Design and Development of a Visible Light Communications Link

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***Abstract*—Visible Light Communications systems, in general, are designed to function as dual-purpose lighting and communications elements. We describe the development of hardware to implement a unidirectional end-to-end visible light communications (VLC) link enabled by a software- defined radio (SDR) framework through the USRP2 radio module and the GNURadio software toolkit. This work in particular is meant to contribute to the body of linear power-efficient circuit designs to allow for further research into complex modulation schemes and multiple input multiple output (MIMO) system topologies. A prototype system, whose optical and electrical power characteristics are suitable for localized home lighting, has been realized with a data rate approaching 3 Mbps at a link distance of 2.6 meters. With this hardware, communications system research at the level of modulation and above can be tested at a more realistic scale of deployment with minimal concern for nonidealities introduced by the transmitter/receiver front ends. Future improvements concerning bandwidth, optical power output, overall system functionality, and the IEEE 802.15.7 standard are also proposed.**

I. INTRODUCTION

The development of wireless communications technology over the last few decades has brought with it an explosion of new applications for consumers. Convenience of access to the internet is unprecedented, with indoor wireless local area network (WLAN) equipment now a commodity. Large-area, high-speed network coverage through metropolitan access networks (MANs) is now being realized, and indeed, such networks are the current state-of-the-art with respect to developing standards, enabling carrier-grade fourth-generation mobile applications and high-speed wireless municipal access networks [1]–[3].

Moving forward, the natural inclination is towards faster, more reliable wireless communications. As a result, development of complex schemes that allow for high sample/symbol rate and high signal-to-noise ratio is an open research topic in both academia and industry, complicated not just by the difficulties of transmitting in multipath fading channels, but also by interference from other users of the same frequency band. The latter is of increasing concern, especially as more and more wireless applications are refined. Effective interference detection/suppression systems, generally operating at the physical (PHY) or media access control (MAC) layer, remain an open research topic with a great deal of complexity. Newly developed standards generally achieve higher throughputs by enabling the usage of higher order modulation schemes and raising of the signal-to-noise (SNR) ratio through the use of multiple-output multiple-input (MIMO) systems that utilize techniques such as adaptive beamforming, spatial multiplexing, and space-time diversity gain schemes [1], [2]. Frequency hopping is also commonly employed to move off of subbands that exhibit interference. However, all of these methods increase transmitter and receiver design and operational complexity.

As these new schemes evolve and become more elaborate, current technology is challenged to maintain an adequate level of performance with respect to speed and accuracy. For this reason it becomes important to investigate alternative systems. These systems can serve either as a disruptive technology, as optical fiber was to the traditional all-copper long distance backbone, or as a system to be used in tandem with the existing wireless infrastructure to provide additional bandwidth.

A. Visible Light Communication

Visible light communication (VLC) is one of the aforementioned alternative systems now under serious consideration. VLC is a subset of free-space optical communications (FSOC). FSOC has come to refer to the use of light (≈ 400 nm $< \lambda < 1700$ nm) propagating in free space as a carrier of information. In modern systems, the light in question is generated through the use of either LEDs or laser diodes. VLC specifically refers to the use of light visible to the human eye. The most interesting application of VLC systems is that of white LEDs as lighting elements in headlights, traffic lights, and buildings. These LED light sources can replace older, less energy-efficient technologies, but also can be leveraged to transmit information. VLC systems can be integrated into these new LED lighting elements, providing more efficient overhead indoor lighting in tandem with a localized high throughput communications link that offers high unregulated bandwidth.

B. *Merging Lighting and Communications*

Network transmission elements and lighting are very often used in the same space, and thus combining the two devices into one would save on overall component and power cost. Similarly, light sources such as traffic lights can be retrofitted with VLC capabilities to enable vehicular communications, or at the very least, road-to-vehicle communications, where traffic lights can be used to transmit information about upcoming traffic [4]–[6]. All of these use cases rely on the implementation of a modulated light source for communication. Given the ease of modulating LEDs electrically, the extension of LED lighting towards communications seems a natural next step. Additionally, research has demonstrated that white LEDs are a viable low-cost next step with respect to power-efficient lighting [7]. See table I for a comparative assessment of the luminous efficacy of different light sources. VLC should be viewed as an opportunistic paradigm: it is not meant to supplant wireless radio technology, but rather to augment communications in locales where it would be easy to retrofit the lighting system with communications capabilities.

