Software Defined Visible Light Communication

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Abstract

Software Defined Radio (SDR) has proven to be a practical and effective tool in RF communications, allowing flexible and rapid exploration of dynamic RF signal processing techniques while accelerating advancement of configurable RF antennas and front-end hardware. SDR concepts can be adapted to other physical media; we investigate a Software Defined Visible Light Communications (SDVLC) solution that adapts SDR platforms to the constraints of an Optical Wireless (OW) channel using the visible spectrum. Such a platform can be dynamically modified in order to meet both the data communications and illumination requirements of a dual-use VLC system. The platform enables concurrent development of signal processing techniques and front-end hardware that, along with the ability to quickly bring up an OW system, makes SDVLC a powerful concept for facilitation of VLC research and experimentation. We describe SDVLC characteristics and review the use of an instance to investigate tradeoffs in the delivery of room lighting and simultaneous adaptive modulation.

Keywords – Visible Light Communication (VLC), Software Defined Radio (SDR).

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1. Introduction

Optical Wireless Communications, specifically Visible Light Communications (VLC), have gained recent interest as dual-use lighting and communication systems due to the ubiquity of emerging solid-state lighting [1,2]. The high speed switching capability of LEDs allows data to be transmitted in the visible spectrum by modulating optical intensity levels at rates faster than the response of the human eye. As illumination-grade LEDs begin to replace conventional incandescent and fluorescent lights, the opportunity arises to provide wireless data from every luminaire using the visible spectrum as 'Visible Light Communication.' For this reason, VLC has recently emerged as an exciting area of research in the field of wireless communications.

VLC has certain advantages over RF-based technologies. Light signals can be directed and sequestered, unlike omnidirectional RF, thus achieving excellent spatial reuse of channels. This leads to increased bandwidth densities (Mb/s/m^2) and the potential to deploy many small cells in close proximity (e.g., cells in adjacent rooms or cells within a single room). This same property helps make VLC more secure against eavesdropping as compared to RF. VLC also uses vast, free, and unregulated spectrum and the high illumination levels typically required for lighting can translate into high power irradiances for communication [3].

Fundamental differences between OW and RF media also lead to challenges in adapting an SDR platform to the optical medium. VLC systems, with non-coherent sources, typically implement Intensity Modulation with Direct Detection (IM/DD); therefore limitations in the bandwidth of illumination-grade LEDs constrain modulation to low frequency or baseband techniques. Optical devices have nonlinear electro-optic conversion characteristics and require a positive drive signal; therefore device-dependent signal pre-distortion and biasing is needed. To achieve a desired illumination profile for lighting, a specific irradiance is required at the surface under consideration; therefore the modulation of the optical signal must be adaptable to meet constraints on average optical power in contrast to satisfying the maximum average electrical power requirement as is necessary in an RF link. Finally, optical receivers are inherently directional and the received signal is dependent on the angles emission and arrival; therefore the use of multi-channel optical diversity receivers should be explored when considering the optimization of a VLC network.

Given the early stage of development in the area of VLC and the complexities involved in implementing signal chain components in a testbed, we have found a need for tools to accelerate the development and testing of VLC prototypes, solutions and protocols. Software-defined systems offer an efficient low-cost platform with the flexibility to assist in development by (a) providing a modular separation of front-end hardware and signal processing techniques, (b) offering the agility to modify and test various signal processing techniques without any hardware updates, and (c) allowing for dynamic variations of the signal processing techniques in order to adapt to changes in the lighting requirements. We have implemented an SDVLC system [4] to assist with our own research as well as our collaborations with other universities and others have followed suit with similar implementations [5].

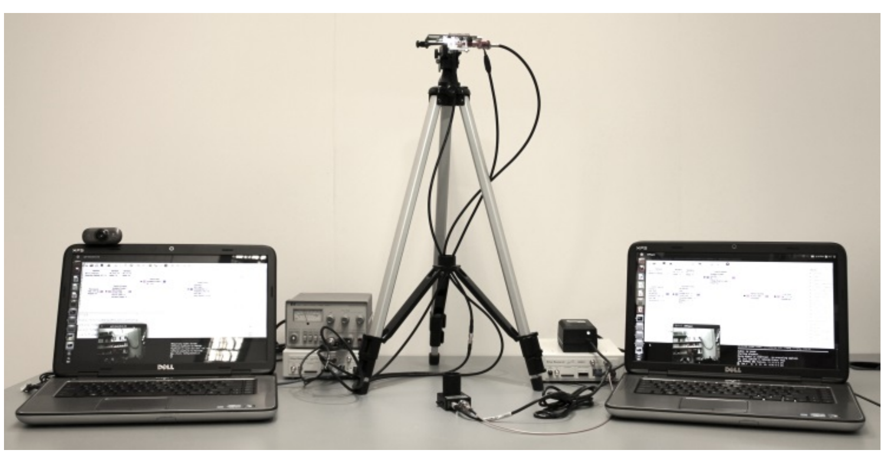


Figure 1: Software Defined VLC Implementation

In this paper, we report on the development of an SDVLC system, shown in Figure 1, which uses SDR tools to implement, integrate, and operate VLC links. A brief introduction of dual-use VLC is provided in Section 2, along with a review of recent literature. Section 3 presents a detailed description of the considerations for SDVLC front-end hardware. Section 4 reviews our adaptation of SDR platforms, namely GNU Radio and Simulink, and specifies the various hardware devices used. In Section 5, we describe how the SDVLC system is used to explore an adaptive modulation scheme based on illumination requirements. Section 6 concludes the paper.

2. Dual-Use VLC

VLC has a variety of niche applications in areas such as underwater communication, near-field communication, indoor positioning, wireless communication in RF restricted areas, and secure wireless communications [1]. In our work in the NSF Smart Lighting Engineering Research Center, we consider dual-use – lighting and communication – as the primary use case for VLC. The main benefits of dual-use VLC are the ability to piggyback on the existing lighting infrastructure, strategically place access points where humans are located, and integrate with other functions such as sensing and lighting control for health and energy conservation goals.

