Amplify-and-Forward Integration of Power Line and Visible Light Communications

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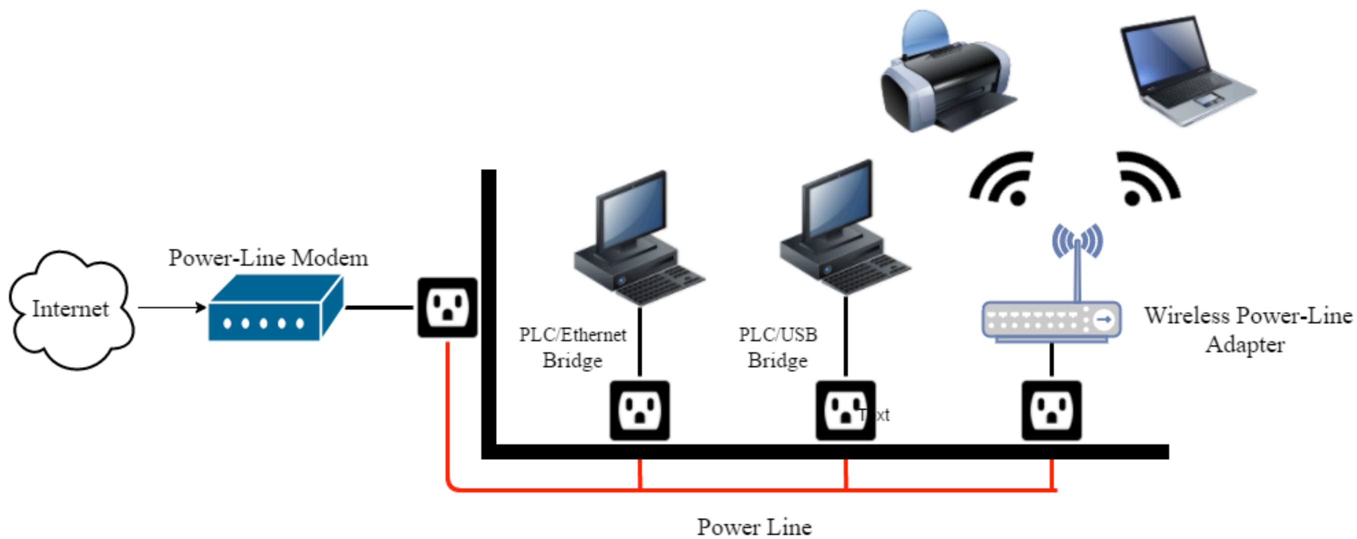
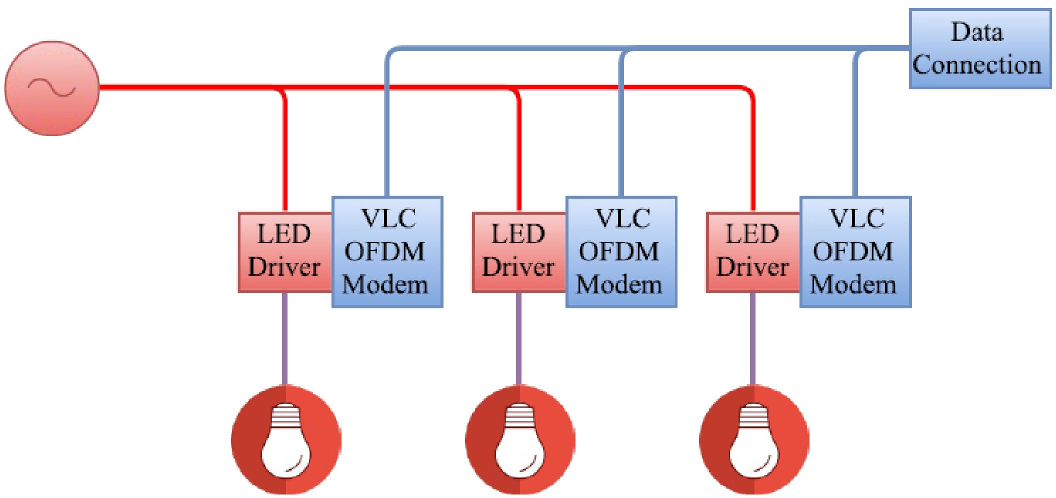
Power-Line Communications

- Powerline communication exploits the existing AC electric power transmission infrastructure for data communication.
- However, stand-alone PLC networks do not support mobility or the ability to broadcast data over a wide area.



Stand-Alone Visible-Light Communications

- VLC systems use existing luminaries based on energy-efficient light-emitting diodes (LEDs) to transmit data by imperceptibly modulating their brightness.
- Although VLC networks have the potential to provide wide-spread coverage indoors, they require a fast and cost-effective backbone.