C. *IEEE 802.15.7*

The IEEE 802.15 working group is responsible for creating standards for wireless PAN systems. The most well known of these is ZigBee, intended for low-power PANs, but a subgroup for investigating visible light communications exists as IEEE 802.15.7 [9]. The standard defines PHY and MAC layers for short-range optical wireless communications systems that use visible light, with details of implementation left to the manufacturer. In this section, we briefly describe the PHY layer operation, and focus on transmission requirements.

The PHY layer comes in three flavors, increasing in complexity from flavor to flavor. PHY I is geared towards outdoor application, with data rates up to 266.6 Kbps only. PHY I specifies support of on-off keying (OOK) and variable pulse-position modulation (VPPM). PHY II and PHY III are similar: they occupy the same frequency band, higher than and disjoint from the band used in PHY I, and specify similar data rates, up to 96 Mbits/s. PHY II specifies support for OOK and VPPM, where PHY III specifies support for colour-shift keying (CSK). CSK uses RGB LEDs transmitting simultaneously and maintains a constant average optical power and perceived colour. By definition, however, CSK systems must use RGB LEDs, with all of the deficiencies thereof.

Source	**Luminous Efficacy (lm/W)**	**Source Lifetime (hrs)**
25 W incandescent	8.6	2500
100 W incandescent	17.1	750-1125
50 W quartz incandescent	19.0	2000
T-8 fluorescent	75-100	12,00-24,000+
Compact fluorescent	27-80	6,000-10,000
Metal halide	80-115	10,000-20,000
High-pressure sodium	90-140	10,000-24,000+
High-power White LED	69-93	20,000-50,0000+
Theoretical White LED limit	260-300	100,000+

TABLE I: Approximate luminous efficacy [8].

In addition to these PHY layer specifications, there are cross-layer features that the specification demands in the form of dimming and flicker-mitigation. Though these abilities are controlled by the MAC layer, they require interaction with PHY layer capabilities, and thus transmission hardware must be able to implement these features in addition to attaining the specified PHY layer performance in order to be IEEE 802.15.7 compliant.

D. *Proposed Work*

Current research regarding VLC has been focused on the abstracted system. Because of this, the objective of this work is to develop communications hardware that can be used by both the academic community as well as industry. Current VLC systems are low bandwidth and too low power to be used as dual purpose lighting solutions. Additionally, development of front end hardware has been limited to the simplest of circuit topologies. This work is meant to demonstrate results seen in academia, but with improved effectiveness as a lighting source, and low power consumption relative to modern lighting fixtures with which LEDs are competing. The proposed high-level system topology is depicted in figure 1.

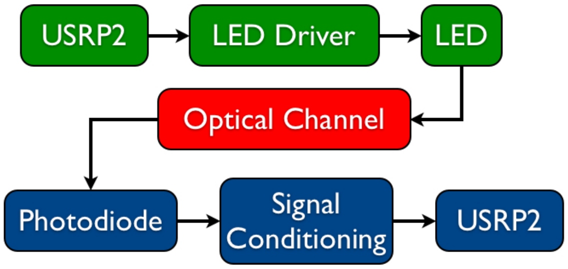

Fig. 1: High-level system topology

This work outlines the design process thus far in the development of such a VLC system as well as proposing future areas of study to improve said system.

II. SYSTEM DEVELOPMENT

The following high-level specifications guide the design: minimum throughput of 1 Mbps at 1 m using on-off keying, a total power consumption of less than 10 W, and eventual compliance with 802.15.7 PHY I. The transmitter should output at least 500 lm, and the receiver should be able to detect a minimum incident optical power of 20 lm. These specifications were based on what could be achieved in the time dedicated towards this project and current bandwidth demands, electrical component performance, and average illumination necessary in working environments. The latter specifications are subordinate to the overall link performance.

