

---

# SDR Beyond Radio: An Out-of-Tree GNURadio Library for Simulation and Deployment of Multi-Cell / Multi-User Optical Wireless Communications

---

Arsalan Ahmed<sup>3</sup>, Gregory Dzhezyan<sup>2</sup>, Hussam Aboutahoun<sup>1</sup>, Victor Chu<sup>1</sup>, Jordan DiViccaro<sup>2</sup>, Vahae Ohanian<sup>2</sup>, Sharareh Rezaeiboroujerdi<sup>1</sup>, Ilyas Saheb<sup>1</sup>, Evan Urban<sup>1</sup>, James Wu<sup>2</sup>, Michel Kulhandjian<sup>4</sup>, Hovannes Kulhandjian<sup>2</sup>, and Michael B. Rahaim<sup>1\*</sup> MICHAEL.RAHAIM@UMB.EDU\*

<sup>1</sup>Engineering Department, University of Massachusetts, Boston, MA, USA

<sup>2</sup>Department of Electrical and Computer Engineering, California State University, Fresno, CA, USA

<sup>3</sup>School of Built Environment, Engineering, and Computing, Leeds Beckett University, Leeds England

<sup>4</sup>Electrical and Computer Engineering Department, Rice University, Houston, TX, USA

## Abstract

Research in the field of optical wireless communications (OWC) has led to significant advances in high speed point-to-point communication links, but there is much work to be done in the area of multi-cell/multi-user OWC systems. In order to make experimental research in this area more approachable, we have developed an SDR framework for OWC systems and provided an open-source out-of-tree (OOT) software library, namely *gr-owc*, that allows for quick development and testing of novel OWC techniques. In this paper, we describe our recent improvements to *gr-owc*, including the addition of new OWC channel characteristics, modules for DC-Biased Optical OFDM/OFDMA, and resource allocation capabilities for custom hardware that applies multi-color channels and enables research in wavelength division multiplexing (WDM) or wavelength division multiple access (WDMA) systems. Furthermore, the hardware deployment process is detailed to enable a workflow that spans from simulated system analysis to experimental evaluation.

## 1. Introduction

Optical wireless communication (OWC) technologies have gained significant interest over the past two decades; however, early research focused on point-to-point links and novel modulation techniques. More recently, the field has moved towards higher layer design and analysis of multi-cell / multi-user systems, leading to novel schemes for resource allocation across devices and overlapping OWC ac-

cess points (APs). However, much of this work has been based in theory and simulation since significant effort is required to develop proof-of-concept implementations of such systems. This limits the opportunity for experimental evaluation of novel techniques for resource allocation and/or handover.

To address this need, we apply the software-defined radio (SDR) tools and concepts that have benefitted the RF research community (Valerio, 2008; Rondeau et al., 2015). Namely, SDR has created a more equitable opportunity for research in the wireless communications field by reducing the barrier to entry and making it more feasible for researchers to physically instantiate novel ideas. We bring this accessibility to OWC systems research by developing a baseline resource allocation implementation for multi-user and/or multi-cell systems. By developing this implementation within the widely used GNURadio SDR signal processing toolkit, we can offer the module as an open-source tool for other researchers to use as a “golden reference” that can be compared with novel resource allocation techniques and/or iterative improvements to the baseline technique.

GNURadio provides an ideal platform for SDR implementation. In particular, GNURadio’s out-of-tree (OOT) modules allow for the addition of custom signal processing blocks. Using this feature, we have developed *gr-owc*, an open source OOT module for OWC (Ahmed & Rahaim, 2021). In this paper, we will describe our recent contributions to *gr-owc*, including further development of our DC-biased Optical OFDM (DCO-OFDM) modules and implementation of resource allocation modules for merging multiple data streams via DCO-OFDMA. We also introduce our methods for using *gr-owc* to instantiate a physical OWC testbed using X310 USRPs and a combination of custom and COTS front-end OWC hardware.

