IEEE 802.11  
Wireless LANs

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| Optical Frontend Model | | | | |
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Abstract

This document describes a model of the optical frontend behavior for PHY simulations.

# Introduction

The performance evaluation and comparison of PHY proposals for Light Communication (LC) requires link level simulations with some level of detail. In comparison to system-level simulations, the behavior of single individual wireless links for given transmissions and respective receptions is of interest. The optical frontend for LC imposes impairments, which have a non-negligible impact on the performance, on the signal. Hence, these effects must be modeled in addition to the propagation channel. Figure 1 depicts the integration of the frontend model into the overall PHY link level simulation.

PHY TX

model

Channel model

TX

frontend

model

PHY RX

model

RX

frontend

model

Input bits

Figure 1: Link-level simulation overview and frontend model integration

Output bits

BER

# The LC TX Frontend

The TX frontend comprises driver electronics and a LED or laser diode. A 50 Ω interface connects the DSP with the driver. The driver performs impedance matching from 50 Ω to a few Ωs typically at the LED. Through sophisticated circuit design, moreover, the bandwidth can be increased. The bandwidth is limited by a large area of the active zone of the high-power LED. Radiative / non-radiative recombination effects play a minor role.



Figure 2: LC TX signal generation

The driver is custom-designed for each LED. Moreover, modulation and bias currents can be changed in the driver. Of the LED’s total optical output power, only a fraction is actually modulated. This non-DC part is determined by the so-called modulation index. The modulated part of the LED current impacts the coverage range of the LC link.

## LC TX Frontend Response

The response was measured with a vector network analyzer from 1 to 300 MHz using a receiver with multiple GHz bandwidth. A CREE XPE RED-L1-R2\_N3 LED was used. Results for two different measured frontends are depicted in Figure 6.

A high pass characteristic with a cut-off frequency of few 100 kHz is typically included in the frontend design. The high-pass characteristics enables adding the modulated AC part of the signal to the DC part needed for the bias. The high-pass is shown here for frontend sample#2. The gain of frontend sample#1 is slightly higher until around 10 MHz. Thereafter, it has an almost flat frequency response until 240 MHz with some ripple. Beyond 240 MHz, the TX frontend acts as a steep low-pass.

## LC TX Frontend Model

Figure 3 shows the entire TX frontend model.

A variable gain amplifier (VGA) is assumed to model the variable modulation index of the LED current [A]. A subsequent low-pass filter with a variable cut-off frequency, e.g. 20, 100 or 200 MHz models the low-pass behavior of the driver. The cut-off frequency can be matched to the signal bandwidth i.e. usually this is the highest TX signal frequency which need to be transmitted. To model attenuation at very low frequencies, a high-pass with a cut-off frequency at 100 kHz is introduced. For pulsed modulation such as on-Off keying (OOK) or Pulse Amplitude Modulation (PAM), the high-pass may imply baseline wander effects. A constant bias current [A] is finally added to the signal before passing it into an electrical-to-optical (e/o) converter (i.e. LED or LD) for which infinite bandwidth and conversion efficiency ηTX [W/A] are assumed. For simplicity, non-linear effects are ignored.



Figure 3: LC TX frontend model

The involved filters can be modeled in MATLAB as follows:

f\_bw = 5e8; % Reference bandwidth [Hz]

%% Highpass filter

n\_hi = 2; % Filter order

f\_c\_hi = 2.6e5 ; % cut-off frequency [Hz]

[z\_hi, p\_hi, k\_hi] = butter(n\_hi, f\_c\_hi/f\_bw, 'high');

[sos\_hi, g\_hi] = zp2sos(z\_hi, p\_hi, k\_hi);

%% Lowpass filter

n\_lo = 8; % Filter order

f\_c\_lo = 2.34e8 ; % Cut-off frequency [Hz]

[z\_lo, p\_lo, k\_lo] = butter(n\_lo, f\_c\_lo/f\_bw);

[sos\_lo, g\_lo] = zp2sos(z\_lo, p\_lo, k\_lo);

%% Combined bandpass filter

passband\_gain = -23.17; % Passb. gain [dB]

sos = [sos\_hi; sos\_lo];

g = g\_hi\*g\_lo\*10^(passband\_gain/20);

H = dfilt.df2sos(sos, g);

In the script, first two Butterworth IIR filters are generated with the respective cut-off frequencies of the filters in the model. After transforming them into the second order sections form, both are combined and used to generate the following output:

sos – second-order-sections parameter matrix

g - gain factor

H  - Matlab filter object

## TX filter parameters and graphical representation

The transfer function and parameters for the second-order-sections form are shown in Figure 4 and 5, respectively:

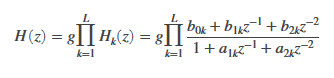


Figure 4: Filter transfer function

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *k* | *b0* | | *b1* | | *b2* | *1* | | | *a1* | | *a2* |
| 1 | | 1 | | -2 | | | 1 | 1 | -1,997689701897980 | 0,997692367559178 | |
| 2 | | 1 | | 2 | | | 1 | 1 | -0,101589252729636 | 0,012231136945395 | |
| 3 | | 1 | | 2 | | | 1 | 1 | -0,109848714714527 | 0,094528076541712 | |
| 4 | | 1 | | 2 | | | 1 | 1 | -0,129268374764007 | 0,288024770756935 | |
| 5 | | 1 | | 2 | | | 1 | 1 | -0,168095248634957 | 0,674894145483214 | |

Figure 5: TX filter parameters in matrix sos

Figure 6 compares the measured TX frequency responses with the modeled one. Although not all effects are reflected, the main features of the high-pass at low frequencies and the low-pass at high frequencies are included.