A. USRP2-Tx/Rx Interface

1) Motivation: To verify that the VLC system performs as predicted, and to demonstrate its viability as a possible choice for a communications system, it is paramount that the system is tested in conditions and with equipment that most closely resemble a real setting. With VLC research still very much in its infancy, some researchers are using software-defined radios (SDRs) to quickly implement reconfigurable front ends with which to test the system.

Their Universal Software Radio Peripheral (USRP) hardware provides an interface between a computer and a separate front end. The USRP2 is a reconfigurable hardware platform that consists of a basic communications processing unit, digital down converters, analog to digital converters, and digital to analog converters on a main motherboard. The USRP's versatility is a key feature that has allowed for its success. An SDR is ideally completely reconfigurable, and the USRP2 comes close by allowing the user to choose between an array of already developed daughterboards for use from DC to 6 GHz. The daughterboards used in this work are the LFTX and LFRX boards, designed to operate from DC to 30 MHz. Notably, this allows for the testing of hardware with all optical clock rates specified in PHY I with OOK, and a subset of the optical clock rates specified in PHY II with OOK.

2) GNU Radio and the USRP: GNU Radio is an open-source software platform used to develop applications for the USRP2 SDRs. The software provides code libraries that can be linked together to emulate a flexible front end for any communications system. In particular here, requirements from the IEEE 802.15.7 standard such as Manchester line coding for PHY I, run-length limited (RLL) coding and Reed-Solomon coding for forward error correction can be implemented trivially in GNURadio, obviating the need for constructing dedicated hardware and allowing this work to focus on front-end development.

3) USRP2 Hardware: GNU Radio, utilizing the UHD API, configures the USRP for either transmission, reception, or both. The USRP2 interfaces with the host computer via gigabit Ethernet, allowing transmission or reception at a symbol rate of 50 MHz for 16-bit complex data, or 100 MHz for 16-bit real data. The data, after being sent to the USRP and passed through digital up converters (DUC), is then processed by a 400 MS/s 16-bit digital to analog converter (DAC). The signal is then sent to the daughterboard for translation up to the transmitting frequency and transmission. When receiving, the signal passes through a 100 MS/s 14-bit analog to digital converter (ADC), digital down converter (DDC), and is then passed to the computer for further processing.

4) USRP VLC Interface: On the LFTX, the transmitter board, and the LFRX, the receiver board, there are two connectors to allow for the use of up to two transmission of reception elements at one time. Each port includes a low pass filter to remove any out of band noise. The LFTX board has a maximum output voltage swing of 2 V_{pp}. Both passband and baseband transmission are possible; the center frequency for passband transmission is specified in software and the signal is mixed up to the desired frequency on the USRP2. For proper functionality, the received signal must fit into the internal 16-bit representation. With no internal gain, the input dynamic range of the LFRX board is ±1 V.

The USRP2 daughterboards, as stated before, provide two ports accessible to the user to connect an antenna, cable, or in this case, an LED or photodiode. Signal conditioning chains are required to convert the signals from the USRP2 to those compatible with the constructed hardware.

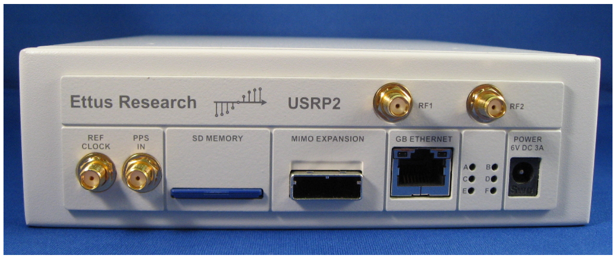

Fig. 2: Ettus Research Universal Software Radio Peripheral 2 (USRP2)

B. Circuit Design and Construction

1) Receiver: The receiver is implemented in a straightforward manner: change in intensity of light impinging on a photodiode generates a current through that photodiode, which is converted to a voltage signal through the use of a transimpedance amplifier. This signal, which should range from 0 V to V_{cc} given ideal transimpedance conversion and ideal ambient conditions is then shifted into a range of ±1 V using op-amp circuits in order to interface with the main ADC on the USRP2.