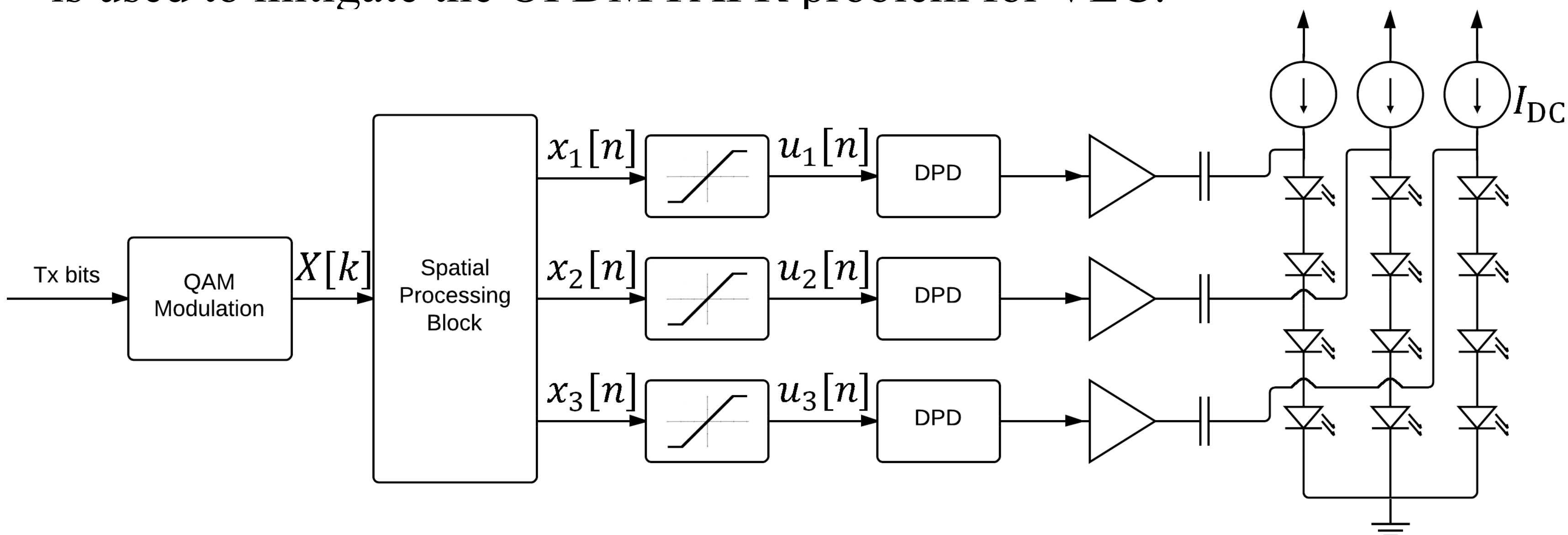


VLC Using OFDM

- VLC systems have a limited bandwidth due to the limited bandwidth of the LED (in the range of a few MHz).
- However, VLC systems enjoy a high SNR (70 dB) due to minimum illumination requirements.
- Therefore, a spectrally efficient modulation technique, such as OFDM, suits the needs of indoor VLC systems.
- Moreover, the use of OFDM in VLC facilitates the integration of PLC and VLC systems, as OFDM is already used for PLC and adopted in PLC standards (IEEE 1901 and HomePlug AV).

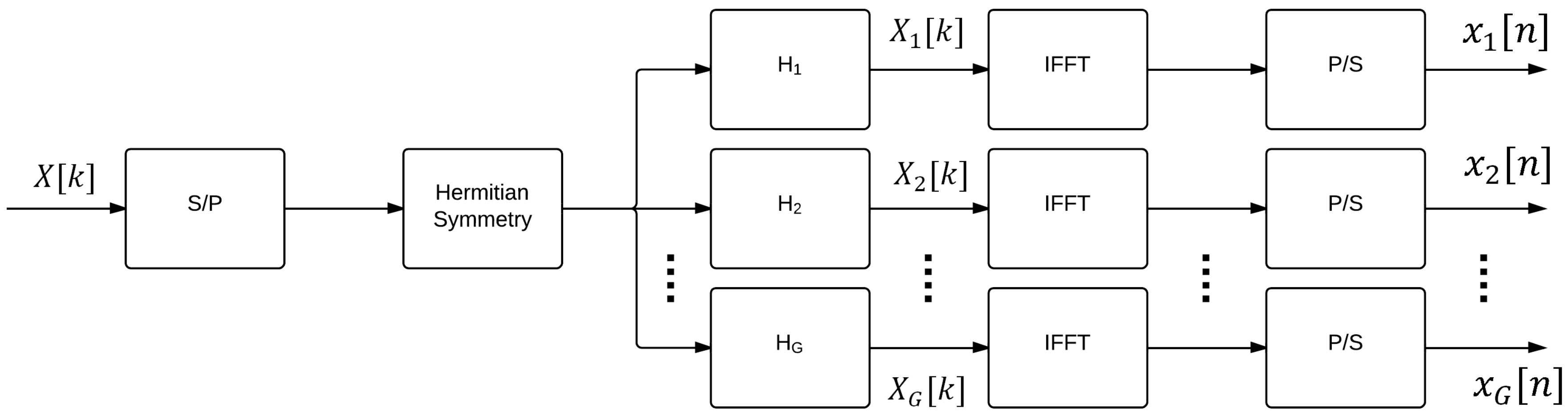
Spatial Optical OFDM

Spatial summing of the intensities of multiple LEDs in a given luminary is used to mitigate the OFDM PAPR problem for VLC.

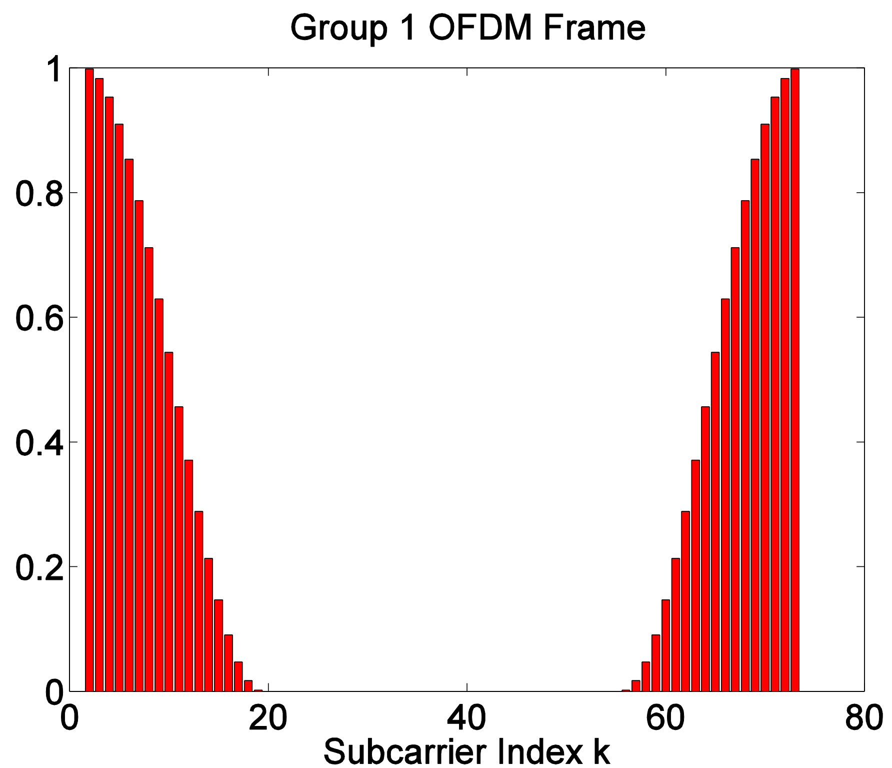


M.S.A. Mossaad, S. Hranilovic, L. Lampe, "Visible Light Communications Using OFDM and Multiple LEDs," IEEE Trans. Commun., Nov. 2015