Much of the published work on VLC focuses on the physical communication channel to implement a single high speed point-to-point link by combining some or all of the following techniques [6-8]: (1) Equalization at the transmitter or receiver to flatten the spectral response and increase bandwidth. (2) Pulse shaping (peaking) to improve rise and fall time of the optical channel. (3) Use of micro-LEDs to improve bandwidth of the optical channel. (4) Use of multiple narrow-band LEDs (e.g., RGB) to provide white light, allowing additional bandwidth through wavelength division multiplexing. (5) MIMO schemes to take advantage of the directionality of light – providing diversity or multiplexing via parallel channels. (6) High order modulation schemes to improve bandwidth efficiency (b/s/Hz). (7) Optical OFDM schemes to combat frequency selectivity. A single system combining these and other approaches clearly has a high degree of complexity in implementation. This is a primary motivation for the SDVLC system that allows flexible integration of hardware prototypes with signal processing techniques implemented on a general-purpose processor.

Recent research in VLC has produced instances of multi Gigabit per second data rates [8] demonstrated in laboratory settings at short range with off-line processing. Other demonstrated systems achieve real time data rates on the order of 100 Mb/s at distances of a few meters; however many implementations lack link robustness, require precise alignment, and ignore lighting requirements. These constraints, along with the infancy of system-level VLC research, limit the use of such implementations for practical scenarios and motivate further research and development. We next discuss the OW channel and the constraints that differentiate dual-use VLC from RF communications.

2.1 Optical Wireless Channel

In an IM/DD optical channel, we define $x(t)$ as the instantaneous optical signal power, or intensity (W), of a light source; therefore $\min\big(x(t)\big) = 0$ and the constraint $x(t) \geq 0$ holds for all t. The transmitter generates an average signal power, P_t, and an optical receiver in view of the light source produces an instantaneous received signal current, $y(t)$, such that

$$P_t = \lim_{T\to\infty} \frac{1}{2T} \int_{-\infty}^{\infty} x(t)dt$$

$$y(t) = R\big(x(t) * h(t)\big) + n(t)$$

where $h(t)$ is the channel impulse response, R is the responsivity of the photodiode (A/W), and $n(t)$ is the electrical noise which has two dominant components: shot noise from ambient light and thermal noise from receiver electronics. Multipath fading is negligible since the area of a photodiode is many times larger than the wavelength of light. In general, there is some multipath channel distortion, but in practice this is small for scenarios where there is a dominant line-of-sight (LOS) path. Simply, the direct path dominates because signal from reflected paths is greatly attenuated and minimally delayed in most room-size environments; hence, the approximation $h(t) = H\delta(t)$ is typically very good.

Due to the directionality of the optical medium, the LOS DC Channel Gain, H, is dependent on the angle of emission, ϕ, and angle of arrival, ψ. For the specific instance in this implementation, we use concentrator optics at the receiver such that the channel gain is defined by

$$H = \begin{cases} \frac{A}{d^2} R_o(\phi) g(\psi) \cos(\psi), & 0 \le \psi \le \Psi_c \\ 0, & \psi > \Psi_c \end{cases}$$

where A is the area of the photodiode, d is the distance between transmitter and receiver, Ψ_c is the concentrator field of view (FOV), $R_o(\phi)$ is the radiation pattern of the transmitter, and $g(\psi)$ is the concentrator gain function. For a non-imaging hemispherical concentrator with internal refractive index n, the concentrator gain is constant $g(\psi) = n^2/\sin^2(\Psi_c)$ for all angles in the FOV ($\psi \le \Psi_c$). The radiation pattern of an optical source without additional optics is typically considered Lambertian with order m where m is related to the semi-angle at half power, $\Phi_{1/2}$, by $m = -\ln 2/\ln\left(\cos\Phi_{1/2}\right)$. In this case, $R_o(\phi)$ is defined as

$$R_o(\phi) = \frac{m+1}{2\pi} \cos^m(\phi)$$

Note that the received signal in an OW link is dependent on the orientation of the transmitter and the receiver. This differs from conventional omnidirectional RF communication where orientation is irrelevant as well as directional RF media (e.g., 60GHz and mm-Wave) where the received signal is dependent on the orientation of the transmitter, but not necessarily of the receiver. Since the receiver is often associated with a mobile user, we cannot assume that the device is directed towards the transmitter. Two options to resolve this issue are to use a wide angle lens that has a high probability of observing a LOS signal or to use a diversity receiver with multiple sensors aligned in different directions so there is high probability that at least one of the sensors will observe a LOS signal. The selection process in the latter is another motivation for the SDVLC system as the optimal sensor or subset of sensors can change rapidly under the dynamics of a mobile OW receiver.

2.2 Communication Constraints

In dual-use VLC systems, the constraints on the communication link come from the physical limitations of the medium as well as requirements of the primary illumination functionality. These constraints, including signal bandwidth, average power, and range, are similar to the constraints of an RF channel; however they stem from a different set of limitations and requirements.

2.2.1 Bandwidth

The major limitation in the design of a dual-use VLC system is the bandwidth of illumination-grade LEDs. White illumination LEDs are commonly implemented as a blue LED coated with a phosphor that down-converts the blue light into a broad (white) spectrum. The LED itself may achieve close to 20MHz of bandwidth, however the slow decay of the phosphor material limits the 3dB bandwidth of the system to approximately 2-5MHz [9]. Other luminaires implement multicolor LEDs (e.g., RGB) that combine to generate white light; however bandwidth on the order of 10MHz still limits the signal to relatively low frequencies when compared to coherent RF communications. Laser Diodes and Micro-LEDs have potential for much higher bandwidth; however they are not common for use in illumination-grade luminaires.

Given this limitation, baseband techniques such as On-Off Keying (OOK), Pulse Amplitude Modulation (PAM) or Pulse Position Modulation (PPM) are often used in OW systems. Performance of these techniques is affected by the rise and fall times of the optical channel and in many cases the rise and fall time may not be equivalent. Baseband OFDM, or Discrete Multi-Tone (DMT) modulation, is also used to improve bandwidth efficiency. OFDM techniques allow the signal to be extended beyond the 3dB cutoff of the LED by partitioning bandwidth into multiple smaller slots that are nearly flat in the frequency domain. Since higher frequency components are highly attenuated, lower order modulation schemes are used in these slots. The alternative option is to implement a passband signal with a low frequency carrier such that the frequency components of the signal fall within the bandwidth of the optical channel. Both methods have been implemented in the SDVLC setup and are described in detail in Section 4.