Figure 6: Measured and modeled LC TX Filter responses

# The LC RX Frontend

The RX frontend comprises a photo diode and a bootstrap transimpedance amplified (TIA) as shown in Figure 7.



Figure 7: LC RX signal detection

The bootstrap TIA matches the impedance from the MΩs which are typoical at the PD in low light situations to the standard 50 Ω interface at the DSP. The bandwith is limited by the large area of the PD. The bootstrap TIA compensates the high capacitance of the PD at the cost of little more noise. Through the sophisticated bootstrap TIA design, bandwidth can be significantly increased compared to connecting the PD to a standard 50 Ω amplifier. The boostrap TIA is custom-designed for a given PD. The interface from the TIA to the DSP may be single-ended or differential.

## LC RX Frontend Response

Again, the response was measured with a vector network analyzer between 1 and 300 MHz. As a transmitter, a laser with several GHz bandwidth was used. Figure 9 displays the amplitude and phase response. The measurement shows that also the LC RX response has high-pass characteristic of some 100 kHz in order to block i) the DC part of the received signal and occasionally modulated ambient light such as from incandescent light bulbs. Up to 250 MHz the frequency response is almost flat, exhibiting slight ripple. At higher frequencies, it exhibits low pass characteristics.

## LC RX Frontend Model



Figure 8: LC RX frontend model

The o/e converter is assumed to have infinite bandwidth and a conversion efficiency of hRx [A/W]. For avalanche PDs (APDs), shot noise is modeled by adding AWGN with an RMS *i*shot [A] directly after the PD. For Positive-intrinsic-negative (PIN)-PDs, shot noise can be ignored. The resulting electrical signal then undergoes a first order high pass with a cutoff frequency of 100 kHz. Thereafter, thermal noise is added to the signal, having an RMS of *i*thermal [A]. Subsequently, an automatic gain control (AGC) compensates for the overall losses through TX, channel, and RX. Finally, the signal passes through a low-pass filter, whose cut-off frequency should be matched to the required RX signal width like at the TX in order to minimize the overall noise power. For example, fg could be 20, 100 or 200 MHz.

The following MATLAB-code can be used to generate the LC RX model filter:

f\_bw = 5e8 ; % Reference bandwidth (Hz)

%% Highpass filter

n\_hi = 4; % Filter order

f\_c\_hi = 4.8e4; % Highpass cut-off frequency (Hz)

[z\_hi, p\_hi, k\_hi] = butter(n\_hi, f\_c\_hi/f\_bw, 'high');

[sos\_hi, g\_hi] = zp2sos(z\_hi, p\_hi, k\_hi);

%% Lowpass filter

n\_lo = 4; % Filter order

f\_c\_lo = 2.58e8; % Lowpass cut-off frequency (Hz)

[z\_lo, p\_lo, k\_lo] = butter(n\_lo, f\_c\_lo/f\_bw);

[sos\_lo, g\_lo] = zp2sos(z\_lo, p\_lo, k\_lo);

%% Combined bandpass filter

passband\_gain = 4.6; % Passb. gain (dB)

sos = [sos\_hi; sos\_lo];

g = g\_hi\*g\_lo\*10^(passband\_gain/20);

H = dfilt.df2sos(sos, g);

Similar to generating the LC TX model, first two filters are created and subsequently their combined transfer function in the second-order-sections form is stored in SOS, g and H.

## Modeled LC TX filter parameters and graphical representation

Figures 9 and 10 presents the formulas and parameters, respectively, for the resulting filter.

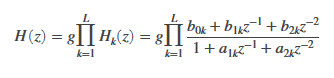


Figure 9: SOS filter formula for the LC RX

The measured frequency response as well as the modeled response is depicted in figure 11.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *k* | *b0k* | | *b1k* | *b2k* | *1* | | | *a1k* | *a2k* | |
| 1 | | 1 | | -2 | | 1 | 1 | -1,999442793302530 | | 0,999442884235466 |
| 2 | | 1 | | -2 | | 1 | 1 | -1,999769106485430 | | 0,999769197433208 |
| 3 | | 1 | | 2 | | 1 | 1 | 0,052263991330401 | | 0,040197045632214 |
| 4 | | 1 | | 2 | | 1 | 1 | 0,072701946219595 | | 0,446968510140276 |

Figure 10: RX filter parameters in matrix sos



Figure 11: Measured and modeled LC RX filter responses

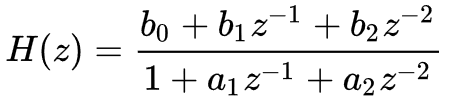
# Summary

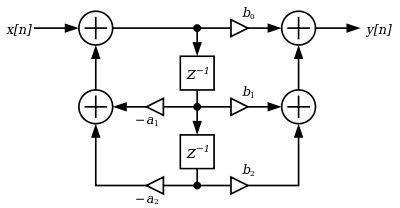
The proposed models allow to include realistic impairment effects of optical frontend to be included in link-level simulation results on the performance of physical layer proposals in TGbb. MATLAB code for the generation of models as well as realistic parameters for the generated filters were provided.

# Appendix

The second-order-sequence form is a serial cascade of biquadratic IIR filters.

Every section is represented by the transfer function

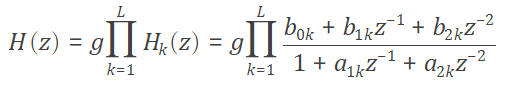




It may be implemented as follows:



# The complete transfer function is subsequently



With g being the scaling gain factor.

# References

[1] L. Grobe, V. Jungnickel, K. Langer, M. Haardt and M. Wolf, "On the impact of highpass filtering when using PAM-FDE for visible light communication," *Proc. IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, Doha, 2016, pp. 239-245.