SO-OFDM Spatial Processing Block



Example: Overlapped SO-OFDM (OSO-OFDM)



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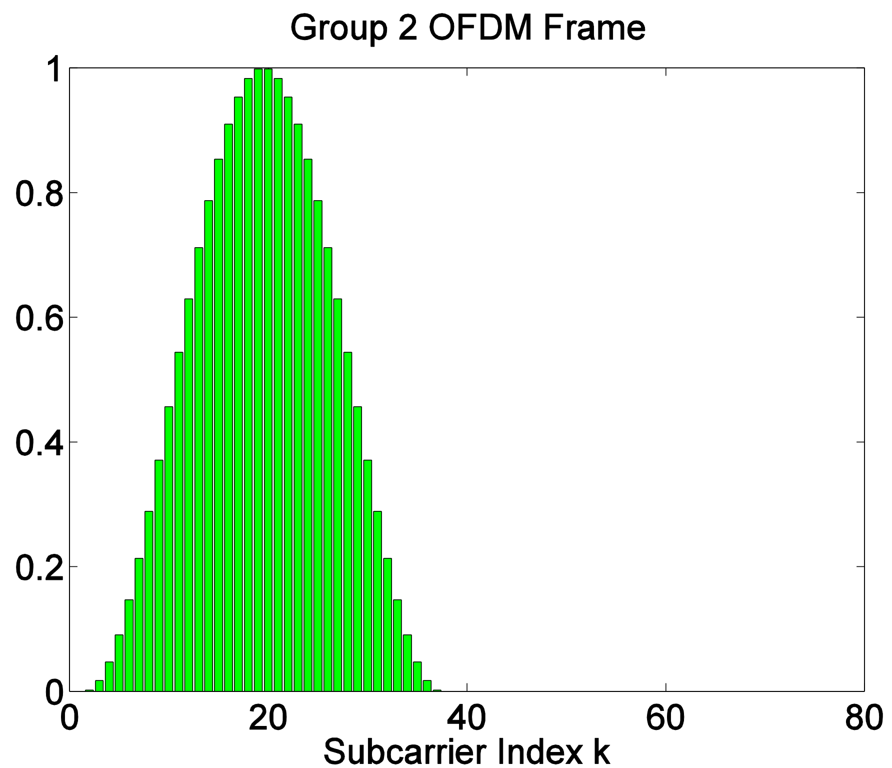

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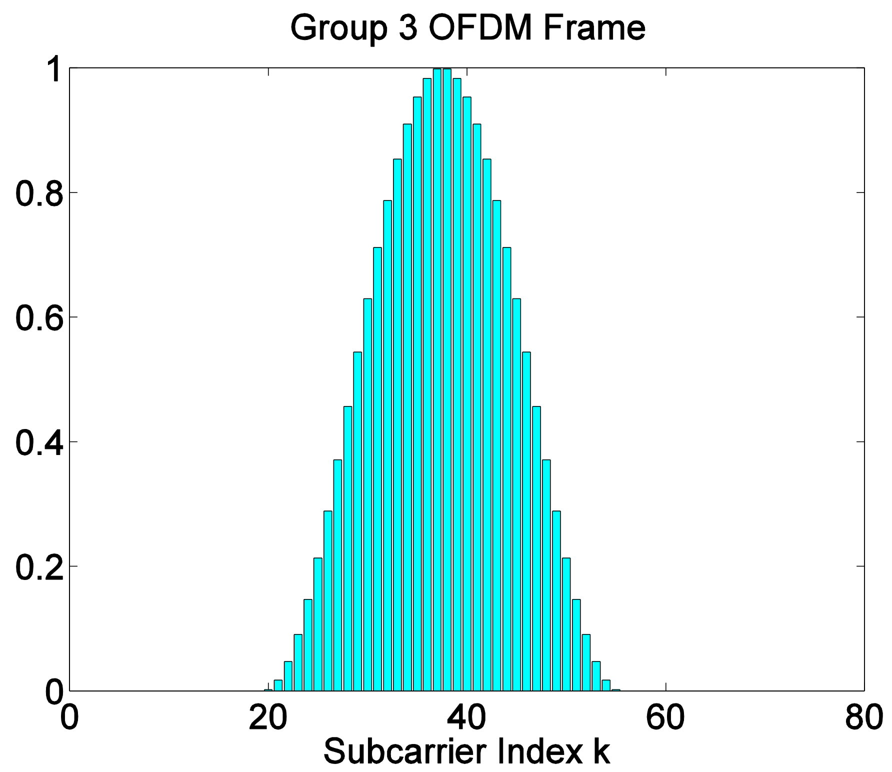

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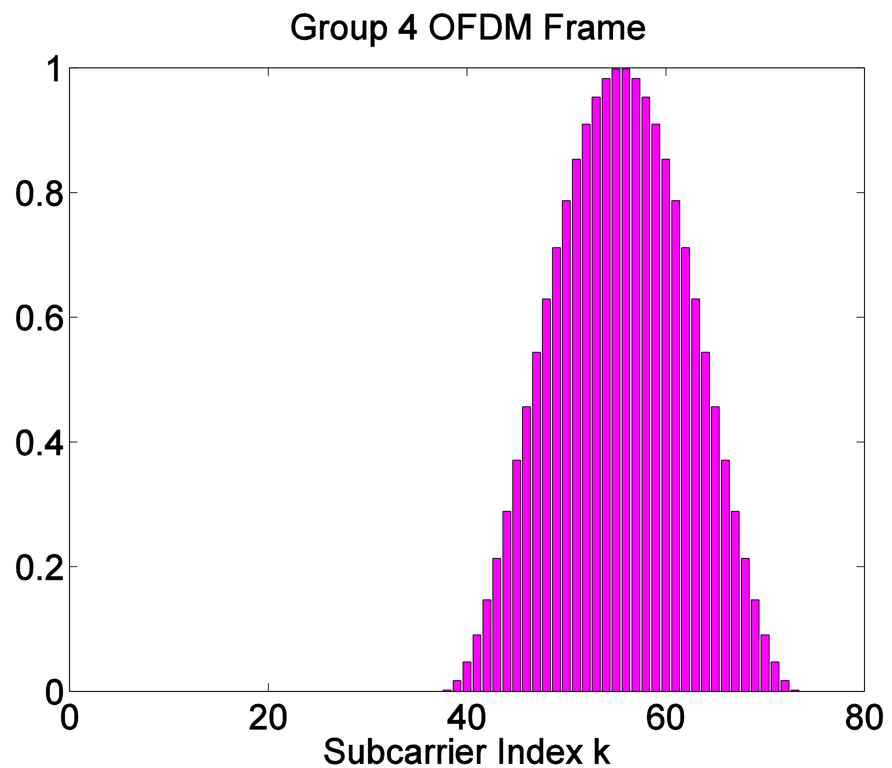