2.2.2 Average Power

When implementing an OW link, constraints are imposed on the average optical power (i.e., for eye safety purposes in infrared or illumination requirements in dual-use VLC systems). This varies from the usual average electrical power constraints due to energy efficiency requirements.

In a system implementing dual-use VLC devices, the lighting requirement is to provide a specified illumination profile. In the simplest case, 400 lux is often required at the working surface; however various dimming levels can be required and newer intelligent lighting systems can provide the capabilities to adapt the illumination profile to match the lighting desired by users in the environment. This can include changing the average optical power from luminaires (i.e., dimming) or changing the average optical power from each color source in a color tunable RGB luminaire. In either case, the average power of the signal is specified rather than bounded from above. Due to the requirements on average optical power, Signal to Noise Ratio (SNR) of an OW link is defined as:

$$SNR = \frac{(RHP_t)^2}{\sigma^2}$$

where σ^2 is the total noise variance. Note that this definition relates to average optical power as opposed to the conventional SNR definition (ε_b/N_0) that relates to average electrical power. The conversion of optical power to electrical current creates a square proportionality between optical power and electrical power.

The requirement of a specific average power adds complexity to the modulation methods used in dual-use VLC systems. As a simple example, an equally weighted OOK signal produces an average power of half the peak optical power when the entire range is used. In order to vary the average, you can add overhead to weight the code at a cost to the throughput (e.g., 8b/10b encoding) or you can vary the min or max values at a cost to the SNR. Another example of a modulation scheme that depends on average power is variable pulse position modulation (VPPM) that is defined in the IEEE 802.15.7 specification.

2.2.3 Dynamic Range

The aforementioned variation in signal range in order to meet the average power requirements is one of the considerations for dynamic range of the optical signal in dual-use VLC systems. While intensity modulation constrains the signal to positive values, there is also a limit on the peak optical power that a device can generate. Given these bounds, the range of the received signal is dependent on the DC channel gain. Due to the effect of distance and receiver rotation, this range can vary greatly when considering mobile user devices. Also, systems that use diffuse communication must accommodate drastic variations in the received signal range when switching between a LOS channel and a multipath channel.

Another constraint on the available range of an OW channel comes from non-linearity of the optical conversion at the transmitter and electrical conversion at the receiver. When implementing two-level discrete modulation schemes such as OOK or PPM, the linearity of the channel can be ignored; however the performance of low frequency passband schemes or multi-level schemes such as PAM and DMT can be affected by this non-linearity. Since the range of the drive signal is determined in software for an SDVLC system, it is possible to dynamically equalize the signal to accommodate the non-linearity or to adjust the signal to operate only in the linear range of the channel.

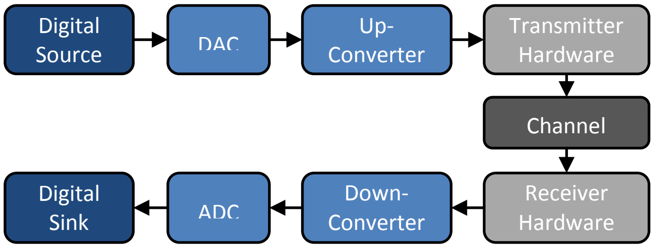


Figure 2: High-level signal chain for a software defined communication link.

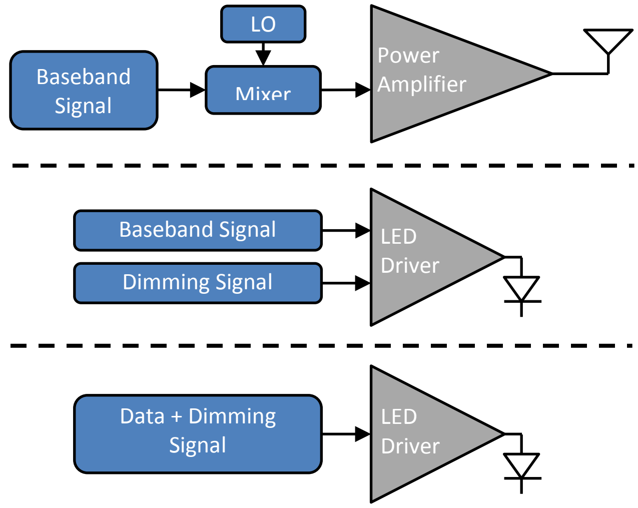


Figure 3: Signal chains for an SDR transmitter (*top*), an SDVLC transmitter with dimming and data as separate inputs (*center*), and an SDVLC transmitter with a single input with combined data and dimming signal (*bottom*).

3. SDVLC Hardware Architecture

Figure 2 shows a high-level signal chain for a software defined communication link. From a hardware perspective, the major differences between an SDR link and a link in an SDVLC system are that (a) the up-converter and down-converter (i.e., carrier frequency modulation/demodulation) can potentially be ignored in the SDVLC system, and (b) the front end hardware is either a set of RF antennas for SDR or an optical transmitter and receiver for SDVLC.

3.1 Transmitter Architecture

The emergence of interest in dual-purpose VLC systems has generated a need for optical devices that meet the requirements of both high-speed communications and illumination. As such, this application introduces new challenges in the development of LED driver circuits. The ideal driver will combine techniques from high-speed RF transmitters and illumination-grade luminaires.

RF transmitters are an essential part of a modern communication system. Designed and assembled from core RF components, RF transmitters have various architectures. The conventional architecture for a transmitter consists of a baseband modulator, a mixer/up-converter, a power amplifier and an antenna as shown in Figure 3. If the transmitter is designed to send amplitude-modulated or multi-carrier signal, the power amplifier must have adequate linearity. This power amplifier may be implemented as multi stage to provide the linearity and also enable a good matching to the antenna; however this increases the complexity of the design. One of the key merits of optical wireless systems, which operate at baseband, is the relatively low transceiver complexity compared to RF systems. In addition, transceiver integration using well-developed silicon processing paradigms (e.g., CMOS), which are inherently low-power, show promise in providing combined illumination/communication networks with “net-zero” energy increase using LEDs [10].