As a testbed, the key benefit of SDR is that the system is built off modular design principles such that front end transmitter/receiver hardware can be interchanged, and the

waveforms generated in software can be parameterized to align with the characteristics of hardware currently in use. As such, we will also introduce our custom-built multi-color OWC transmitter where each color channel can be directly driven by a single real-valued signal from the US-RPs with LFTX daughter cards. This enables experimental analysis of wavelength division multiplexing (WDM) and/or wavelength division multiple access (WDMA) systems. In summary, we present our recent work that extends the initial functionality of *gr-owc* to include various resource allocation capabilities for testing multi-cell and multi-user OWC systems.

## 2. Background and Overview

There are a number of prior works in software defined OWC (Qiao et al., 2014; Aly et al., 2020), including our early work in (Rahaim et al., 2014; Little et al., 2018). However, this prior work has typically been focused on specific research objectives. Also, the underlying source code is not easily available to the research community. In developing an open-source framework for SDR-based OWC tools, we first introduced the GNURadio *gr-owc* library (Ahmed & Rahaim, 2021) for simulated analysis of indoor OWC systems. We now extend *gr-owc* to incorporate a fully developed DCO-OFDM signal processing chain and demonstrate its use in simulation and in multiple hardware deployments. While DCO-OFDM is our initial point for developing an OWC OFDM implementation, this foundational work also allows for further development to incorporate other Optical OFDM schemes that are of interest to the research community (Dissanayake & Armstrong, 2013; Zhang et al., 2021).

In the process of developing a toolbox for OWC, we must recognize the key characteristics that distinguish optical links from conventional RF links. In particular, we focus specifically on OWC designs that implement intensity modulation with direct detection (IM/DD). Such systems use a drive signal to modulate the intensity (i.e., optical power) of an optical transmitter and use a photosensor to directly convert the received optical power into an electrical current. OWC links are also highly directional in relation to characteristics of the emitter (e.g., LED) and the receiver (i.e., photosensor). These points are accounted for in the optical channel model which commonly considers the DC channel gain from transmitter  $i$  to receiver  $j$ :

$$H_{ij} = \frac{C_T G_T(\phi_{ij}) C_R G_R(\psi_{ij})}{d_{ij}^2} \quad (1)$$

Here, the channel parameters  $\phi_{ij}$ ,  $\psi_{ij}$ , and  $d_{ij}$  represent the emission angle, acceptance angle, and distance between transmitter and receiver (See Fig.1). The parameters  $C_T$  [W/A] and  $C_R$  [A/W] are the conversion factors from

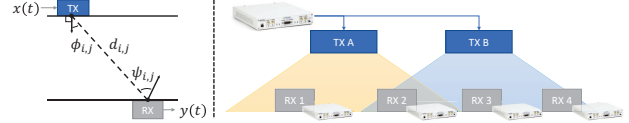


Figure 1. OWC channel model (left), and depiction of an OWC system with multiple-cells and multiple users (right). Notice that Tx A and B must allocate resources to avoid interference at Rx 2. Also, Tx B must divide its resources amongst Rx 3 and Rx 4.



Figure 2. Modular Front-End hardware (transmitters / receivers) for software defined OWC system.

electrical to optical and optical to electrical, and the functions  $G_T(\cdot)$  and  $G_R(\cdot)$  define the transmit and receive gain as functions of the emission and reception angles, respectively. There are two key observations from this model. First, the conversion between the electrical and optical domain is assumed to be linear. Furthermore, transmitter and receiver gain functions are highly directional and depend on the characteristics of the front-end optical hardware. These hardware characteristics are further defined in (Ahmed & Rahaim, 2021).

