Direct Detection Optical OFDM (DD-OOFDM): Theory and First Experiments

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Motivation

• In DD-OOFDM, modulator bias was shown by simulation to
  – be a key parameter to achieve high sensitivity
  – allow for balancing spectral efficiency versus sensitivity

• Aim of this contribution:
  – to show the improvement of sensitivity due to optimized biasing by a theoretical model
  – to experimentally verify the impact of modulator bias on sensitivity
  – to show several experiments aiming at optimization of sensitivity
Outline

1. Introduction

2. Theoretical model for impact of MZM biasing

3. Experimental results
   – first experiments (proof of concept)
   – experiments aiming at improved sensitivity

4. Conclusion
Introduction: OOFDM Principles

- **Direct detection optical-OFDM**
  - ✔ Simple (low effort)
  - ✗ Needs carrier (low sensitivity) and frequency gap (spectrally inefficient)

  ![Diagram of Direct Detection Optical-OFDM]

- **Coherent detection optical-OFDM**
  - ✔ High sensitivity (no carrier) and high spectral efficiency (no gap)
  - ✗ Complex receiver

  ![Diagram of Coherent Detection Optical-OFDM]
Introduction: Modulator (MZM) bias

• Transfer characteristic of MZM

Optical

Relative field and power

$P_{\text{out}}, E_{\text{out}}$

-1

-0.8

-0.5

0

1

Bias at quadrature

Bias at $|V_{\text{bias}}/V_{\pi}|=0.8$

Electrical

$V_{\text{mod}}/V_{\pi}$

Bias point

- Strong carrier power
- More linear impact

$|V_{\text{bias}}/V_{\pi}|=0.8$ (quadrature point)
Theoretical Model: Setup for Receiver

- Optically preamplified receiver

\[ E_a(t) \rightarrow \text{EDFA} \rightarrow \text{Back-to-back transmission:} \]

\[ E_p(t) \rightarrow \text{photo detector} \rightarrow i(t) \]

\[ \Rightarrow \text{receiver input signal} \ E_a(t) \ \text{is equal to MZM output signal} \]

- Back-to-back transmission:

- Modeling in bandpass domain:

\[ E_{MZM}(t) = E_a(t) = \cos \left[ \frac{\pi}{2} \frac{s(t) + V_{bias}}{V_\pi} \right] \cdot \sqrt{2P} \cos(2\pi f_c t) \]

with:
- \( s(t) \): OFDM-signal driving the MZM
- \( V_{bias} \): bias voltage of MZM
- \( V_\pi \): switching voltage of MZM
- \( P \): optical output power of CW-laser
- \( f_c \): optical carrier frequency
Theoretical Model: Computation

• After EDFA and optical filter:

\[ E_p(t) = \cos \left[ \frac{\pi s(t) + V_{\text{bias}}}{2} \right] \sqrt{2GP} \cos(2\pi f_c t) \]

\[ + n_i(t) \cos(2\pi f_c t) + n_q(t) \sin(2\pi f_c t) \]

with:

\[ n_i(t), n_q(t) \]: in-phase and quadrature component of EDFA noise

\[ G \]: EDFA gain

• After photodiode with responsivity \( R \):

\[ i_p(t) = R \left( GP \cos^2 \left[ \frac{\pi s(t) + V_{\text{bias}}}{2} \right] \right) \]

\[ + n_i(t) \sqrt{2GP} \cos \left[ \frac{\pi s(t) + V_{\text{bias}}}{2} \right] + \frac{1}{2} \left[ n_i^2(t) + n_q^2(t) \right] \]
Theoretical Model: Expression for BER

- First-order approximation results in **electrical signal-to-noise ratio**:

\[
\frac{S}{N} = \frac{\pi^2}{2} \cdot \frac{B'_o}{B_e} \cdot OSNR \cdot \left( \frac{\sigma_s}{V_{\pi}} \right)^2 \cdot \tan^2 \left( \frac{\pi V_{bias}}{2 V_{\pi}} \right)
\]

with:
- \( OSNR \): optical signal-to-noise ratio
- \( B'_o \): optical reference bandwidth
- \( \sigma_s \): standard deviation of OFDM-signal

- In case of QPSK-modulation:

\[
BER = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{1}{2} \cdot \frac{S}{N}} \right) = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{1}{2} \cdot \frac{\pi^2}{2} \cdot \frac{B'_o}{B_e} \cdot OSNR \cdot \left( \frac{\sigma_s}{V_{\pi}} \right)^2 \cdot \tan^2 \left( \frac{\pi V_{bias}}{2 V_{\pi}} \right)} \right)
\]
Theoretical Model: Results

• 10Gb/s DD-OOFDM b2b with QPSK subcarrier modulation

• OSNR(0.1nm) req. for BER=10^{-3} vs. modulator bias

• Solid line: theoretical model
  – neglects nonlinearity of
    • modulator
    • photo diode