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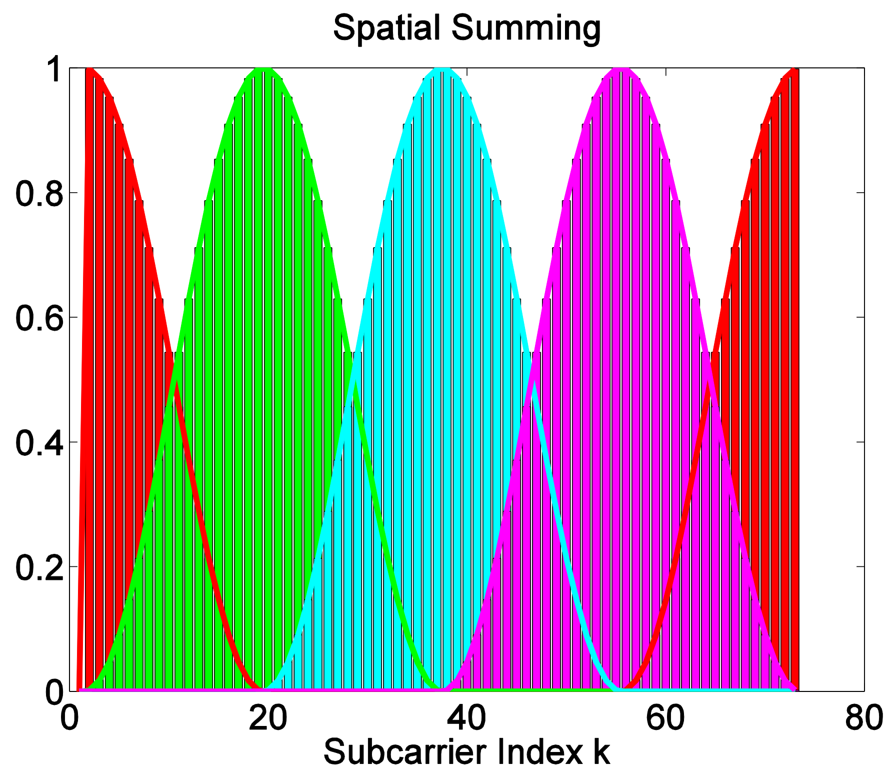
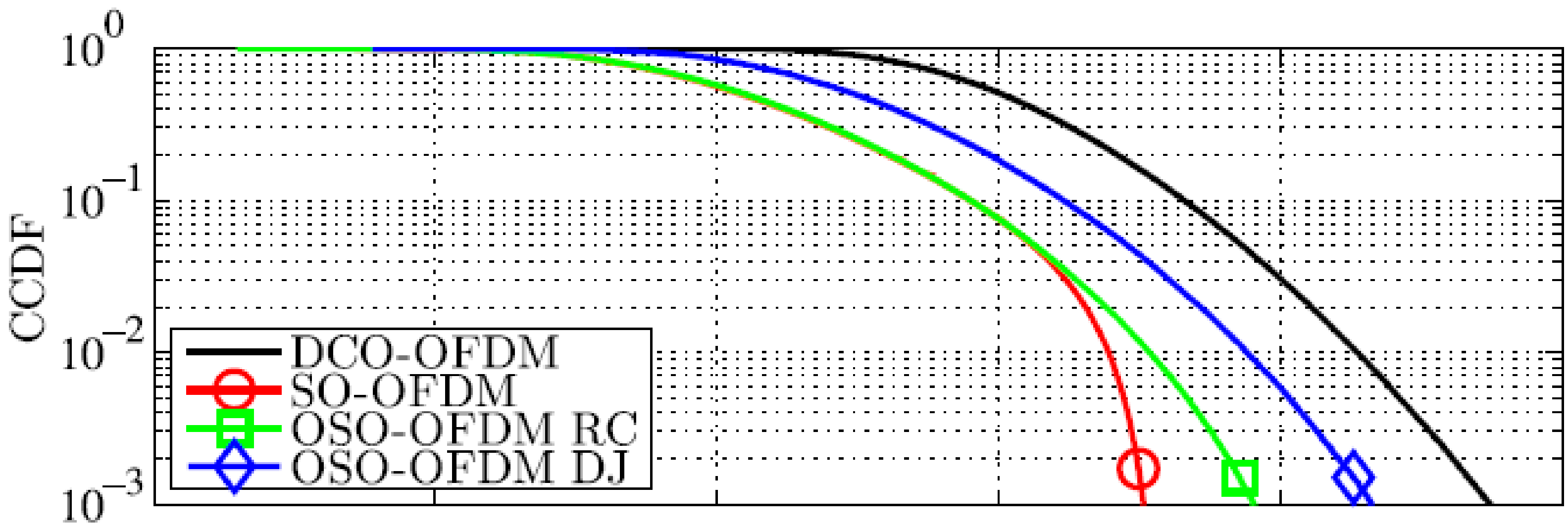