Considering the impact of front-end hardware characteristics, it is valuable to have a test system capable of adapting to various transmitter and receiver designs. The modular design of an SDR-based system allows for interchangeable front-end hardware and testing of various signal processing chains. Accordingly, we can interchange optical transmitters or receivers in the same way that a conventional SDR system would exchange antennae (Fig.2). On the transmit side, this could be the option to change from a simple low-power single-LED, to inexpensive LED boards, or to more expensive commercial transmitters with higher bandwidth capabilities (e.g., (Hyperion Technologies, 2022)). At the receiver, there is a variety of commercial photosensors available through Thorlabs and other companies, and the modular design also enables testing with different lenses and/or optical filters. This also offers a cost/performance tradeoff where researchers can deploy an initial test system with low cost, and improve the front-end hardware capabilities over time. Custom hardware can also be incorporated, as we discuss in Section 3.2 with regards to our custom multi-channel transmitter with individual control over red, green, and blue signals from multi-color LEDs.

Front-end hardware characteristics also play a significant role in the performance and resource allocation decisions within multi-cell/multi-user OWC systems (Fig. 1). The-



Figure 3. SDR-Based signal chain for IM/DD OWC with modular Tx/Rx hardware and parameterizable signal processing within the GNURadio toolkit using the *gr-owc* library.

oretical work for such systems has proposed and analyzed via simulation for multiple access (Wang et al., 2017; Hammouda et al., 2018; Lian & Brandt-Pearce, 2019), handover (Dastgheib et al., 2018; Younus et al., 2021), and other system-level protocols; but we hope that the availability of our software defined OWC tools will help to bring experimental testing capabilities to researchers working in these areas.

### 3. System Design and Implementation

As a testbed, SDR systems benefit from the application of modular design principles such that front-end OWC hardware can be interchanged, and the waveforms generated in software can be parameterized to align with the hardware characteristics. This is depicted in Fig. 3, where we show a single link software-defined OWC signal chain. Since the front-end Tx/Rx hardware is decoupled from the underlying signal processing of the OWC signal, a variety of hardware can be used and we can adapt the GNURadio flowgraph parameters to align with the current hardware. Similarly, different signal processing techniques can be applied to the same hardware in order to compare performance. In this section, we introduce the system’s software/signal processing design and front-end hardware configurations, along with additional modifications to implement multiplexing or multiple-cell/multi-user systems.

#### 3.1. Simulation and *gr-owc* Software

Our *gr-owc* library is available on GitHub and in the Comprehensive GNURadio Archive Network (CGRAN), allowing for easy installation and integration with the core GNURadio library. The *gr-owc* library also includes example flowgraphs to demonstrate simulated and experimental OWC systems. At present, the *gr-owc* library includes signal processing blocks for the following OWC functions:

- IM/DD OWC channel modeling blocks
- Modulator and demodulator blocks for OWC pulsed modulation schemes
- Hermitian symmetry blocks for implementing DCO-OFDM and/or DCO-OFDMA

The channel blocks implement the DC channel gain of a point source Lambertian emitter and optical receiver. This

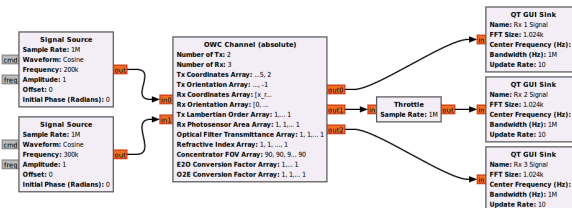


Figure 4. GNURadio flowgraph with custom *gr-owc* channel model for simulating multi-cell and multi-user OWC environments. Transmitter and receiver location and orientation can be modified in real time, and OWC hardware characteristics are individually parameterized for each modeled Tx/Rx device.

Lambertian model is commonly used for indoor OWC links. The channel blocks can also model multi-cell and multi-user systems, including interference from neighboring OWC access points (Fig. 4). The channel model blocks are also being improved to include the enhanced capability of modelling propagation delays, path blockages and OWC-specific noise characteristics. The pulse modulation schemes in *gr-owc* include on-off keying, pulse-amplitude modulation and variable pulse-position modulation. Each of these blocks allow for parameterization related to OWC hardware (e.g., range and bias). More information about these blocks can be found in (Ahmed & Rahaim, 2021).

