Optical transmitter characteristics for GEPOF technical feasibility

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Agenda

• Objectives

• The optical transmitter ➤ main characteristics

• LED non-linear response and capacity penalties

• Conclusions
Disclaimer

• Technical characteristics provided in this presentation are limited to those directly affecting the optical link budget and, therefore, the Shannon’s capacity analysis.

• Other characteristics, like the ones related to the physical semiconductor parameters, integration, manufacturing process, etc. are intentionally left outside of the scope of this presentation.
Objectives

• This presentation provides technical characteristics of the optical transmitter used today for automotive applications as well as for consumer applications
  • This optical transmitter is a red LED, and it is the light emitter most widely used by the industry for POF communications
  • The red LED has been qualified for automotive applications, being demonstrated its reliability during the last +10 years

• The main objective of this presentation is to analyze the red LED from the perspective of the aspects that directly relates to the Shannon’s capacity based technical feasibility assessment

• The results presented here will be used for Shannon’s capacity analysis in [perezaranda_01_0514_shannononcap]
The optical transmitter ➤ main characteristics
The optical transmitter - architecture

• The optical transmitter is composed by the current driver IC and the LED IC
• The red LED converts the electrical current into optical power
  • In general, the I-P characteristic of LED is not linear; this topic is covered later on
  • Electrical-to-electrical response is well approximated by a 1\textsuperscript{st} order low pass system
  • Achievable -3dB bandwidth of LED itself is between 75 and 95 MHz, depending on the internal structure of LED
  • Wavelength center ~650 nm; wavelength width ~30 nm
• Typically, the driver is a trans-conductance amplifier in charge to convert the voltage communication signal from the PHY into the adequate current to drive the LED, providing:
  • Bias current control to ensure reliability of the LED
  • Extinction Ratio (ER) control, to avoid switching off the LED (optical power clipping) and ensure the quantum noise from PD is low
  • Typical target ER = 10 dBo
  • Typical process and temperature variation of ER < ±2 dBo
  • Frequency pre-emphasis, to enhance the bandwidth of the LED
  • Frequency pre-emphasis gain is limited based on reliability criteria ➤ max peak current
The optical transmitter - architecture

![Diagram of the optical transmitter architecture](image-url)
The optical transmitter - pre-emphasis

No pre-emphasis, MOST line-coding

LED current (A) and voltage out (arbitrary units)

ILED avg
ILED max
ILED pk+
ILED pk−

Arbitrary time unit

LED response for ILEDavg: 20 mA; ER: 10.0 dB; LED Fc−3dB: 100 MHz; Preemphasis: Fz is 60 MHz, GHF is 0 dB

Saturated samples ratio: 0.0e+000
The optical transmitter - pre-emphasis

Pre-emphasis, MOST line-coding

LED current (A) and voltage out (arbitrary units)

LED response for $I_{LED_{avg}}$: 20 mA; $ER$: 10.0 dB; $LED_{-3dB}$: 100 MHz; Preemphasis: $F_z$ is 60 MHz, $G_{HF}$ is 6 dB

Saturated samples ratio: $0.0e+000$

LED current

Rx Vout

The optical transmitter - pre-emphasis
The optical transmitter - pre-emphasis

No pre-emphasis, high M PAM

LED current (A) and voltage out (arbitrary units)

LED current

Rx Vout

ILED\_{pk+}

ILED\_{pk-}

ILED\_{avg}

ILED\_{max}

ILED\_{min}

Arbitrary time unit

LED response for $I_{LED,\text{avg}}$: 20 mA; $E_R$: 10.0 dB; LED Fc\_{-3dB}: 100 MHz; Preemphasis: $F_z$ is 60 MHz, $G_{HF}$ is 0 dB

Saturated samples ratio: 0.0e+000
The optical transmitter - pre-emphasis

Pre-emphasis, high M PAM

LED current (A) and voltage out (arbitrary units)

LED current

Rx Vout

LED response for $I_{LED_{avg}}$: 20 mA; ER: 10.0 dB; LED $F_{c - 3dB}$: 100 MHz; Preemphasis: $F_z$ is 60 MHz, $G_{HF}$ is 6 dB

Saturated samples ratio: 0.0e+000

Pre-emphasis, high M PAM
The optical transmitter - response

Lab measurement of real product qualified for automotive

Driver + MOST red LED E–to–E response

Electrical-to-electrical magnitude response (dB)

Frequency (MHz)

Lab measurement of real product qualified for automotive
Performance with temperature

AOP coupled into POF (lab measurements)

Temp (°C)

AOP (dBm)

#15
#41
#27
Avg

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Performance with temperature

OMA coupled into POF (lab measurements)
Non-linear response and capacity penalties
Non-linear distortion (-40 °C, 15.6 MHz)

Lab. measurements of a real product
Non-linear distortion (+25 °C, 15.6 MHz)

Lab. measurements of a real product
Non-linear distortion (+105 °C, 15.6 MHz)

Lab. measurements of a real product
Non-linear distortion (-40 °C, 44.6 MHz)

Lab. measurements of a real product
Non-linear distortion (+25 °C, 44.6 MHz)