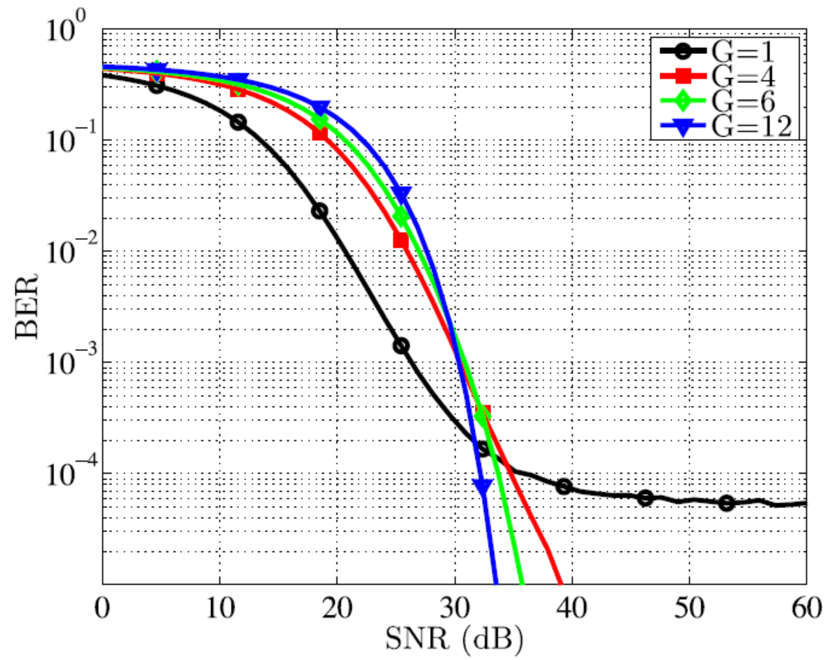
PAPR Results



- The CCDF of the PAPR for the different techniques based on (a) spatial optical OFDM and (b) optical SC-FDMA. In all cases, the FFT size N = 194, the number of LED groups G = 12 and the excess bandwidth β = 1 for overlapping techniques.
- Spatial optical OFDM achieves a PAPR reduction gain by distributing the OFDM subcarriers over G LED groups.

BER Results

- BER performance of SO-OFDM with contiguous subcarrier mapping, G = 1, 4, 6, 12, N = 26.
- For small values of SNR, AWGN is the dominant source of noise, and DCO-OFDM, having a larger useful power, outperforms Spatial Optical OFDM.
- Clipping distortion dominates at high SNR. Lower BER is achieved by using more LED groups, thereby reducing the PAPR and non-linear clipping distortion.

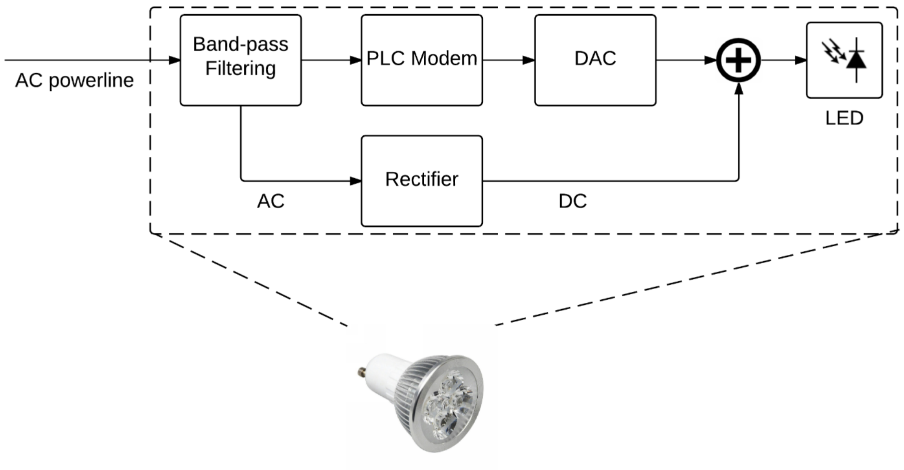


Integration of PLC and VLC–Motivation

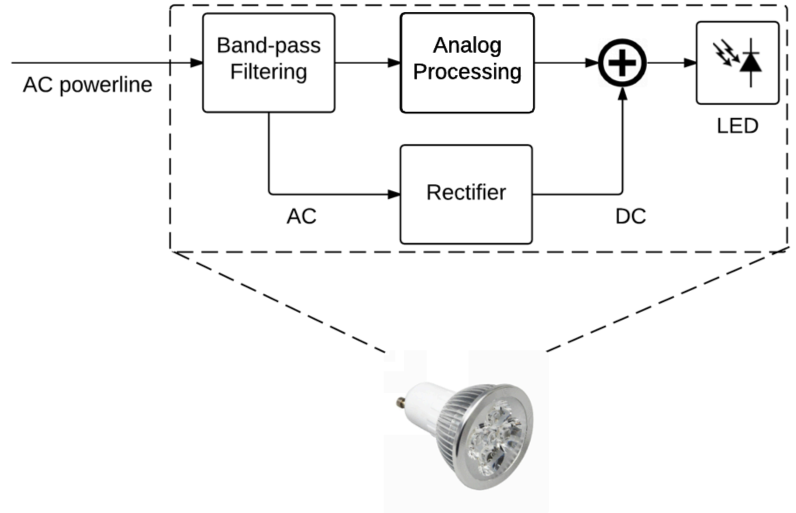
- The LED light bulb is already connected to the power line.
- The integration of PLC and VLC means that the power line serves as the backbone for VLC while powering the LED light bulb.
- This setup does not require additional cables and is easy to install.