A future goal for the receiver is implementation of a diversity receiver. The use of diversity combining in order to increase SNR and enable functionality in a diffuse (non-line of sight) link environment is well-known for wireless radio communications and has been demonstrated for infrared communications [10]. If some form of diversity combining could be incorporated into the system, the overall performance and robustness would increase.

Maximal ratio combining is optimum for independent AWGN channels, and thus is the first choice for implementation. Maximal ratio combining requires knowledge of SNR at each receiver; this can be achieved in tandem with generation of a received signal strength indicator (RSSI) signal, a commonly available diagnostic signal in large-scale communications systems. A RSSI circuit was constructed on a breadboard using an application specific IC (ASIC), the AD8307. The output of the RSSI circuit is a DC voltage that is linearly related to the RMS input voltage, 20mV/dB, with offset and slope control. If this signal is generated for each individual photodiode channel, then a variable gain amplifier (VGA) and a summing amplifier may be used to accomplish maximal ratio combining. This setup does not scale well. The component overhead may be reduced by multiplexing the received signals into one RSSI circuit, and then demuxing the resultant measurement. By adding a sample and hold circuit to each channel, the overall cost can be brought down and the system made more scalable.

A single cell for a diversity receiver was fabricated for testing purposes on the receiver board; the schematic fabricated on PCB is displayed in figure 3.

2) Transmitter: The proposed transmitter topology is a modified precision gain transconductance amplifier that enables current drive of the LED seen in figure 4. The voltage at the gate/base of a transistor is controlled in such a way as to sink a precision current through said transistor. Two transistors are used here to sink the nearly 1 A current through the LED. The use of current driving is informed by the close-to-linear intensity response of the LED to LED current.

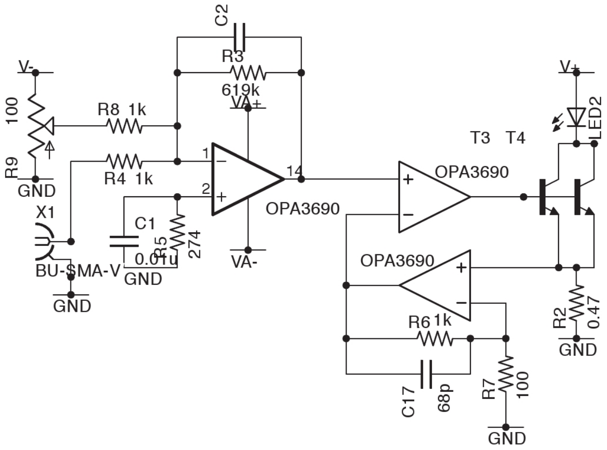

Fig. 4: Constructed Transmitter Schematic

Using switchmode driving to at least source the bias current represents the logical next step in decreasing power consumption. Proper modulation of the LED requires a static DC bias current, and while this can be sourced through DC bias of the voltage signal driving the transconductance stage, this incurs a high static power dissipation in the feedback resistor and the current sinking transistors. If the anode of the LED is instead driven by a switchmode voltage supply configured in a feedback configuration to draw the DC bias current, then the power consumption decreases due to the high efficiency of the switchmode stage. The circuit illustrating this idea is displayed in figure 5. An added benefit of this type of system design is that dimming can be controlled via the DC bias current. The IEEE 802.15.7 standard specifies an dimming pattern in which the pulse width can be modified to increase or decrease the time that the LED is on. However, this reduces system throughput as this pattern must be maintained to ensure a constant average illumination level. The system implemented here bypasses this problem completely.