Models of transmitters for VLC are also shown in Figure 3. The challenge in the design of these transmitters is to provide a good tradeoff between the communication and illumination benchmarks. Both data and desired dimming level determine the optical signal. Note that the brightness and data input can be (a) processed independently as input to an LED driver capable of controlling both signal and dynamic range, or (b) processed together in the signal processing unit to generate a single drive signal. The latter provides more flexibility for the signal processing unit, which is ideal in a software-defined system. The design proposed in [11] is a case that is capable of combining the data signal and illumination level digitally to maintain data transmission over a wide range of illumination levels.

VLC drivers can also be implemented for either analog or discrete level output. Again, the former provides the ideal flexibility of a software-defined system; however the latter can be designed with improved bandwidth and still provide some degree of flexibility for analysis of schemes such as VPPM. Regarding the transfer function of the LED drivers we have implemented for analog modulation schemes, the conversion is nonlinear across the attainable output range of the LED; however, there is typically a near-linear range that can be used without equalization. This is due to the relationship

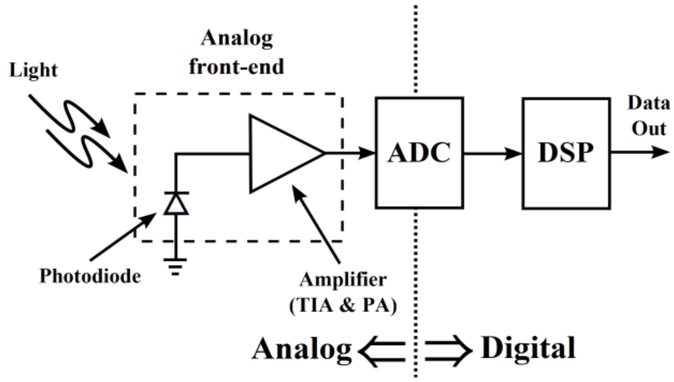


Figure 4: SDVLC Optical receiver front-end.

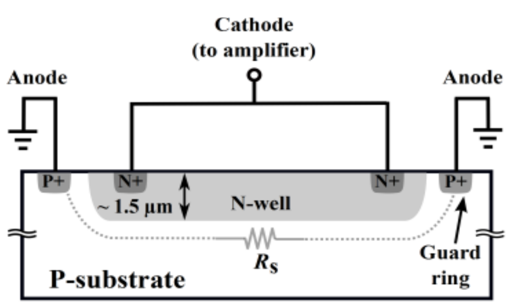
between voltage and current through the MOSFET as well as the relationship between forward current and optical power provided by an LED.

3.2 Receiver Architecture

Software defined communication, by definition, needs to be adaptive to multiple communication standards and modulation schemes. Unlike conventional optical receivers, therefore, receivers for the SDVLC system need to maintain certain linearity characteristics analogous to specifications for a SDR. A software-defined receiver typically consists of an analog front end and a digital signal processing (DSP) unit. This section describes the design of an optical front end adaptive to multiple standards in a software-defined scenario and focuses on its implication on signal processing performance in the digital domain.

Figure 4 depicts a typical optical front end consisting of a photodiode followed by a transimpedance amplifier (TIA) and a limiting amplifier (LA). Despite the similarities, there are some subtle differences between an optical and RF front end. Since light intensity cannot be negative, the current generated by the photodiode can only be unidirectional. Therefore, a DC illumination is generally necessary for analog modulation to ensure that the signal is not clipped. Moreover, in an IM/DD system, the carrier frequencies are located in the baseband [12], eliminating the necessity of oscillators and down-conversion mixers as used in a typical SDR system [13]. Most importantly, the LA in conventional optical receivers is designed to be heavily non-linear.

Although efficient for binary modulation schemes such as OOK, these amplifiers will generate severe distortion in single/multi-carrier modulation with envelope variation. The non-linearity in an optical receiver chain, however, can result from any part of the circuit including the photodiode. We discuss the source and possible solution of these non-linearities and propose a receiver architecture for software-defined applications. Next, we discuss the characterization techniques of receiver non-linearity in single and multi-carrier modulation and present some simulation results.



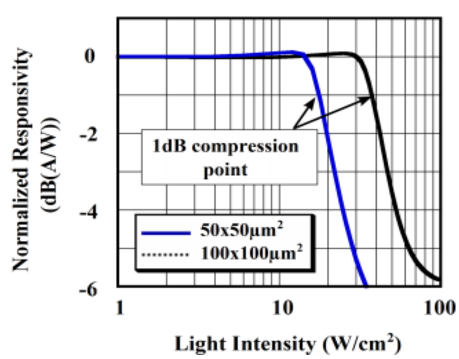


Figure 5: Non-linearity in Si photodiodes: (*left*) a Si N-well/P-substrate photodiode showing bulk series resistance, (*right*) simulated responsivity vs. input power showing the effect of area on photodiode non-linearity.

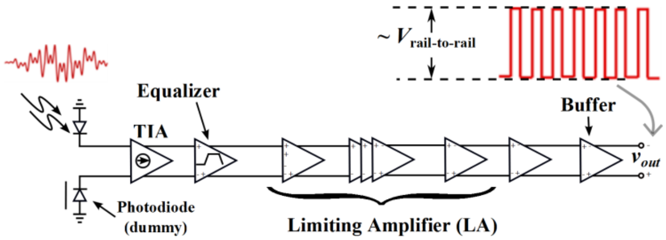


Figure 6: Conventional optical receiver based on limiting amplifier (LA) (Offset cancellation network not shown).

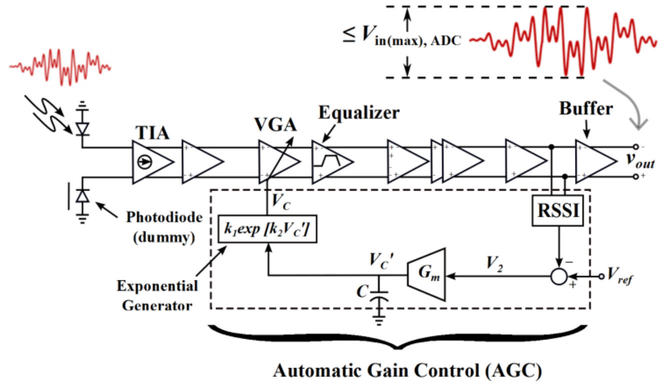


Figure 7: Example of an analog optical receiver architecture for software defined optical communication.