Integration of PLC and VLC

Decode-and-Forward (DF)



Amplify-and-Forward (AF)



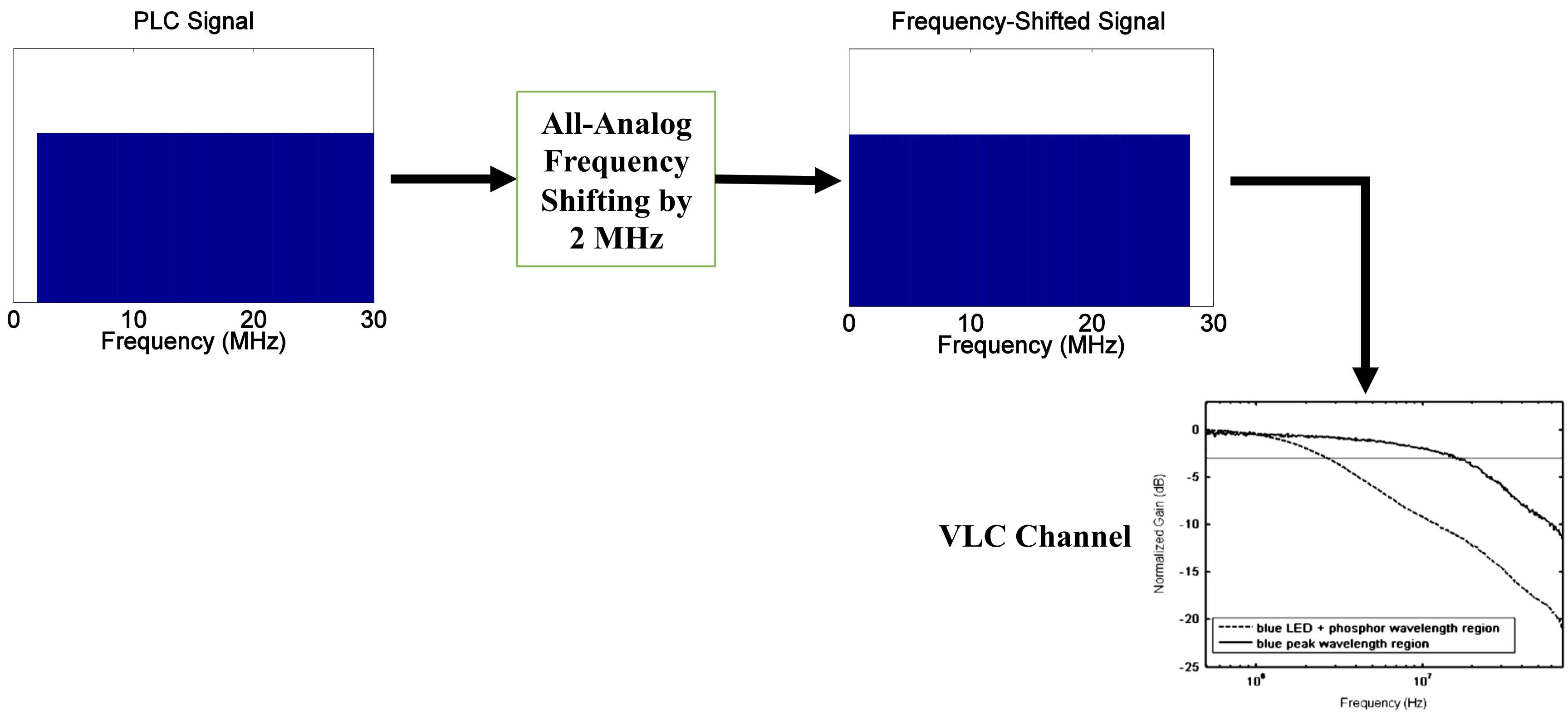
Decode-and-Forward (DF) vs. Amplify-and-Forward (AF) Relaying

Decode-and-Forward	Amplify-and-Forward
Each luminary demodulates and decodes the incoming data on the PLC link and retransmits on the VLC link using appropriate modulation.	The luminary is able to filter and amplify the incoming analog signal from the PLC link before adding a DC bias and driving the LEDs.
Requires significant signal processing which will negatively impact energy efficiency and cost of the luminary.	Can be implemented using simple analog circuits which can be power efficient and will result in a more compact luminary.

Amplify-and-Forward (AF) Integration of PLC and VLC

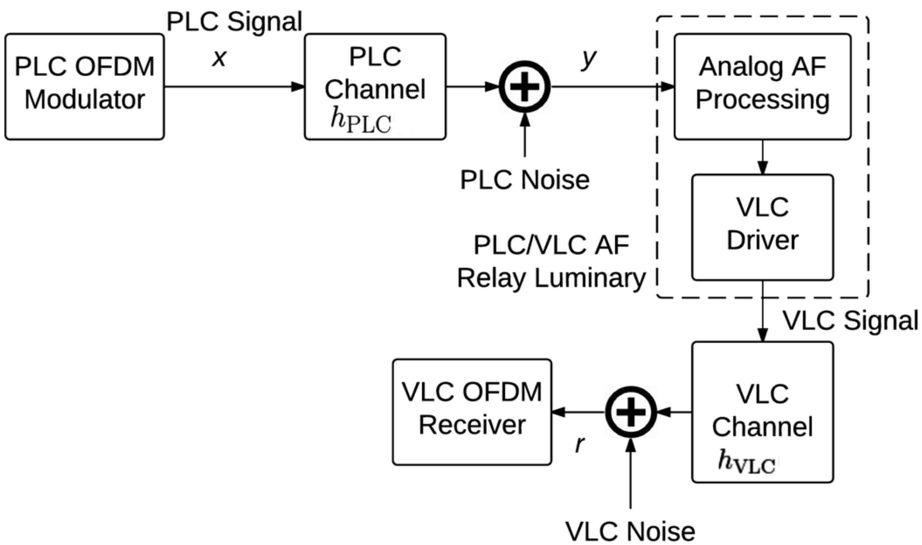
- Low-complexity scheme for the integration of PLC and VLC.
- Rather than decoding the PLC signal prior to transmission from an LED luminary, a simple all-analog PLC/VLC amplify-and-forward (AF) module is used.
- The incoming PLC signals, which occupy a band of 2-30 MHz, are ***frequency down-shifted*** prior to transmission to increase the usable bandwidth of the LEDs.

Frequency Shifting



AF Integration of PLC and VLC

- The required DC bias is then added to make the signals compatible with IM/DD.
- In addition to DC-biased Optical OFDM (DCO-OFDM) ***SO-OFDM*** is applied to PLC/ VLC integration.