For the signal processing blocks, our key addition is a new module to apply Hermitian symmetry as required by DCO-OFDM. We discuss a DCO-OFDM implementation in (Ahmed & Rahaim, 2021), but this example is based off the OFDM modules in GNURadio’s core library. It implements digital up/down conversion to generate the desired signal, but this is not ideal. By adding a Hermitian symmetry block to *gr-owc*, we can use a broken out OFDM signal chain to generate the DCO-OFDM waveform more efficiently, and to have more control of the packetization and other overhead. This Hermitian symmetry block is developed as a GNURadio custom block such that a vector stream holding the complex-valued symbols for specified subcarriers are streamed as input and, for each input vector, a Hermitian symmetric vector of size  $N$  is output from the block. The broken out OFDM signal chain also enables more flexibility in the subcarrier assignment, packet overhead, and other waveform characteristics.

The *gr-owc* library also provides example flowgraphs to benchmark signal processing schemes and/or system implementations. These flowgraphs act as a baseline for further experimentation while accelerating the start up process for the new users. Currently, there are example flowgraphs which demonstrate the use of the channel blocks along with the modulators and demodulators blocks. Additionally, example flowgraphs related to DCO-OFDM are also provided. The DCO-OFDM examples are split into simulation flowgraphs and full system flowgraphs. The simulation flowgraphs are intended for simulating and evaluating physical layer performance of point to point DCO-OFDM and DCO-OFDMA scenarios. On the other hand, the full system flowgraphs with full support for synchronization and packetization are produced for packet level analysis. These full system flowgraphs can be easily moved from the simulated environment to a real-time physical instantiation using SDR hardware and front-end OWC equipment as described in Section 3.2.

### 3.2. Hardware Deployment

When moving from a simulated OWC environment to an experimental setup, we consider three primary components as depicted in Fig. 3:

- SDR Hardware (e.g., USRPs)
- OWC Transmitter Front-End Equipment
- OWC Receiver Front-End Equipment

While other SDR hardware can be used, a key aspect of our design is the use of universal software radio peripheral (USRP) hardware with modular daughter cards (i.e., X/N/2900 series USRPs). When using the LFTX and LFRX daughter cards, these USRPs can bypass the carrier up/down conversion and directly connect to baseband OWC hardware to implement an IM/DD OWC link. More importantly, each LFTX/LFRX daughtercard has SMA output for the real and imaginary (i.e., I and Q) components of a complex baseband RF signal. Complex valued signals are sent to/from the USRP hardware, but the real and imaginary components can be broken out within GNURadio to observe two separate real-valued signals. This is incredibly valuable to systems-level OWC experiments since the USRPs can actually transmit and receive two real-valued OWC signals for each RF signal chain.

There are various characteristics of the OWC front-end hardware that will impact the emission and reception patterns, signal strength, available bandwidth, and color band. Fig. 5 depicts a generalized signal chain for the transmitter and receiver, noting that these analog components may be designed within the hardware or implemented as discrete components in order to provide additional testing flexibility. When applying the USRP output to an OWC transmitter, a linear optical conversion is ideal and the conversion

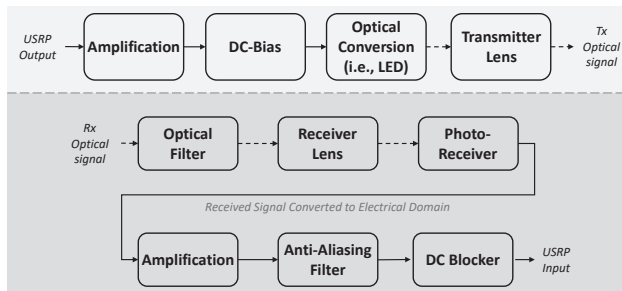


Figure 5. Generalized signal chains for OWC transmitter (top) and receiver (bottom) hardware.

