On the Superposition Modulation for OFDM-based Optical Wireless Communication

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Introduction
Looming Spectrum Crisis

- RF spectrum is limited.
- Visible light spectrum is an unregulated potential solution to the looming Spectrum Crisis.

Visible Light Communications (VLC)

- Existing lighting infrastructure reuse
- High security, no harmful interference.
- Potential energy savings.
- Remarkable experimental results for VLC:
  - > 3.5 Gbit/s with a single 50-µm LED. [2]
  - > 14 Gbit/s with RGB LD [3]
  - > 224 Gbit/s 3m Li-Fi link [4]

Physical Constraints of VLC

- Incoherent off-the-shelf white LEDs are most likely candidates for front-end devices => Only Intensity modulation and direct detection (IM/DD) is possible.
- OOK, M-PPM, PWM and M-PAM implemented in a straightforward fashion.
- High data rates require ISI-resilient scheme => OFDM is more suitable.
- Conventional OFDM is bipolar and complex => Hermitian symmetry.
DCO-OFDM Signal Generation

- A DC bias required for the generation of unipolar signals.
- DC bias increases the energy consumption.
- Energy saved with inherently unipolar techniques such as: ACO-OFDM, PAM-DMT, Flip-OFDM, U-OFDM.
Asymmetrically clipped optical OFDM (ACO-OFDM) (Review)
ACO-OFDM Generation (1/2)

- Sub-carriers are loaded on the odd sub-carriers

\[ x[n] = -x[n + N/2] \]

N is the size of the OFDM frame
ACO-OFDM Generation (2/2)

- Clipping distortion affect only the even-indexed sub-carriers [5]:

\[ x^c(n) = \frac{x(n) + |x(n)|}{2} \]

Distortion term \(|x(n)|\) has the property

\[ |x(n)| = |x(n + N/2)| \]

Clipping distortion is orthogonal to the information

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Enhanced ACO-OFDM
Spectral/Power efficiency problem

- The spectral efficiency of ACO-OFDM is half of the spectral efficiency of DCO-OFDM:

\[ \eta_{ACO} = \frac{\eta_{DCO}}{2} = \frac{\log_2(M)N}{4(N + N_{CP})} \]

- The performance of \( M\)-QAM DCO-OFDM is equivalent to the performance of \( M^2\) –QAM ACO-OFDM, therefore, the performance of ACO-OFDM degrades as the spectral efficiency increases.

- For example: The BER performance of 32-QAM DCO-OFDM is equivalent to the BER performance of 1024-QAM ACO-OFDM.
System Design (eACO-OFDM Tx)

- Multiple information streams of ACO-OFDM can be combined as long as the Inter-Stream-Interference falls into the even-indexed subcarriers. \[ |x(n)| = |x(n + N / 2)| \]

Depth-1
- M-QAM → Odd-index loading → N-IFFT → Clip & Scale → \( x_1^c(n) \)

Depth-2
- M-QAM → Odd-index loading → N/2-IFFT → Repeat 2 times & Clip & Scale → \( x_2^c(n) \)

Depth-\( d \)
- M-QAM → Odd-index loading → N/2^{d-1}-IFFT → Repeat \(2^{d-1}\) times & Clip & Scale → \( x_d^c(n) \)

Cyclic prefixes are ignored in this illustration.
System Design (eACO-OFDM waveforms)

- Notations: $A_{dl}$ and $B_{dl}$ are the first and second subframes of the $l$-th frame time domain ACO-OFDM waveform at depth-$d$.

Depth 1

- $B_{11}$

Depth 2

- $B_{21}$
- $A_{21}$
- $B_{21}$
- $A_{21}$

Depth 3

- $B_{31}$
- $A_{31}$
- $B_{31}$
- $A_{31}$
- $B_{31}$
- $A_{31}$

- All additional streams should have the symmetry: $|x(n)| = |x(n + N / 2)|$

Cyclic prefixes are ignored in this illustration.
System Design (eACO-OFDM Rx)

\[ y(n) \]

\[ \sum \]

\[ \tilde{x}_1^c(n) \]

- N-FFT
  - Odd-index subcarriers
  - Depth-1 M-QAM Symbols
  - Depth-1 Remodulation

\[ \frac{N}{2^{d-1}}\text{-FFT} \]

- Odd-index subcarriers
- Depth-d M-QAM Symbols
Spectral efficiency

- The spectral efficiency at each depth is:
  \[ \eta_{ACO}(d) = \frac{\log_2(M_d)N}{2^{d+1}(N+N_{CP})} \text{ bits/s/Hz,} \]

- The spectral efficiency of eACO-OFDM is:
  \[ \eta_{eACO}(D) = \sum_{d=1}^{D} \eta_{ACO}(d) \]

- In order to match the spectral efficiency of DCO-OFDM, the constellation sizes at each depth should follow the constraint:
  \[ \log_2(M_{DCO}) = \sum_{d=1}^{D} \frac{\log_2(M_d)}{2^d}, \]

The ratio of the spectral efficiency of eACO-OFDM to the spectral efficiency of DCO-OFDM.
Performance Comparison
Theoretical Performance Model

Theoretical performance bound has been established for BER at depth-$d$:

\[
\text{BER}_{eACO}^{(D,d,\gamma)} \approx \frac{4}{\log_2(M_d)} \left(1 - \frac{1}{\sqrt{M_d}}\right) \times \sum_{l=1}^{R} \sum_{k=1}^{N} \Phi \left((2l-1)\sqrt{\frac{3|\Lambda_k|^2 E_{b,\text{elec}} \log_2(M_d)}{2\alpha_{\text{elec}}^{eACO}(D,d)(M_d - 1)N_o}}\right)
\]

where \(E_{b,\text{elec}}/N_o\) is the electrical SNR of real OFDM, \(R = \min(2, \sqrt{M_d})\), \(\Lambda\) is an \(N \times N\) diagonal matrix with the Eigen values of the channel, and \(\alpha_{\text{elec}}^{eACO}(D,d)\) is the eACO-OFDM SNR penalty per bit compared to ACO-OFDM:

The average BER can derived by taking into account the spectral contribution of each depth \(\xi_d\):

\[
\text{BER}_{eACO} \approx \sum_{d=1}^{D} \left(\text{BER}_{eACO}^{(D,d,\gamma)} \xi_d\right)
\]
Electrical Energy Efficiency (Flat ch.)
Optical Power Efficiency (Flat ch.)
Electrical Energy Efficiency (Nonflat ch.)
Optical Power Efficiency (Nonflat ch.)

\[
\text{BER} = \frac{E_{b,\text{opt}}}{N_0} \quad [\text{dB}]
\]

\[
\eta = 1.5 \quad \eta = 4.5
\]
Conclusion

- The ACO-OFDM modulation scheme BER performance degrades as the spectral efficiency increases.
- The enhanced ACO-OFDM proposes a significant electrical energy savings at an equivalent optical energy dissipation (Illumination).
- The optimal combinations of constellation sizes at each depth and their corresponding scaling factors have been determined at different spectral efficiencies.
- The modulation scheme is not limited to OWC only, but applies to any IM/DD system.
Thank you!!!

Questions?