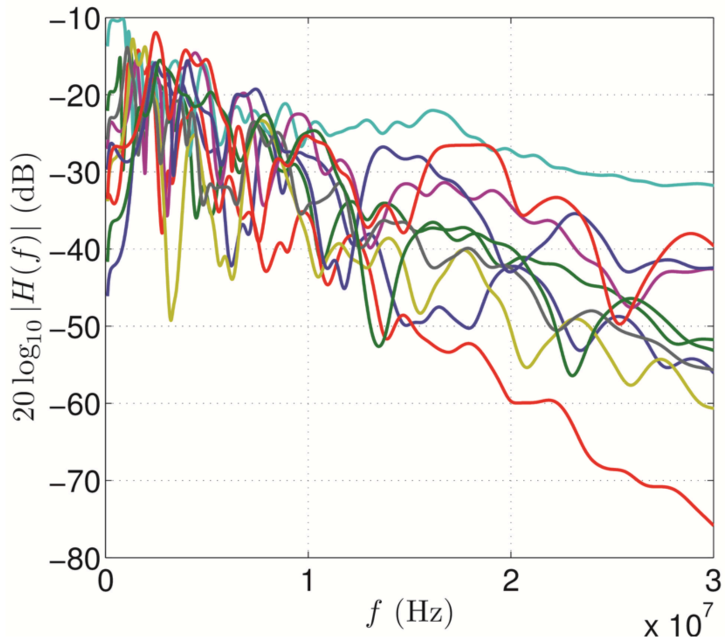


PLC Channel Characteristics

1. A high attenuation exceeding 50 dB in some links.
2. Many deep notches at certain frequencies, in which the attenuation increases abruptly by up to 30 dB.
3. Some frequency bands are forbidden for transmission by electromagnetic compatibility regulations to avoid interference with other radio systems.
4. The useful band for PLC systems is not contiguous.

Frequency Response

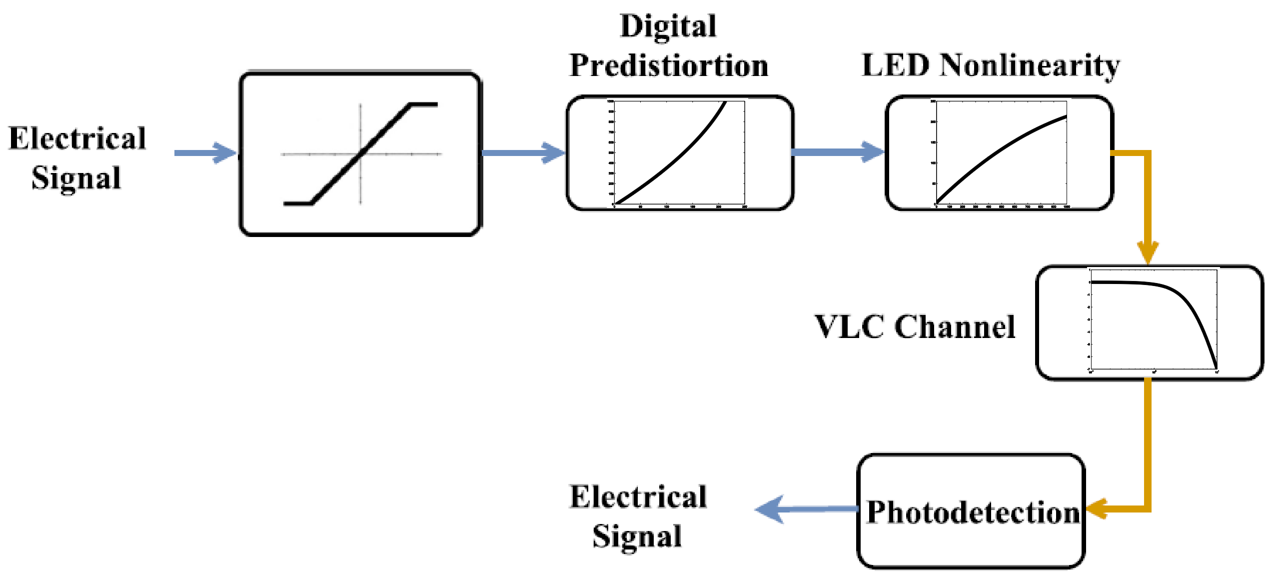
- The frequency response amplitude obtained for 10 channels generated at random is depicted.



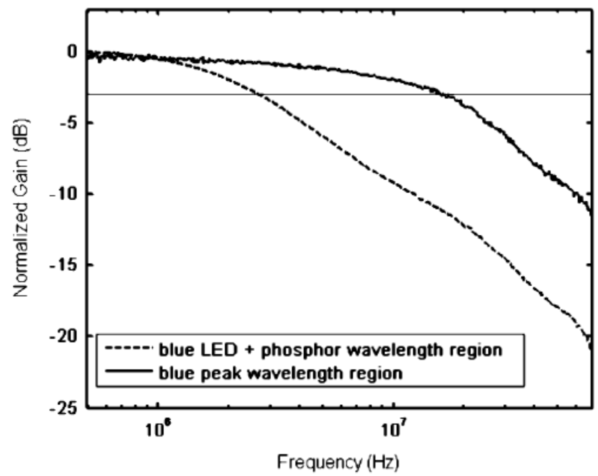
VLC Channel Model

- The nonlinearity and the lowpass frequency response of the LED are considered.
  - Nonlinearity is modeled by a hard-clipper.
- The power detected by the photodetector follows an inverse-square law with the distance from the transmitter.
- The multipath effects are negligible.

VLC Channel Model



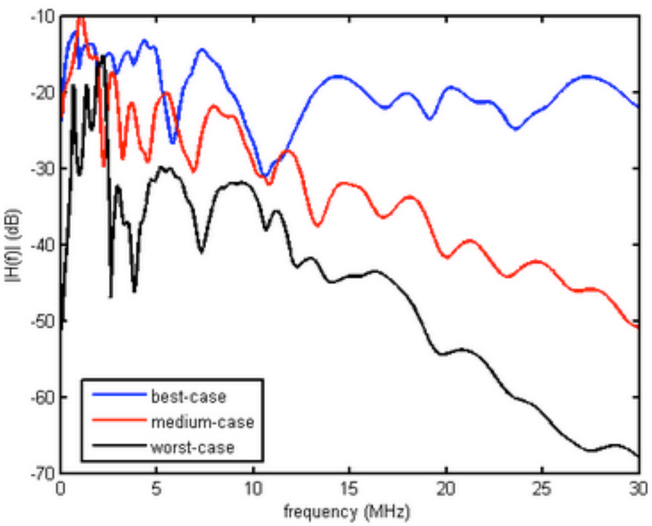
VLC Channel Model



- J. Grubor, S. Randel, K.-D. Langer, and J.W. Walewski. Broadband information broadcasting using LED-based interior lighting. Journal of Lightwave Technology,26(24):3883–3892, Dec 2008.