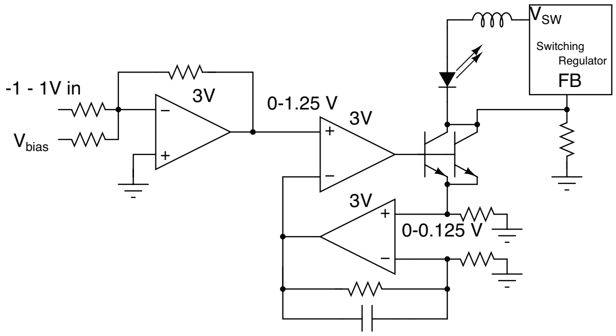

Fig. 5: Proposed Transmitter Topology

With the topologies designed, components were

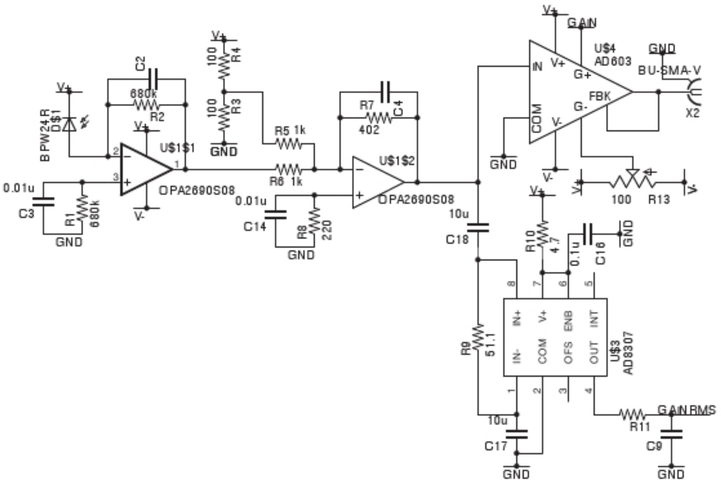

Fig. 3: Constructed Receiver Schematic

selected.

a) LED: This work employs the Cree XM-L product line due to its high luminous efficacy ratings, maximum optical output power, price, and general compatibility with the aforementioned requirements. This LED is phosphor-based, as are the majority of white LEDs entering the market. At a maximum forward current of 3 A, an XM-L LED can deliver 1000 lumens of optical radiation at a luminous efficacy of 100 lm/W.

b) Photoreceiver: The telecommunications standard photoreceiver devices are avalanche photodiodes and PIN diodes. Between avalanche photodiodes and PIN diodes, it is logical to choose to only employ PIN diodes in the receiver. This is motivated by their ease of setup, as well as their lower cost. A full discussion of operating principles is beyond the scope of this paper. The diode selected for use is the Vishay BPW24R [11], a PIN photodiode fabricated on silicon, with a sensitive area of 0.78 mm^2, and a 10% sensitivity range from approximately 400 nm to 1100 nm. The absolute sensitivity at $\lambda = 870$ nm and a reverse bias voltage of 5 V is 0.60 A/W. At this operating point, the junction capacitance is 3.8 pF.

c) Operational Amplifiers: The signal conditioning into and out of the USRP2s, as well as modulation of the LED in the transmitter and current-voltage conversion at the receiver can all be constructed out of op-amp circuits. Given that one of the imposed specifications is operation at at least 1 Mbps, all closed-loop op-amp circuit functional blocks must be able to function at the required frequency. The OPA690, a VFA with a 500 MHz unity gain bandwidth, was chosen as the op-amp used in both transmitter and receiver. The triple package OPA3690 was used for the transmitter and the dual package OPA2690 was used for the receiver.

3) Fabrication: Two layer PCBs were used for both the receiver and transmitter and were populated with surface mount components. The circuit boards were designed using RF techniques intended to minimize performance loss at operating frequencies. The availability of a ground plane, the ability to place bypass capacitors close to ICs, and the ability to use guard rings around sensitive nodes all were leveraged in our design.

4) Circuit Testing and Verification: Initial testing of the transmitter revealed instability in the transconductance stage with an input voltage above 0 V. This instability was rectified by adding a capacitor, C17, across the feedback resistor R6 in figure 4. This solution did however adversely effect the operational bandwidth of the transmitter, increasing the average fall time of a pulse from tens of nanoseconds to a few hundred nanoseconds.

As previously mentioned, preliminary designs of an MRC circuit were included on the receiver board to test the functionality of the selected components. The gain of the MRC circuitry is controlled by the output voltage of the RSSI IC. Measuring this voltage, which should correspond to the incident optical power, revealed that it remained constant, regardless the incident power. Attempts were made to rectify this issue but had to be cut short in order to begin full system testing. The VGA, an AD603, functioned as desired, applying anywhere from -11 to +31 dB to the received signal. The input to this stage was not AC coupled, resulting in saturation of the VGA’s output at high ambient light levels. Further testing and modification are needed to verify the MRC design.