3.2.1 Photodiode Non-Linearity

Photodiode non-linearity may stem from increased recombination rate of minority carriers due to higher intensity of light or illumination dependent reverse bias due to high series resistance [14]. Figure 5 shows the simulated saturation characteristics of a simple N-well/P-substrate photodiode for two different sizes. It can be predicted from the figure that the non-linearity will become more severe for larger devices as the series resistance will increase. Careful design along with good layout techniques such as use of multiple fingers to reduce the series resistance can mitigate photodiode non-linearity to a large extent. Moreover, the input impedance of the following stage will have to be low so that it does not add too much to the series resistance of the photodiode itself.

3.2.2 Amplifier Non-Linearity

The input power in a VLC system is on the order of several mW/cm^2. For typical transimpedance values and light collection area, this will result in a peak-to-peak voltage of tens of millivolt at the output of the TIA. Even in submicron CMOS technologies, this voltage swing will be in the linear range of the amplifier, making the LA the major contributor of non-linearity in the receiver chain. Figure 6 shows the consequence of passing a multi-carrier modulated signal, for example, through a conventional OW receiver based on LA.

It can be inferred from the figure that the envelope variations are lost due to high gain in limiting amplifiers in conventional optical receivers. Moreover, the input power may vary significantly in VLC resulting in possible issues for interfacing with a fixed dynamic-range analog-to-digital converter

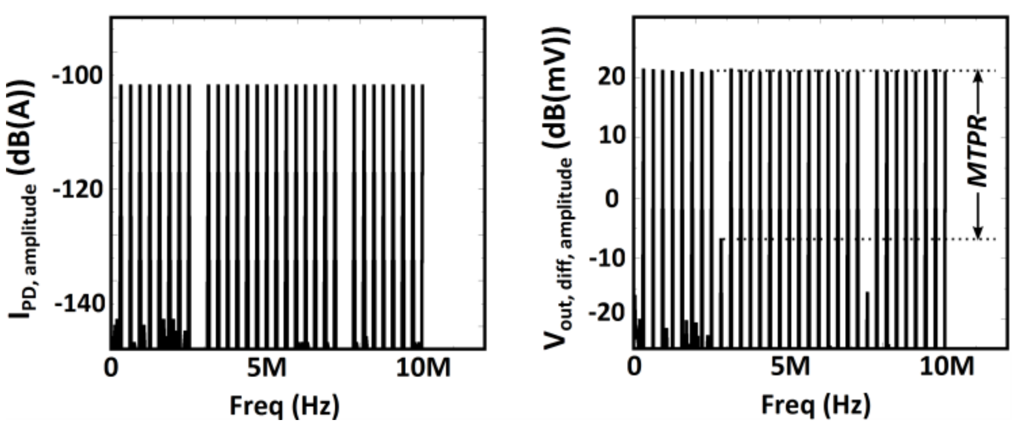


Figure 8: Simulation results for MCM: (*left*) 30-subcarriers with 2-missing tones at the input (PAR=4.86dB), (*right*) Spectral-regrowth in missing sub-carrier location at the output (MTPR=28dBc for $V_{out,p-p}$ = 200mV).

(ADC). To address the non-linearity due to clipping in limiting amplifiers and input power variation, an optical receiver based on constant settling time automatic-gain controlled post amplifier (PA) is proposed in this work as shown in Figure 7. A received-signal strength indicator (RSSI) detects the input power level and adjusts the gain control voltage in order to maintain a certain peak-to-peak output compatible with the ADC. The exponential function generator ensures constant settling time of gain from the automatic gain control (AGC) irrespective of input power variation, which is important for fast signal acquisition, low error rate, and overall system stability. The loop bandwidth of the AGC, however, must be designed so that it is small enough for the lowest modulation frequency but fast enough to respond to the slow fluctuations in input power.

3.2.3 Receiver Non-Linearity

As explained previously, optical receivers designed for SDVLC must be optimized in terms of linearity. A performance parameter indicating receiver linearity in single carrier modulation is input third intercept point (IP3) and can be quantified as [15]:

$$\frac{1}{A^2_{IP3,cascade}} = \frac{1}{A^2_{IP3,1}} + \frac{\alpha_1^2}{A^2_{IP3,2}} + \frac{\alpha_1^2\beta_1^2}{A^2_{IP3,3}}$$

where A_{IP3} indicates the input third intercept point of the gain stages and α_1, β_1 indicates the voltage gain of the second and the third stage.

The characterization of non-linearity in a multi-carrier modulation (MCM) such as OFDM/DMT, however, is more complicated compared to the single carrier scenario. Because of the presence of multiple carrier tones, IP3 cannot be defined for an MCM receiver. Moreover, the peak-to-average ratio (PAR) in MCM is high compared to single carrier and its probability distribution depends statistically on the number of subcarriers. A technique used to characterize such receivers in asynchronous-digital subscriber loop (ADSL) systems is called multi-tone power-ratio (MTPR) [16]. MTPR test method characterizes the receiver for a certain input PAR assuming that the receiver design has been optimized for that value and adjusts the phases of the input tones to yield that PAR. One or more tones is removed from the input signal to check the spur at the output waveform in the missing locations. We propose to adopt this technique for characterizing optical receivers for MCM in an SDVLC scenario, as well. Figure 8 shows the simulation results for an MTPR test with an input PAR of 4.8dB and output peak-to-peak of 200mV. The results show good linearity performance with an MTPR of 28dBc.

4. SDVLC Platform

Our SDVLC platform can implement either low frequency passband VLC modulation schemes or baseband VLC techniques. The setup for both is similar, with minor modifications for the LED drive signal. Figure 9 displays the signal chain of the implementation shown in Figure 1.