Simulation Parameters

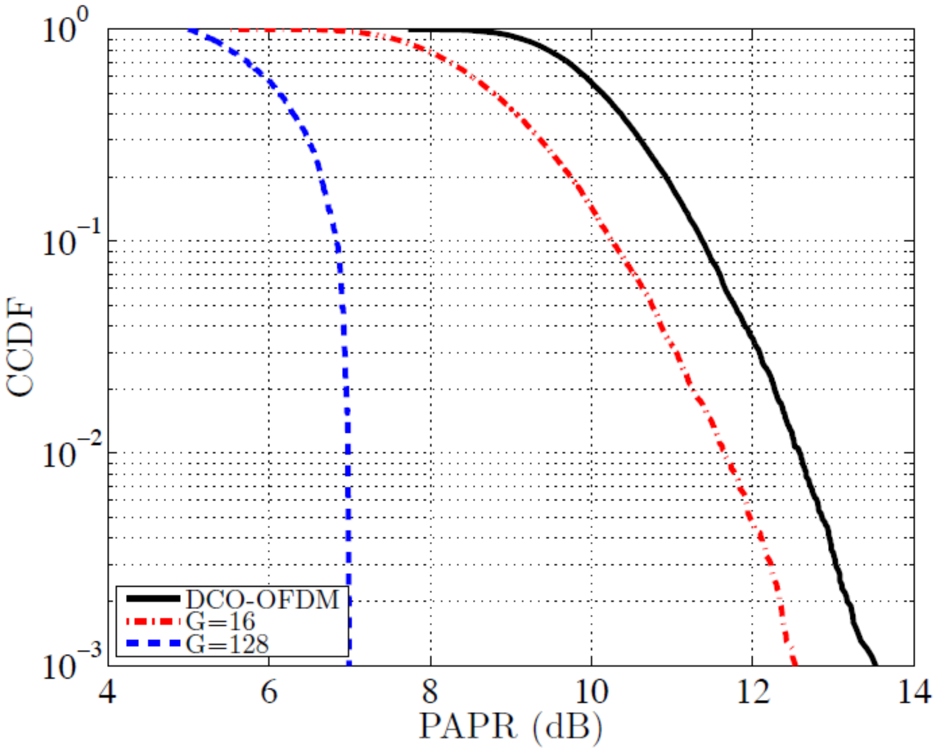
PLC Channel: Medium.



Parameter	Value
Number of independent data-carrying subcarriers	N_D=256
Smallest subcarrier frequency	2.026 MHz
Subcarrier spacing	24.4 kHz
SNR_{PLC}	55 dB

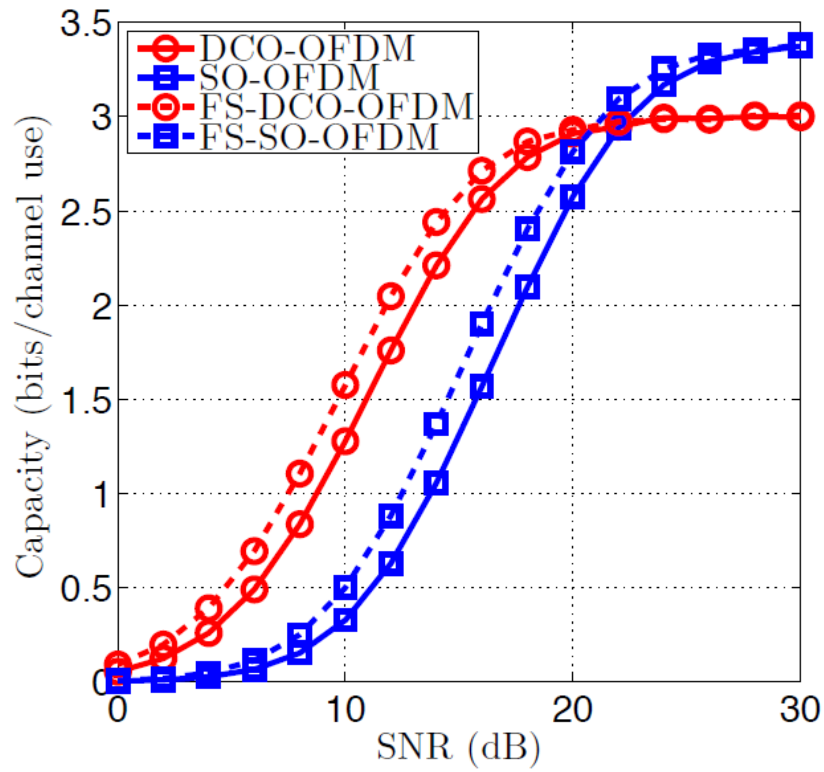
PAPR Results

- CCDF of the PAPR for DCO-OFDM (G = 1) and SO-OFDM (with G = 16, 128). In all cases, ND = 256.
- As the number of groups grows, SO-OFDM becomes less impacted by clipping noise.
- This comes at the expense of needing more drivers for the groups.
- However, since they have lower PAPR, energy efficient narrow band LED drivers are available.



Capacity Results

- Capacity comparison between DCO-OFDM and SO-OFDM using RC pulse filtering with G = 16, both conventional (solid curve) and frequency-shifted (dotted curve).
- Since SO-OFDM has a lower PAPR than DCO-OFDM, it is more robust to NLD effects, arising due to the limited dynamic range of the driver and the LED nonlinearities, which translates into a higher capacity at high SNRs.
- Frequency-shifting improves the capacity of both DCO-OFDM and SO-OFDM compared to the corresponding conventional cases where no frequency-shifting is used.



Conclusions

1. All-analog PLC/VLC integration via amplify-and-forward yields a simple and effective downlink.
2. Frequency down-conversion of the PLC spectrum prior to forwarding provides an improvement in capacity.
3. SO-OFDM provides a PAPR reduction which translates into improved capacity when the VLC link is operating in the high-SNR regime.