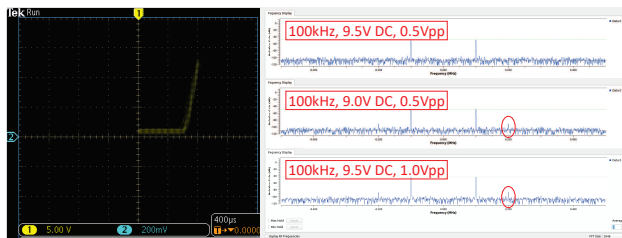


Figure 6. OWC conversion characteristics (left) and impact of nonlinearities introduced due to signal clipping (right). The conversion plot appears linear between 8-10V, but upon inspection in the frequency domain we see harmonics in the lower 2 plots.

should be carefully evaluated to ensure that no harmonics occur due to clipping. Accordingly, the amplification and bias of the USRP's output AC signal should aim to place the drive signal within the linear range of the optical conversion, while also aiming to maximize the signal power. This range is depicted in Fig. 6 along with an example depiction of harmonics due to clipping. However, we note that these nonlinearities can also be addressed with digital pre-distortion techniques in order to extend the dynamic range of the transmitted OWC signal. Lastly, we note that the OWC transmitter can optionally incorporate optical lensing in order to adjust the emission pattern to be more or less directional. This is highly valuable for evaluating the impact of transmitter locations and coverage in multi-cell environments, and for analyzing the impact of emission profiles on inter-cell interference, handover, and other system-level characteristics.

At the receiver, we use a variety of commercially available optical receivers with adjustable lenses, optical filters, and gain settings. The lenses and lens tubes applied to the receiver impact the field-of-view and, more generally, the receiver's acceptance pattern. The optical filters allow for use of multi-color channels when the transmitter is capable of transmitting via different colors. Furthermore, blue filters are commonly used when white phosphor LEDs are used at the transmit side since the blue light LED behind the phosphor has a much faster response than the energy

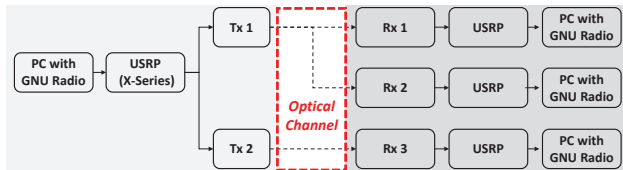


Figure 7. Signal chain for a multi-cell and multi-user system similar to the one depicted in Fig. 1.

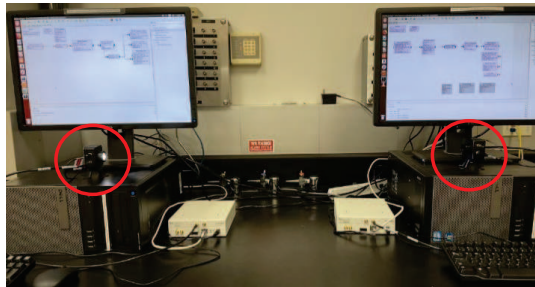


Figure 8. SDR-Based OWC hardware using COTS transmitter and receiver hardware from Hyperion Technologies for a single simplex OWC link. Hardware specifications indicate  $\sim 20\text{MHz}$  bandwidth, but we have not tested the full capabilities due to real-time processing limitations for data modulation/demodulation.

down conversion from the phosphor (i.e., what generates the broader spectrum white light). Accordingly, these filters allow for increased bandwidth in exchange for reduced signal power. Depending on the bandwidth characteristics of the front-end hardware (Tx and Rx), we can also include an anti-aliasing filter that reduces noise when downsampling to allow for more complex signal processing chains to be executed in real-time on a general purpose processor. LFRX daughter cards have onboard  $30\text{MHz}$  anti-aliasing filters, but the additional filter can be applied prior to the USRP as needed. Furthermore, a DC blocking capacitor is useful to mitigate the signal bias and any additional bias from ambient light sources.

Finally, the single-link signal chain described above can be extended to incorporate more complex OWC multiplexing or multiple access scenarios. The signal chain in Fig. 7 shows a configuration similar to the two transmitter / three receiver scenario depicted in Fig. 1. This two cell system can be implemented with a single USRP RF by applying the I and Q LFRX output to different transmitters. Similarly, X Series USRPs (e.g., X300 or X310) are capable of driving 4 unique OWC transmitters. A similar scenario can be implemented for wavelength division multiplexing (WDM) implementations by, for example, using three X Series output signals to individually drive a red, green, and blue color channel while receiving the three signals at a single X Series USRP through three photosensors with red, green, and blue filters.