Beginning at the source, data is passed to the signal processing block on the source workstation – implemented in either GNU Radio or Simulink – which generates the desired digital signal. This signal is passed to the Universal Software Radio Peripheral (USRP) that provides digital to analog conversion (DAC) and interpolation. The Low Frequency Transmitter (LFTX) daughter card either modulates the signal on a low frequency carrier to generate the passband signal or generates the baseband signal

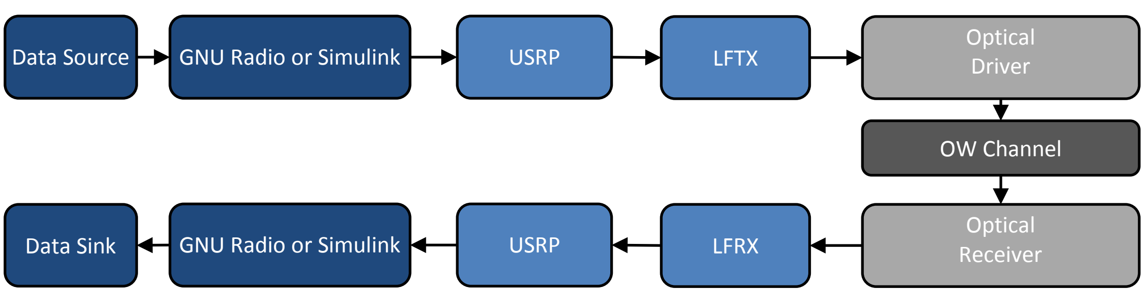


Figure 9: Signal chain for the SDVLC implementation.

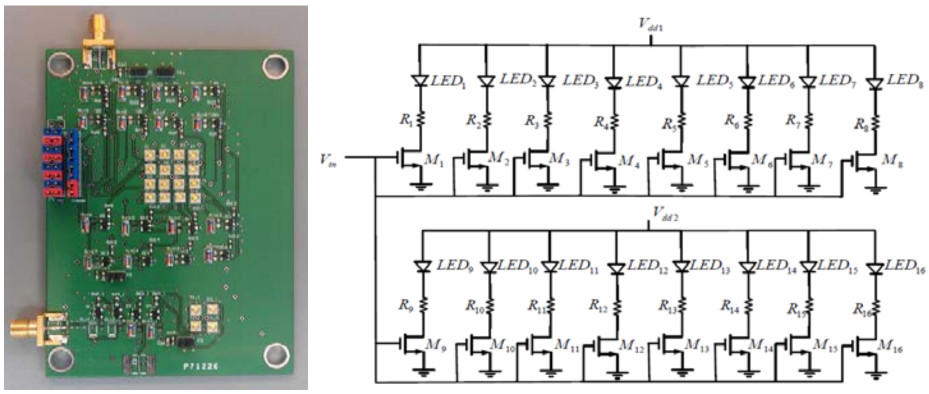


Figure 10: Analog LED driver (*left*) and circuit (*right*).

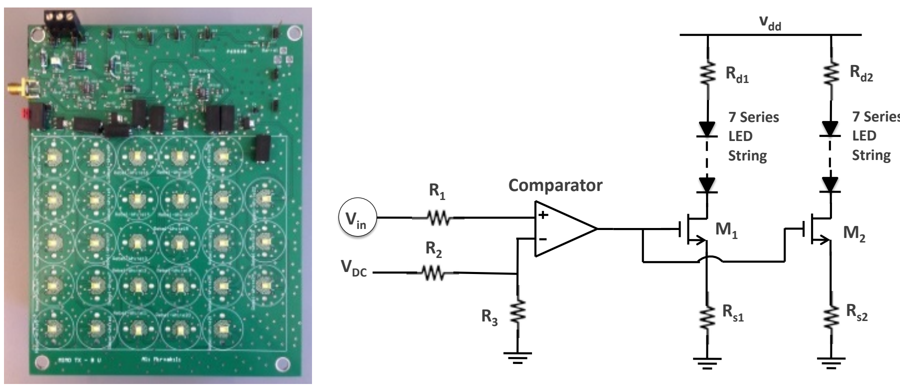


Figure 11: Two-level LED driver (*left*) and circuit (*right*).

directly. This voltage signal is then biased to operate in the desired range of the transmitter in use by either sending the passband signal through an RF bias Tee (Mini-Circuits ZFBT-4R2GW+), or using a DC-DC adder circuit to shift and amplify the baseband signal. The resulting signal is used as the drive signal for one of the transmitters described in Section 4.1. Since baseband signals are generated in software, they can be matched to the transfer function of the optical channel if required; however passband signals are modulated in hardware (by the LFTX) and require the bias be set such that the entire signal operates in the linear range.

The receiver hardware (described in Section 4.2) generates a voltage signal proportional to the received optical power and sends this to the Low Frequency Receiver (LFRX) daughter card of the USRP that either converts the passband signal to the baseband equivalent or passes the real valued baseband signal directly to the USRP motherboard. The USRP provides decimation and ADC before sending the sample values to the sink workstation. These values are processed in the signal processing block and the processed data is sent to the data sink.

4.1 Transmitters

The LED driver in Figure 10 acts as an analog optical transmitter. It is composed of 16 identical LEDs, each tied to the same drive signal and in series with a MOSFET (M), a limiting resistor (R) and power supply. The light emitted from each LED is controlled by the MOSFET that generates a current proportional to the level of incoming voltage from the USRP. This voltage has a DC component as well as an AC component. The DC keeps the transistor in its saturation region and the AC component modulates the LED. The 16 LEDs are divided into two groups that can be powered by separate supply voltages (Vdd1 and Vdd2), while the gates of all 16 MOSFETs are connected together. In this design, we use Osram Semiconductor LEDs (LUW CN5M) and MOSFETs (2N7002).

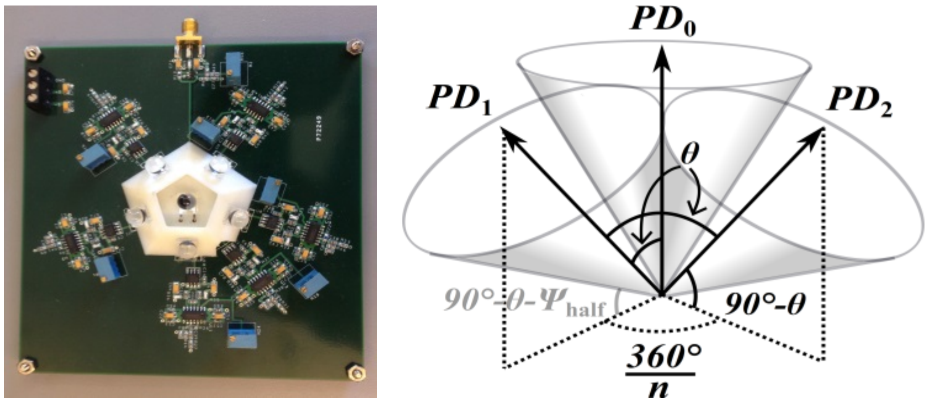


Figure 12: Diversity receiver (*left*) and the FOV design model for an arbitrary n (*right*).