Lab. measurements of a real product
Non-linear distortion (+105 °C, 44.6 MHz)

Lab. measurements of a real product
Non-linear distortion - preliminary conclusions

• Based on previous measurements we can do some conclusions:
  • The non-linear response of the LED depends on the temperature
  • The harmonic distortion measurement with input single tone depends on the frequency of the tone

• Based on this very basic measurements we could conclude that only low spectral efficiency modulation schemes would be feasible with the LED

• However, we are going to demonstrate that this conclusion is false, by analyzing the non-linear response in deeper detail

• The idea behind the following analysis is that the non-linear response of the LED can be adaptively compensated by the PHY in the same way the ISI is equalized in modern Ethernet PHYs to approach the channel capacity
Non-linear response - the Volterra model

• In order to analyze the effect of LED HD in the communication system we need to develop a correct model for the non-linear response

• Truncated Volterra series expansion is selected to model the optical TX non-linear response
  • Volterra series expansion is a well known technique and it have been used by the industry in a wide range of engineering fields to model non-linear systems
  • It is attractive from the mathematical point of view ➔ linear combination of non-linear functions of the input signal
  • It fits a large class of non-linear systems
  • Well known adaptive filtering algorithms are suitable for Volterra series estimation

\[
y(k) = w_{o0} + \sum_{l_1=0}^{L} w_{o1}(l_1)x(k-l_1) + \ldots + \sum_{l_1=0}^{L} \sum_{l_2=0}^{L} w_{o2}(l_1,l_2)x(k-l_1)x(k-l_2) + \ldots + \sum_{l_1=0}^{L} \sum_{l_2=0}^{L} \ldots \sum_{l_p=0}^{L} w_{op}(l_1,l_2,\ldots,l_p)x(k-l_1)x(k-l_2)\ldots x(k-l_p)
\]

DC offset + linear filter ➔ 2nd order convolution ➔ Higher-order convolutions
Non-linear response - the Volterra model

DC offset

1st order response

2nd order response

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Non-linear response - the Volterra model

- The optical transmitter is well modeled by a 3rd order Volterra system.
- Higher order kernels are negligible.
Non-linear response: Volterra DC and 1\textsuperscript{st} order

\[ -40 ^\circ C \quad \text{and} \quad +105 ^\circ C \]

\[ F_s = 312.5 \text{ MHz} \]
Non-linear response: Volterra 2\textsuperscript{nd} order

-40 °C

\[ F_S = 312.5 \text{ MHz} \]
Non-linear response: Volterra 2\textsuperscript{nd} order

105 °C

$F_s = 312.5$ MHz
Non-linear response: Volterra 3\textsuperscript{rd} order

-40 °C

\[ F_s = 312.5 \text{ MHz} \]
Non-linear response: Volterra 3\textsuperscript{rd} order

105 °C

FS = 312.5 MHz
Non-linear response: Volterra analysis

• Bandwidth of the optical TX increases with temperature, although impulse response could be considered approximately constant

• The magnitude of the 2nd and 3rd order Volterra kernels increases with temperature and frequency ➤ it confirms the basic single tone HD measurements

• It is important to note that most part of energy of 2nd and 3rd order responses is delayed respect to 1st order
  • We can conclude that optical TX cannot be modeled as a Wiener or a Hammerstein non-linear system

• The morphology of Volterra (2nd and 3rd) kernels basically does not change with temperature ➤ good from the implementation point of view
Capacity penalties - channel linearization

Light Source (Driver + LED) → POF → Photodiode → Trans-Impedance Amplifier (TIA) → Antialias Filter

POF non-linear channel

POF non-linear channel
Linearizer

Linear Channel
Capacity penalties - Linearizer is not implemented

PHY input

SNR_e = 39.8 dB

DFE output

25.4 dB

39.8 dB

14.4 dB
Capacity penalties - Linearizer is implemented

PHY input

- RX signal
- Noise
- Noise + NL

SNR$_e$ = 39.8 dB

DFE output

- Linearizer + DFE: Detector signal
- Linearizer + DFE: Detector Noise
- Linearizer + DFE: Noise Bound

36.7 dB

39.8 dB

3.1 dB

Magnitude Response (dB)

Magnitude (dB)

DFE after linearizer: FFE+FBF
DFE after linearizer: FFE
DFE after linearizer: FBF

Normalized Frequency ($\times \pi$ rad/sample)

Normalized Frequency (÷ rad/sample)
Capacity penalties

Capacity penalty caused by the LED non-linear response

- Linearizer + DFE
- DFE

Capacity loss < 1dB for SNR_e < 30 dB

High spectral efficiency schemes are feasible
Conclusions

• Technical characteristics of the optical transmitter used today for automotive applications as well as for consumer applications have been presented

• The non-linear response of I-P characteristic of LED has been analyzed in detail, concluding that high spectral efficiency modulation schemes are also feasible with low capacity penalties, opening the use of LED beyond OOK schemes

• The results presented here will be used for Shannon’s capacity analysis in [perezaranda_01_0514_shannononcap]
Questions?