• Dashed line: numerical results
  – include nonlinearity
  – best sensitivity ≈13dB OSNR

\[
BER = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{1}{2} \frac{\pi^2}{2} \frac{B_p}{B_v} \frac{\text{OSNR}}{\sigma_s} \cdot \left( \frac{\sigma_s}{\nu} \right)^2 \cdot \tan^2 \left( \frac{\pi V_{bias}}{2} \nu \right)} \right)
\]

15 GHz

OSNR[dB] @ BER=10^{-3}

\( \frac{V_{bias}}{\nu} \)

\( \sigma_s = 0.01 \nu \)

\( \sigma_s = 0.05 \nu \)

\( \sigma_s = 0.1 \nu \)

\( \sigma_s = 0.2 \nu \)
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Complex conjugate extension $\rightarrow$ real signal
OFDM signal is generated offline and transferred to the AWG via LAN
AWG (arbitrary waveform generator): 20GS/s, 5.8GHz, interleaving mode
Amplifier: two-stage amplification to use the full characteristic of MZM
Experimental setup (Receiver)

- **Optical Att.1**: *OSNR* tuning
- **Optical Att.2**: controls input power to photodetector
- **Scope** (real-time sampling oscilloscope): 50GS/s, $BW=18$GHz
- **Synchronization**: first 4 OFDM symbols (reference signal) to find maximum correlation (start of time signal)
System parameters

- Back-to-back transmission
- QPSK modulation
- 1024 OFDM symbols
- $N_{\text{FFT}} = 2048$
- Data rates
  - 10 Gb/s: $N = 511$, no frequency gap $W_g = 0$
  - 5 Gb/s: $N = 256$, with frequency gap $W_g = N$
Experimental results

- DSB transmission
- Direct output from AWG

Synchronization

Received constellation
due to noise from AWG
Experimental results

10Gb/s: comparison between theoretical and measurement results

- DSB transmission

- $V_{\text{bias}} = 0.5V_\pi$ (quad. point), $\sigma_s = 0.05V_\pi$

- deviation from theoretical because of impacts of IMD and thermal noise

- BER floor @ BER $\approx 10^{-5}$
Experimental results

10Gb/s: influence of modulation depth $\sigma_s$

- DSB transmission

- $V_{bias} = 0.5V_\pi$ (quad. point)

- Measured improvement is less than theoretical improvement

- BER floor for small and large signals

- BER floor for $\sigma_s = 0.2V_\pi$ starts earlier because of high MZM nonlinearity
Experimental results

5Gb/s: benefit of frequency gap

• DSB transmission

• $V_{\text{bias}} = 0.5V_\pi$ (quad. point), $\sigma_s = 0.05V_\pi$

- Improvement of ~6.5dB @ BER=10^{-3}
  - 3dB for half data rate
  - 3.5dB benefit of the gap

- With gap no BER floor
Experimental results

5Gb/s: influence of modulation depth $\sigma_s$

- DSB transmission

- $V_{bias} = 0.5V_{\pi}$ (quad. point)

- Modulation depth should be between $0.1V_{\pi}$ and $0.2V_{\pi}$

- $\sigma_s = 0.2V_{\pi}$, MZM nonlinearity is high → BER floor at BER $\approx 10^{-5}$
Experimental results

5Gb/s: influence of bias point for $\sigma_s = 0.2 V_{\pi}$

- DSB transmission

- Asymmetrical clipping performs better than symmetrical clipping
• **Stability:**
  > A DC voltage applied to the bias port may induce drift in the operating point over time → adjustment is required

• **improvement:**
  > Optical filter after EDFA for ASE noise reduction
  > Electrical filter after PD for thermal noise reduction

• **SSB transmission (with optical channel)**
  > Avoid power fading due to chromatic dispersion
SSB transmission

Transfer function: 3dB BW ≈ 0.4nm
-20dB transition BW ≈ 10GHz

OFDM signal

AWG

Bias

DAC

MZM

EDFA (booster)

tunable

SSB filter

EDFA (preampl.)

FBG 0.2nm

$B_e = 12\text{GHz}$

ASE filter

Scope

ADC

DSP

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SSB Transmission

- **Optimization: trade off between sideband suppression and bias point**
  - Low sideband suppression: biasing near null power point
  - High sideband suppression: biasing near quadrature point
Experimental results

5Gb/s: B2B transmission

-\log_{10}(BER)

OSNR [dB]

DSB
SSB

~2dB

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Experimental results

- SSB transmission
- Received at OSNR=10dB and BER ~ 1e-3

Time signal and spectrum after photodiode

Constellation

Intermodulation distortion
Conclusions

• Analytical:
  - The increase in sensitivity when optimizing MZM bias voltage is treated analytically for DD-OOFDM
  - Good agreement of theoretical analysis and numerical simulation over a wide range of values for the bias voltage

• Experimental: sources of sensitivity degradation
  - MZM nonlinearity → driving signal of appropriate amplitude \( \sigma_s = 0.1 V_\pi ... 0.2 V_\pi \)
  - Photodiode
    - Intermodulation distortion IMD → needs frequency gap
    - Thermal noise → needs filter

• Further aspects (with optical channel)
  - Synchronization: training symbol
  - Channel estimation: number of OFDM symbol required
Thank you