver implementations (optical and electrical) account for the difference in the BER measured for the same pol-mux SSB-OFDM configuration.
- In (a), The step change of SSB and DSB on FPGA-Rx is due to OFDM frame synchronization that lose accuracy under certain amplitude value.
- In (b), DSB has higher BER than SSB since the constant optical power has to be shared among a larger number of loaded subcarriers thus lowering SNR for each subcarrier.

Comparison Of POL-MUX OFDM With IMDD-OFDM

IMDD - Intensity-Modulation Direct-Detection

- At 10 dBm lunch power, IMDD and SSB-OFDM has the same BER.
- At 13 dBm lunch power, IMMD has slighter higher BER than SSB-OFDM.
- At 17 dBm lunch power, SSB-OFDM has lower BER and better receiver sensitivity.

This demonstrates that Pol-Mux scheme is resilient to impairments due to nonlinear effects in the fiber.

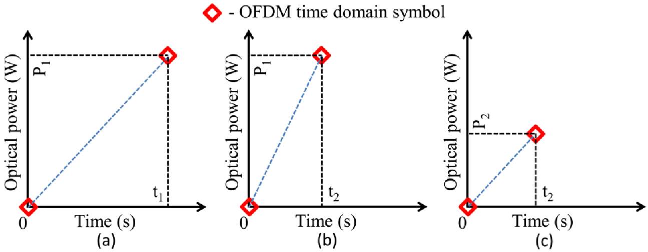


SPM -Self Phase Modulation

Optical carrier frequency is shifted due to nonlinear effect in optical fiber called SPM. The shift is given by:

$$\delta\nu = \frac{-1}{\lambda}\frac{L_{eff}}{A_{eff}}n_2\frac{dP}{dt} \tag{10}$$

where $\delta\nu$ is the frequency shift of the optical carrier, λ is the wavelength of the carrier, L_{eff} and A_{eff} are the effective length and cross-sectional area of the fiber respectively, n_2 is the Kerr coefficient, P is the instantaneous optical power. All parameters in (10) are constants for defined system except dP/dt which varies according to signal time domain. Doubling the sampling rate (e.g $t_2 = t_1/2$) will double the frequency shift. Thus, lowering lunch power by half will have the same SPM effect but with double rate.

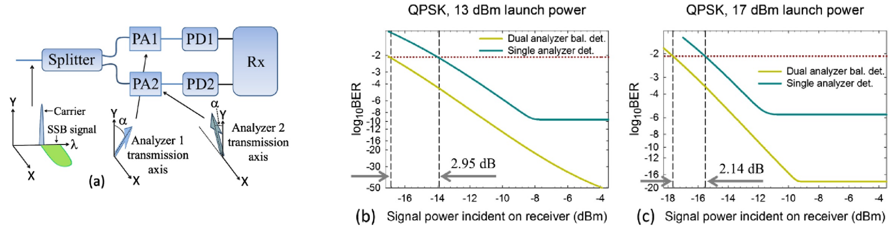


Dual Analyzer Balanced Detection (DABD)

To enhance Pol-Mux SSB-OFDM, Additional PA with angle, $-\alpha_{opt}$, is placed before PIN photodiode.

$$
\begin{aligned}
&[E_{carr} e^{j(\omega_{carr} t+\delta)} \cos(-\alpha) + E_{sig} e^{j(\omega_{sig} t+\delta)} \sin(-\alpha)]^2 \\
&\quad = E_{carr}^2 \cos^2 \alpha + E_{sig}^2 \sin^2 \alpha \\
&\quad - 2E_{carr} E_{sig} \cos[(\omega_{carr} - \omega_{sig})t + (\delta - \delta)] \cos\alpha \sin\alpha \\
&\quad = E_{carr}^2 \cos^2 \alpha + E_{sig}^2 \sin^2 \alpha - 2E_{carr} E_{sig} \cos[(\omega_{carr} - \omega_{sig})t] \cos\alpha \sin\alpha
\end{aligned}
\tag{11}
$$

δ is the residual phase in the second arm. Subtracting these two signals ((6) and (11)) leaves only signal-carrier interference term.



Conclusion and Future Work

Conclusion:

- A Unified Tx for both SSB and DSB OFDM has been demonstrated using Pol-Mux for direct detection and coherent detection.
- Pol-Mux scheme showed resilience to non-linearity (low PAPR). Thus reducing receiver DSP complexity.

Feature Work:

- Simulate and experiment with more complex optical setup (for exapmle: longer fiber with preamplifier and dispersion compensation).
- Transmit with higher samples per seconds and more complex modulation symbols (i.e PAM-4).
- Embed DABD and in silicon photonics.

Reference

- [1] S. Kumar (ed.), Impact of Nonlinearities on Fiber Optic Communications, Chapter 2.
- [2] Optical Orthogonal Frequency Division Systems with Direct Detection Receivers,Juan Miguel Prez Rosas, University 2013
- [3] http://www.optoplex.com/download/coherent_detection_and_optical_hybrid.pdf
- [4] https://www.neophotonics.com/merits-coherent-detection-optical-transmission/
- [5] Self-coherent optical OFDM, an interesting alternative to direct or coherent detection, S. Adhikari, S. L. Jansen, M. Alfiad, B. Inan, V. A. J. M. Sleiffer, A. Lobato, P. Leoni, and W. Rosenkranz.
- [6] All-Optical Signal Processing for High Spectral Efficiency (SE) Optical Communication, Y. Ben Ezra, B.I. Lembrikov, Avi Zadok, Ran Halifa and D. Brodeski