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| TGbb: Analytical channel and blockage model |
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Abstract

This document describes an analytical channel and blocking model which reduces complexity for system-level simulations and enables a predefined occurrence of blocking objects.

# Introduction

For physical layer simulations, the channel impulse response between an optical wireless communication (OWC) transmitter and receiver pair can be calculated with high accuracy via the ray tracing method. For system-level simulations, however, this method is hardy applicable because large numbers of different transmitter-receiver constellations and resulting channel realizations are needed. This would imply a huge computational effort for the ray tracing.

In system-level simulations, protocol-procedures and mobility for potentially many transmitters and receivers must be considered and one is mainly interested in exhaustive statistical results covering good, normal and critical cases in realistic scenarios. Even for short scenarios with mobility, having a duration in the order of few seconds, a large number of snapshots and respective channel realizations are needed.

There are three major steps which could simplify system-level simulations for light communications:

1. It has been observed that in most (but not all, c.f. industrial wireless) scenarios, the LOS path is 10-20 dB stronger than the primarily diffuse reflections. This observation allows simplified ray tracing, considering only the first, i.e. LOS path. It can be computed analytically from the positions of transmitter and receiver in space and by knowing the spatial characteristics of the transmitted power and the receiver sensitivity.
2. Individual LC links can be blocked by objects in the room whose position and dimensions must be known. Unlike RF, where the link is mostly due to non-LOS signals, LOS blocking has severe impact on the LC link quality. Simplifications are needed likewise, as we are only interested in the statistical properties of the blocking but taking correlations of links between adjacent transmitters and receivers correctly into account.
3. Finally, at the system level one tries to overcome the complexity of the physical layer, such as waveform generation, synchronization, channel estimation, equalization, demodulation, channel coding etc. All these sophisticated techniques are often characterized by a single number, i.e. the achievable user throughput. It is often obtained by computing the individual signal-to-interference-and-noise ratio of each device, and plugging this into a look-up table yielding an achievable throughput. Such simplified link layer abstraction models are also known as the link-to-system (L2S) interface. The L2S interface depends on the underlying physical layer, i.e. the PHY needs to be known before any meaningful system-level result can be obtained.

By applying these 3 steps, it becomes feasible to evaluate arbitrary protocol sequences in an exemplary network by using random traffic patterns and to assess the performance at higher layers efficiently.

At the system level, finally, it is only important to know at which receivers scheduled transmissions can successfully be decoded and at which ones not. The following figure illustrates the proposed system-level evaluation method.

System level Link level

 simplification / abstraction

Figure 1: System level simulation overview

Blocking model

Reception?

Transmission

OFE

model

PHY model

Received power

Optical transmit signal power

MAC model

Channel model

Read from top left, the MAC layer transmits a packet passed through the PHY and optical frontends (OFE) resulting in a transmitted optical power. The light is passed through a simplified channel model, which includes potential blockage. Accordingly, the received power is either used or set to zero. If used, it is further weighted by the optical frontend model. The L2S interface then models the physical layer (PHY) and allows to decide whether the transmitted packet has been decoded correctly or is lost.

# Analytical LOS Channel Model

Due to the negligible impact of NLOS signals in many LC scenarios [channel modeling document], the system-level channel model considers only the LOS impulse response in order to reduce computational complexity. Hence, for every transmission performed at a transmitter, the signal’s optical power at a given receiver with respect to the optical transmit power is calculated by using formula 1 as a propagation loss model.

$$\left|H\right|\_{LOS}= f\left(x\right)=\left\{\begin{array}{c}\frac{\left(m+1\right)A\_{PD}}{2πd^{2}} cos^{m}\left(Φ\right)\cos(\left(ϕ\right))g\_{C}\left(ϕ\right)g\_{F} , \left|ϕ\right|\leq ϕ\_{FOV}\\0 , \left|ϕ\right|>ϕ\_{FOV}\end{array}\right.$$

Formula 1: Optical channel DC gain

Here $\left|H\right|\_{LOS}$ is the optical channel DC gain. Furthermore, $m$ is the Lambertian order of the emitting LED, $A\_{PD}$ the area of the receiving photodiode, $d$ the distance between the emitter and receiver, $Φ$ and $ϕ$ refer to the angles of emission and incidence, respectively and $ϕ\_{FOV}$ is the field-of-view (FOV) at the receiving photodiode. $g\_{C}(ϕ)$ and $g\_{F}$ represent an additional concentrator gain and a filter gain at the receiver, respectively.

Given the modulated (i.e. non-DC) optical power at the transmitter $P\_{tx,opt}$ [dBm], the signal’s optical power at the receiver $P\_{rx,opt}$ [dBm] can be calculated by formula 2.