The second driver that we have investigated is shown in Figure 11. In this design, a high-speed comparator (LT1116) is used to increase the level of incoming signal to the appropriate threshold necessary to turn on the MOSFETS (M_1 and M_2). The sensing resistor, R_s, is designed to provide the local feedback and the role of resistor R_d is to limit the current passing through the LEDs. There are 7 LEDs put in series with the MOSFET to provide the required brightness. To prevent noise from turning on the LEDs, the V_{DC} voltage is used to set the decision point after which the output of comparator goes high in order to turn on the MOSFET. The MOSFET used is ZVN4210G, and the LEDs are Luxeon Rebel ES. The PCB of this design uses two sets of the circuit shown in Figure 11 in order to provide the required illumination of 400 lux at a distance of 2 m. Note that this driver does not have the flexibility of the former but it is better suited for Binary level PWM schemes such as VPPM.

4.2 Receivers

Regarding optical receivers, we have used a commercial device as well as a device developed to explore channel selection due to the directionality of the medium. We first used the commercial photodetector (Thorlabs – PDA36A) with an aspheric condensing lens (Thorlabs – ALC2520-A). The detector employs a PIN silicon photodiode with active area of 13 mm^2 and a responsivity of 0.2-0.4 A/W in the visible range, depending on wavelength of incoming light. It is set in a transimpedance amplifier configuration with adjustable gain. We use the highest gain setting for which the receiver has sufficient bandwidth to match the transmitter. That is the 10 dB gain setting, at which the bandwidth is 12.5 MHz.

A diversity receiver was also designed in order to study the effect of signal combining in VLC. Figure 12 shows the diversity receiver with 6-links, each composed of a photodiode (PD), TIA and variable gain amplifier (VGA). Signals from each channel are combined by a summer circuit. To optimize SNR, maximal-ratio-combining technique is utilized by tuning VGA gain. In order to ensure uninterrupted coverage, the number of channels was carefully chosen. Placing one photodiode in the middle and arranging 'n' photodiodes around it with their axes tilted from each other by 'θ' degrees (also shown in Figure 12), the following relationship can be derived:

$$n = \frac{2\pi}{\cos^{-1}(\frac{\cos\theta}{1+\cos\theta})}$$

With a reasonable choice of θ =50° owing to fact that the half angle (Ψ_{half}) of the Hamamatsu S6036 photodiode is ±25°, n is calculated to be 5.37. After rounding to n = 5, the ideal θ is found to be ~43°. Therefore, a total of 6 photodiodes (including one photodiode in the middle) need to be placed at 43° from one another to cover a solid angle of $4\pi\sin^2\left(\left(\theta+\Psi_{half}\right)/2\right)$ = 3.9 sr. This means about 60% coverage over the planar surface of the receiver.

Since the input pole of the transimpedance amplifier (AD8015) is at about 85MHz with 110Ω input impedance and 17pF capacitance, the bandwidth of the receiver front-end is mainly limited by the photodiode (25MHz). With an extrapolated input referred noise of 20pA/√Hz at 17pF input capacitance and 0.56 A/W photodiode responsivity, the sensitivity of the front end is about -38dBm for 25MHz bandwidth. Since all the photodiodes will not be at line-of-sight simultaneously, summing the response of all the links with equal gain will result in degraded SNR. Therefore, a dB-linear gain controlled VGA (LMH6503) is used after the TIA. With a tunable gain of -80dB to 20dB, any link can be completely shut down or amplified 10-fold for optimal SNR. The summer circuit is implemented with a 1.5GHz gain-bandwidth product amplifier (LMH6624). Since the feedback factor of the inverting configuration adder circuit scales down by a factor of the number of channels, the bandwidth also reduces. However, it was made sure that the bandwidth was enough for at least 10MHz operation.

4.3 Signal Processing Software

We have implemented the signal processing blocks of our system in both GNU Radio and Simulink. In our early implementation of the SDVLC system [4], GNU Radio was the preferred software platform for development; however the majority of the established code in the GNU Radio library is based on passband RF communications and the recent addition of the USRP support package for the MATLAB/Simulink Communications System Toolbox allows us to share the SDVLC testbed with the wider community who are familiar with MATLAB/Simulink. In either case, the software offers both a block diagram environment and a scripting language with a wide range of signal processing and communication blocks.

5. SDVLC Applications

5.1 Demonstration and Testbed Application

The initial objective of the SDVLC system was to show a proof of concept for VLC. We developed a real time VLC video streaming application using available signal processing blocks in the GNU Radio library along with the GStreamer multimedia framework for real time encoding of a live webcam data stream. For this application, we modulate a 3MHz carrier frequency onto the optical channel using the analog driver described in Section 4.1. This was shown effectively with various passband modulation schemes including Minimum Shift Keying (MSK), Phase Shift Keying (PSK), and DC Biased Optical OFDM.

5.2 Adaptive Modulation for Dynamic Illumination

In addition to demonstration use, we have implemented a dynamic modulation scheme that benefits from the software flexibility in a way that is unique to dual-use VLC. As dimming percentage varies in such a system, the ideal modulation technique can change [17]. The IEEE 802.15.7 standard [18] specifies VPPM for dimming control with VLC data transmission; however dimming range for this technique can be limited by the rise and fall time of the optical signal. We have implemented a 3-technique modulation scheme that extends the dimming range while maintaining throughput and theoretical error rate.

The premise behind VPPM is to use a 2-PAM modulation scheme with a duty cycle that is varied according to the dimming level. Given a specific symbol period, T_s, we define δ-VPPM as the symbol set shown in Figure 13 where δ represents the percentage of the peak optical power corresponding to P_t. As the dimming level is decreased, the period of the minimum rising pulse, δT_s, decreases. At low values of P_t, the rise time of the optical channel eventually becomes greater than this pulse period. As the dimming level is increased, the period of the minimum falling pulse, $(1-\delta)T_s$, decreases. At high values of P_t, the fall time of the optical channel eventually becomes greater than this pulse period.