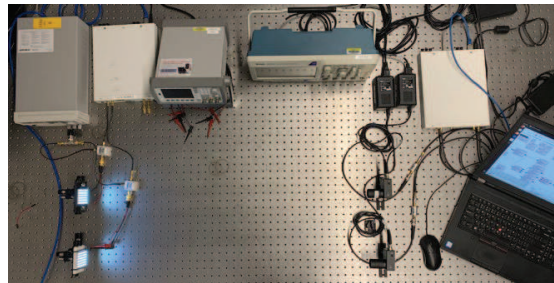


Figure 9. SDR-Based OWC configuration with multiple transmitters and multiple Thorlabs PDA100A2 receivers. The setup is capable of controlling 4 transmitters from a single USRP X310 and can be used for testing multi-cell/multi-user environments, Optical MIMO, visible light positioning, Spatial Modulation, and other OWC system concepts.

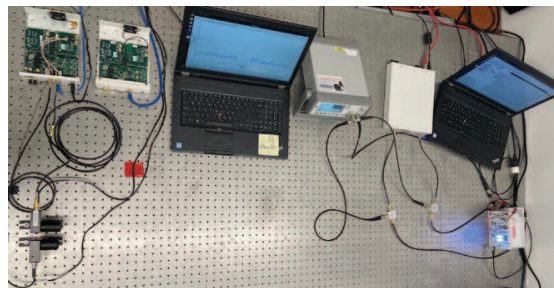


Figure 10. SDR-Based OWC hardware using a multi-color transmitter with Thorlabs APD120A2 and PDA100A2 receivers. The configuration shows a WDM instance with red and blue color channels from a single transmitter to a single receiver, but this can also be implemented in a WDMA design where the two different color receivers connect to two different USRPs. Breadboard prototype is shown here, but we also have demonstrated this configuration with a custom transmitter PCB (shown in Fig. 2).

## 4. Experiments and Test Scenarios

The example flowgraphs in *gr-owc* can be used to test performance in a simulated system, or with USRPs and OWC hardware in an experimental systems. We have implemented experimental proof-of-concept demonstrations with digital data transmission (e.g., file transfer and audio/video streaming) as well as quantitative performance testing to show packet error rate as a function of distance and orientation. Our workflow follows a progression from fully simulated systems using the *gr-owc* channel models, to a loopback system where the channel models are replaced with a USRP hardware driver (UHD) source/sink pair and the Tx/Rx hardware connect to the same USRP, to a functional link where the Tx and Rx signal chains are implemented on separate PCs with different USRPs. With the *gr-owc* multi-cell channel models, this workflow also scales well for testing the impact of interference in OWC networks. We have experimentally demonstrated multiple

simultaneous file transmissions using DCO-OFDMA and observed the benefits of resource allocation to mitigate interference in multi-cell configurations, but we have not yet completed a full quantitative analysis.

Figures 8 through 10 show the experimental setup for different test configurations, including a point-to-point link with high bandwidth ( $\sim 20$  MHz) transmitter and receiver from Hyperion Technologies (Hyperion Technologies, 2022), a system with low cost transmitters and Thorlabs receivers for testing multi-cell and multi-user environments, and a system with our multi-color OWC transmitter with separately controllable RGB signals and Thorlabs receivers with matching color filters. This last system has been used to show WDM and WDMA through waveform separation at the signal level, and we aim to implement the DCO-OFDM transmission on this system for a more complete test in the near future. Currently, *gr-owc* includes example flowgraphs for DCO-OFDM point-to-point links and a basic DCO-OFDMA system. The OFDMA flowgraphs and WDM/WDMA test modules are not currently included in *gr-owc*, but will be added after further testing and verification. Until then, these modules are available upon request.

