Design and Realization of a GNU Radio based Visible Light Communication Testbed

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Introduction

General context

- The growing interest in new technologies (IoT, cloud computing) results in a **massive increase** of the **total mobile network traffic** (**370 EB per month** by the end 2027\(^1\)) ⇒ **frequency raise** to exploit **unused bands** (5G, 6G)

- **Optical Wireless Communication** (OWC) systems constitute a promising **complementary solution** to RF based systems, especially **Visible Light Communication** (VLC) subset

- The concept of **Software-Defined Radio** (SDR) is applied beyond RF spectrum giving rise to **Software-Defined VLC**

\(^1\)Ericsson Mobility Report, Nov. 2021
Introduction

Thesis

- **Context:** partnership with a lightning manufacturer HOLIGHT as part of a research project, in order to develop **low data rate** (< 1Mbps) smart lighting solution for **professional and industrial** environment:
  - indoor localization
  - smart city
  - e-health

⇒ **example:** table lamp transmitting the restaurant’s menu through light variations

- **Theses’s objectives:**
  - Implementation of a **innovative SDVLC testbed** based on GNU Radio
  - Development of a **VLC open-source library**

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Outline

1. Optical Wireless Communication
2. Software-Defined VLC
3. SDVLC Testbed
4. Testbed Validation
5. Conclusion & Perspectives
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Optical Wireless Communication

Radio / Optical wireless comparison

- **OWC:** free-space propagation of light from IR to UV to transmit information
  \[\implies\] complementary solution to RF systems

### Advantages
- Higher and non-regulated bandwidth
- Higher PHY security
- No EM interferences
- Lower cost

### Drawbacks
- Communication blockage
- Ambient light noise
- Limited power (health regulation)
Optical Wireless Communication

OWC subsets

- OWC can be classified in **different subsets** according to the **system specifications**:

<table>
<thead>
<tr>
<th>FSO</th>
<th>Li-Fi</th>
<th>VLC</th>
<th>OCC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmitter</strong></td>
<td><strong>Medium</strong></td>
<td><strong>Receiver</strong></td>
<td><strong>Medium</strong></td>
</tr>
<tr>
<td>LD</td>
<td>IR/VL/UV</td>
<td>PD</td>
<td>IR/VL</td>
</tr>
<tr>
<td>LED</td>
<td>VL</td>
<td>LED</td>
<td>Camera</td>
</tr>
<tr>
<td>LD</td>
<td>VL</td>
<td>LED</td>
<td>LED array/display</td>
</tr>
</tbody>
</table>

- **Free-Space Optics**: *long range peer-to-peer communication*
- **Light-Fidelity**: *bidirectional high data-rate communication*
- **Visible Light Communication**: *illumination and communication*
- **Optical Camera Communication**: *low data-rate indoor communication*
Optical Wireless Communication
Visible Light Communication

VLC systems are generally composed of a **LED** as transmitter and a **photodiode** as receiver.

- Mostly based on **Intensity Modulation / Direct Detection (IM/DD)**
- Signal frequency $> \text{critical flicker frequency}$ ($\approx 100 \text{ Hz}$) to be imperceptible
1. Optical Wireless Communication

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Software-Defined VLC

SDR adaptation

Since SDR was initially designed to the needs of RF systems, adaptation is therefore required to perform VLC transmission:

- Enabling baseband transmission (DC transmission)
- Optical front-end (driver + LED/PD) instead of antennas ($\Rightarrow$ real and positive signal)
Software-Defined VLC

Basic architecture

![Diagram of VLC system with TX, SDR Hardware, Driver, LED, RX, SDR Hardware, TIA, PD.](attachment:image.png)
Based on **USRP 2943R** equipped with **LFTX/LFRX** daughterboards (DC-30 MHz)

**TX**: 10 MHz optical front-end (OP amp. + MOSFET + ×5 white LED)

**RX**: Thorlabs **PDA36A2** photodetector (PIN photodiode + TIA)

⇒ height, orientation and distance adjustable through a mobile trolley
SDVLC Testbed

TX Software

- gr-owc¹: OOT module for **optical channel propagation simulation**
  
  ➞ Different modulation schemes available (OOK, 2PPM, PAM, DCO-OFDM)

![Flowgraph diagram](image)

- **100 kbps OOK emission flowgraph based on gr-owc**

- Working fine in simulation but **not in a hardware implementation**
  
  ➞ lack of synchronization at the receiver

¹https://github.com/UCaNLabUMB/gr-owc
Symbol timing synchronizer\(^1\): samples alignment according to the maximum opening of the eye diagram (⇒ **timing measurement** + **timing adjustment**\(^2\))

- **Matched Filter**: detecting the received signal from the known symbols
- **Interpolator**: moving the asynchronous samples to the desired time instants
- **Timing Error Detector (TED)**: producing a signal that is function of the timing error
- **Loop Filter**: filtering the output of TED
- **Interpolation Control**: generating a synchronous clock for the Interpolator

\(^1\) *Digital Communications: A Discrete-Time Approach*, M. Rice, 2008
**SD VLC Testbed**

**Timing Synchronization**

- **AGC**: maintains a *constant level amplitude*

- **Decimating FIR Filter**: *matched filter*

- **Symbol Sync**: introduced by Andy Wall in GRCon17\(^1\) implementing different TED algorithms (Maximum Likelihood, Mueller & Müller, Zero Crossing...)  
  (≡ *Clock Recovery MM + Polyphase Clock Sync*)

  ➞ **Hervé Boeglen’s presentation**: determination of optimal parameters by simulation rather than trial and error approach

\(^1\) https://www.youtube.com/watch?v=uMEfx_l5Oxk
OOK reception flowgraph based on gr-owc with timing synchronization
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Testbed Validation

SNR Measurement

- **Performance comparison** of **3 TED algorithms** (ML, M&M and ZC) through the evaluation of **Bit Error Rate** with **different SNR**

- **SNR measurement:**
  - **Spectrum analyser** not adapted to baseband power signal measurement $\implies$ use of **oscilloscope** (RMS values)
  - **Ambient noise level** must remain the same along an acquisition $\implies$ need a **complete darkness** due to the **high sensitivity** of the photodetector
  - **Different SNR** values are obtained by changing the **communication distance** (from 1.6 to 3.1 meters)

$$SNR = 20 \log \left( \frac{V_{\text{Signal}, \text{rms}}}{V_{\text{Noise}, \text{rms}}} \right)$$
Testbed Validation

BER Measurement

- **BER measurement:**
  - **Comparison of message sent** with **received bits** recorded in a file (*File sink*) with at least **10 transmission errors**

- **BER curves** are plotted as a function of $Eb/N_0$ (＝ normalized SNR) to **not take bandwidth into account**

$$Eb/N_0 (dB) = SNR (dB) - 10 \log \left( \frac{Rb}{Bw} \right)$$


- **Results** are compared to the **expected error probability of OOK**

$$P_{e-OOK} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{Eb}{2N_0}} \right)$$

*erfc*: complementary error function
As expected, the ZC algorithm is less effective than ML and M&M. ML and M&M algorithms got similar and accurate performances for BER less than $10^{-3}$. 

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Conclusion & Perspectives

Conclusion

- **Adaptation of SDR** to implement a **SDVLC testbed** based on GNU Radio
- **Validation of the testbed** operation through **BER measurement** for different TED algorithms

Perspectives

- **Validation of the testbed** with **Non Light-Of-Sight (NLOS)** transmission
- **Integration of other VLC receivers** (*camera, solar cell*) in the testbed