In order to extend the dimming range, we propose a variation of Return-to-Zero OOK (RTZ) and Inverted RTZ OOK (RTZ-I) (also shown in Figure 13). The value of δ again represents the percentage of peak optical power corresponding to P_t. Note that the dimming range of an equally weighted δ-RTZ symbol set is $0 < P_t \leq 0.5P_{max}$ and the range of an equally weighted δ-RTZ-I symbol set is $0.5P_{max} \leq P_t < P_{max}$. The benefit of these schemes when compared to VPPM is that the short pulses are combined in the same symbol, essentially doubling the length of the shortest pulse. As an adaptive scheme, we use δ-VPPM as the default method while switching to δ-RTZ if δT_s is less than the fall time of the optical

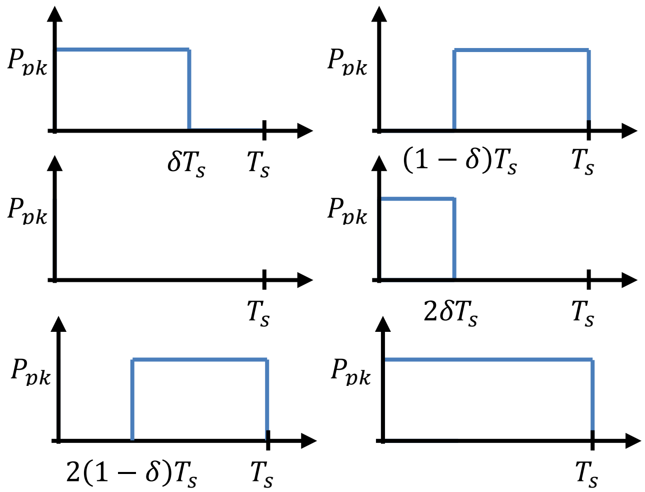


Figure 13: Symbol sets for dimming modulation schemes δ-VPPM (*top*), δ-RTZ (*center*), and δ-RTZ-I (*bottom*).

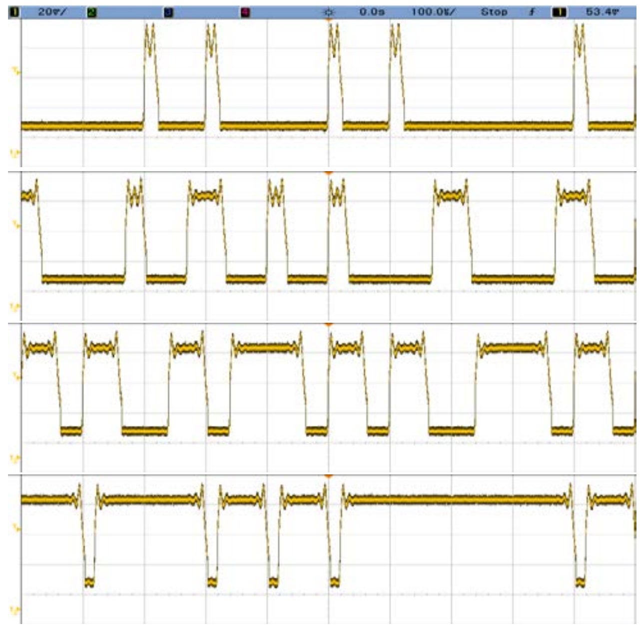


Figure 14: Received electrical signal from the optical receiver for 0.1-RTZ, 0.3-VPPM, 0.6-VPPM, and 0.9-RTZ-I.

channel and switching to δ-RTZ-I if $(1-\delta)T_s$ is less than the rise time of the optical channel. Note that T_s remains constant therefore the throughput is the same for all schemes. Error rate increases as the dimming level moves away from $0.5P_t$, however the minimum Euclidean distance between symbols is the same for all three symbol sets for a given value of δ; therefore optimal error probability does not vary for the different schemes. Figure 14 displays the received electrical signal from the optical receiver for various dimming percentages with a change in modulation to RTZ for $\delta < 0.2$ and to RTZ-I for $\delta > 0.8$. Symbol period in this instance is 100µs and data rate is 10kb/s. The real time throughput is limited by the processing speed rather than the physical media.

5.3 Additional Applications

The SDVLC system as described here has potential for future testing of many other system level VLC applications. One application under consideration is an implementation of a VLC system that optimizes its signal processing scheme to best fit the channel and to dynamically maximize data rate. Due to the large dynamic range of the VLC channel, an ideal system should account for close proximity LOS paths as well as highly attenuated signals at the outer reaches of a VLC cell or multipath signals. As a simple example, a system implementing PAM modulation technique could dynamically change the symbol set size from 4-PAM to 8-PAM under high SNR conditions (close proximity LOS) or to OOK in low SNR scenarios (high attenuation and multipath). The agility of the SDVLC system allows this type of dynamic processing to be achieved.

The SDVLC system can also be applied for dynamic channel selection with the optical diversity receiver. Based on the effect that angle of arrival has on the received signal and the assumption of dynamic rotation of a user device, appropriate selection of a subset of sensors with the transmitting luminaire in its FOV can be implemented in software – mitigating noise from unused sensors.

Finally, we are analyzing is the idea of a heterogeneous system where VLC operates as a supplemental channel in a Wi-Fi enabled environment [19]. In this application, a symmetric RF link is available throughout the environment while an asymmetric VLC/RF link provides a directional hotspot increasing downlink capacity in select locations. Development of software-defined implementations for various physical media is necessary for exploration of heterogeneous systems and Software Defined Networks.

6. Conclusions

In this paper we provided an overview of Visible Light Communication as well as a discussion of the challenges relating to the adaptation of the SDR concept to the visible light medium and a detailed description of our implementation of an SDVLC system. We described the challenges that arise when implementing a dual-purpose illumination/communication platform and provided proof-of-concept results for a dynamic modulation technique that adapts to desired illumination. We also described additional examples of the many potential applications of the SDVLC system. Just as software defined radios have assisted in research and education in the area of RF communications, a fully functional SDVLC system provides the opportunity for rapid implementation and experimentation of optical communications. While much of the current research in SDR is leading the way to next generation radio systems, the idea of SDVLC expands the “Software Defined" concept beyond the RF domain and into the broader classification of Software Defined Communication.

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