## 5. Summary and Conclusion

In summary, the signal processing blocks and flowgraphs in *gr-owc* establish the framework for a work flow that extends from simulated analysis through real-time experimental analysis. We will continue developing this library to incorporate other optical OFDM schemes, dynamic resource allocation techniques for multi-user systems, and modules for higher layer protocols and heterogeneous network integration with RF networks. As part of the comprehensive GNURadio Archive Network, *gr-owc* is easily accessible and offers OWC researchers an open-source toolkit to validate their own work and to compare experimental performance with our baseline protocols and techniques.

## Acknowledgements

Special thanks to the Air Force Research Lab and Wright Brothers Institute for supporting aspects of this project in the 2021/22 Beyond 5G SDR Challenge. In addition, H. Kulhandjian's research work is partially supported by the DoD Instrumentation Grant Number W911NF2110210.

## References

- Ahmed, A. and Rahaim, M.B. *gr-owc*: An open source GNURadio-based toolkit for optical wireless communications. In *Int. Conf. on Wireless and Mobile Computing, Networking and Comms (WiMob)*, 2021.
- Aly, B., Elmassie, M., Kebapci, B., and Uysal, M. Ex-

perimental evaluation of a software defined visible light communication system. In *IEEE Int. Conf. on Comms Workshops (ICC Workshops)*, pp. 1–6. IEEE, 2020.

- Dastgheib, M., Beyranvand, H., Salehi, J., and Maier, M. Mobility-aware resource allocation in VLC networks using t-step look-ahead policy. *J. of Lightwave Tech.*, 36(23):5358–5370, 2018.
- Dissanayake, S.D. and Armstrong, J. Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems. *J. of Lightwave Tech.*, 31(7):1063–1072, 2013.
- Hammouda, M., Vegni, A.M., Haas, H., and Peissig, J. Resource allocation and interference management in OFDMA-based VLC networks. *Physical Communication*, 31:169–180, 2018.
- Hyperion Technologies. LiFi development tools, 2022. URL <https://www.hyperiontechs.com/>.
- Lian, Jie and Brandt-Pearce, Maite. Multiuser visible light communications using OFDMA. In *45th European Conf. on Optical Comms (ECOC 2019)*, pp. 1–4, 2019.
- Little, T.D.C., Rahaim, M.B., Abdalla, I., Lam, E., Mcallister, R., and Vegni, A.M. A multi-cell lighting testbed for VLC and VLP. In *2018 Global LIFI Congress (GLC)*, pp. 1–6, 2018.
- Qiao, Y., Haas, H., and Knightly, E. A software-defined visible light communications system with warp. In *1st ACM Workshop on VLC Systems*, 2014.
- Rahaim, M.B., Mirvakili, A., Ray, S., Hella, M., Koomson, V.J., and Little, T.D.C. Software defined visible light communication. In *Wireless Innovations Forum Conf. on Wireless Comms Technologies and SDR*, 2014.
- Rondeau, T.W., Holland, O., Bogucka, H., and Medeisis, A. On the GNU radio ecosystem. *Opportunistic Spectrum Sharing and White Space Access: The Practical Reality*, pp. 25–48, 2015.
- Valerio, D. Open source software-defined radio: A survey on GNUradio and its applications. *Forschungszentrum Telekommunikation Wien, Vienna, Technical Report FTW-TR-2008-002*, 2008.
- Wang, Yunlu, Wu, Xiping, and Haas, Harald. Resource allocation in LiFi OFDMA systems. In *IEEE Global Communications Conference (GLOBECOM)*, pp. 1–6, 2017.
- Younus, Safwan Hafeedh, Al-Hameed, Aubida A, and Hussein, Ahmed Taha. Novel handover scheme for indoor VLC systems. *IET Comms*, 15(8):1053–1059, 2021.
- Zhang, X., Babar, Z., Petropoulos, P., Haas, H., and Hanzo, L. The evolution of optical OFDM. *IEEE Communications Surveys and Tutorials*, 23(3):1430–1457, 2021.