$P\_{rx,opt} = P\_{tx,opt}+10⋅log\_{10}(\left|H\right|\_{LOS}$)

Formula 2: Received optical power in dBm

The photodiode is characterized by its responsivity $r$ which determines the current caused by incident light power. To obtain the electrical signal power after the photodiode, which is relevant for the digital signal processor (DSP), the optical signal current must be squared, i.e. multiplied by 2 when represented in [dB]. The electrical signal power $P\_{rx,el} [dBm]$ can thus be calculated via formula 3.

$$P\_{rx,el} = 2⋅[P\_{rx,opt}+10⋅log\_{10}\left(r\right)]$$

Formula 3: Electrical signal power at the receiving DSP in dBm

Since only the LOS channel is considered, the channel impulse response is characterized by a single Dirac pulse in the time domain, having just one amplitude and one delay. In the frequency domain, amplitude response is flat. Phase increases linearly versus frequency. Phase is increased by 2π per sample clock interval for the delay.

In real hardware, the OFE may add frequency-dependent signal loss and phase distortion. The OFE effect could be modeled by applying the OFE model, as described in document number 11-18/1574r4, to obtain a frequency-dependent SNR and study the impact at the physical layer, accordingly.

The calculation of noise power $P\_{n} [dBm]$ depends on the used photodiode and trans-impedance amplifier (TIA). The noise from positive-intrinsic-negative (PIN) photodiodes is primarily due to thermal noise at the input transistor of the TIA and can be modeled as AWGN with a given power spectral density (PSD). When using an avalanche photodiode, however, which typically has a smaller area but an intrinsic gain in the order of 10-20 (20-40) dB for the optical (electrical) power, in addition to the TIA noise, shot noise has to be regarded depending on the incident optical signal power.

Based on the electrical signal and noise powers, an effective $SNR [dB]$ can be calculated via formula 4.

$$SNR \left[dB\right]= P\_{rx,el}-P\_{n}$$

Formula 4: SNR at the receiver DSP

## Propagation delay

The delay between transmission and reception of the signal can be calculated using the distance between transmitter and receiver as well as assuming propagation at the speed of light.

# Geometric blocking model

In contrast to blocking in the RF-channel, where the channel depends more on non-LOS components, blocking in the LC channel mainly introduces severe shadowing. It can be characterized by a shadow loss which very high for most materials what prevents the LC signal from propagating through the blocking object. The main point is that it depends on the individual links in each scenario and if one or more links are blocked by the same object. The correlation between the links has to be modelled correctly.

An abstract way to geometrically model blocking in LC is to insert non-opaque spheres into the simulated scenario. The spheres can be described by the position of the center and a radius. Subsequently, a low-complexity intersection test can be applied to determine whether the LOS between a transmitter and receiver is free or blocked by an object. Having multiple transmitters and receivers, the blocking spheres inherently provide spatial and temporal consistency in the MIMO link.

## Deterministic blocking

Although it is possible to randomly insert blocking spheres into the simulation scenario, this approach would require an appropriate stochastic characterization of blockages for the corresponding environment. Moreover, that method is better suited for analyzing the statistical absolute performance through a high number of simulation runs.

For the purpose of evaluating differences between proposals and parameters, however, it is sufficient to have some well-defined scenarios for comparison. Thus, the presence of geometrical blocking objects should be deterministic. This can be reached by providing the set of all blockages to the simulator prior to simulation start. For each blockage, the set includes the point in time it appears, the point in time at which it disappears, as well as the position and dimensions.

For example, a blocking object (sphere) may reside from second 1 to second 4 at a location [x, y, z] = [4, 5, 2.2] m and have a diameter of 1 m. Several subsequent blockages can be gathered in a list as shown in table 1.

|  |  |  |  |
| --- | --- | --- | --- |
| **Start [s]** | **End [s]** | **Center Position** | **Diameter** |
| 1 | 4 | [4, 5, 2.2] | 1 |
| 3 | 7 | [2, 2, 1.5] | 2 |
| 5 | 6.4 | [4, 5, 2.2] | 0.25 |
| 10 | 13 | [2, 6, 0.75] | 1.5 |

Table 1: Example blocking script data

The simulation logic performs book-keeping about all active blocking spheres at the given times. Pseudo code for that process is given in listing 1.

Load list with all blockages

Start simulation

**while** Simulation is running

{

 **if** Simulation time equals start of blockage

 {

 Add blockage with corresponding position and diameter to list of active blockages

 }

 **if** Simulation time equals end of active blockage

 {

 Remove corresponding blockage from list of active blockages

 }

 **if** Transmission started

 {

 **for each** Potential receiver

 {

 **for each** Blockage in the active blockages list

 {

 **if** Blocking object intersects with line between transmitter and receiver

 {

 Skip receiver and continue with next potential receiver

 }

 }

 Proceed with reception at the receiver (respecting the channel model)

 }

 }

}

Listing 1: Pseudo code for scripted blocking

The simulation of each individual link between each LC transmitter and each LC receiver must then consider the potential blocking sphere at every single transmission snapshot between the given start and end time while the device is moving.

# Calibration and accuracy assessment

[TODO]

# References

[TODO]