III. RESULTS

With the completion of the PCB prototypes and initial circuit testing completed, focus turns towards full system testing and characterization. It is at this stage in development that the choice to use a SDR platform begins to make a significant difference. In analyzing communications systems, the first and most important metric is the bit error rate (BER), the percentage of incorrectly received bits. As such, a test bench was developed to measure the BER of the system. Additionally, an application specific test was developed not only to test the system performance, but also provide a demonstration of the viability of VLC systems. With these test benches, the system viability can be validated and the performance quantified.

A. Quantitative Testing

The BER of a communications systems depends on two variables: the link SNR and operational frequency. By varying the test conditions under which a system is placed, a metric can be developed describing the total system performance. Because the testing platform that is being used was not initially designed for BER testing, the accuracy of the results is somewhat unknown. As such, a baseline must be established. To establish this baseline, two USRP2 radios were connected via an SMA cable and a 10 dB attenuator. Common BERs for communication systems are on the order of one bit error per hundred thousand to millions bits (10^{-5} to 10^{-6}). Transmitting at 1 Mbps, this would require that the test be run for at least a few seconds before any errors were recorded. All BER tests were run for at least five minutes, with the total number of errors being recorded. The baseline tests revealed that in the time span specified, no errors were recorded. This test held for an operational frequency up to 5 MHz, at which point the computers running the transmitter and receiver could no longer run at sufficient speeds to provide valid data.

B. Qualitative Testing

An application-specific demonstration is conceptually appealing as well. One such application that can be easily demonstrated is the streaming of video. A video test pattern consisting of colored line-up patterns is commonly used for the calibration and testing of video equipment. The test pattern being used consists of the colored vertical bars previously mentioned, time stamp, title, and a box consisting of visualized gray scale white noise. The test pattern is being used because it allows the user to visualize the performance of the link. Bit errors manifest themselves in skipped frames, blurred lines, and overall degradation of the video. Just as before, a baseline test was performed with an SMA cable. The test revealed that the streaming of video, although not perfect, worked rather well with very few skipped frames and generally clean video. However, there were points at which the video being decoded clearly exhibited bit errors. This contradicts the earlier BER testing which reported to show zero BER. This is a subject to explore further with different test settings.

C. System Performance

The testing of the system began with the more basic qualitative test. Testing was limited to OOK BPSK modulation due to problems with implementing a complete pulse amplitude demodulator. However, the focus of this project was to develop the hardware to allow other researchers to explore future modulation schemes such as PAM or those defined in the 802.15.7 standard. Therefore, the testing of more complicated modulation schemes will be the focus of future work.

The first test conducted was to determine the maximum achievable data rate that the system could function at without experiencing any degradation in performance. The transmitter and receiver were placed approximately one meter apart and the transmission rate was varied. The results of the test showed that the system worked up to 3 Mbps. Anything over that speed experienced pulse spreading that most likely can be attributed to the driving of the junction capacitance of the LED. Another limiting factor at these speeds is the phosphor used in the LED. The response time of the LED can be improved by using a blue filter at the receiver or resonant driving of the LED [12], [13]. These qualitative results were verified by further BER testing of the system. Free space optical channel characterization is very complex with no single model defining the response [14]–[16], thus channel action as a limited factor cannot be assumed conclusively.

The next test focused on the spatial performance through. two metrics: maximum link distance, and the field-of-view (FOV). Determining the first involves the slow separation of the transmitter and receiver until the link performance, as discussed above, degrades. Given that optical channels tend to be binary channels, that is, either full transmission or zero transmission, this breakpoint was easy to determine, and was found to be 2.64 m. It should be recalled that the transmitter being tested was a low power variant; as the power consumption of the transmitter increases, so does the maximum link distance. Increases in radiant optical power and receiver sensitivity will increase the range.

The FOV of the system can be described with two values: the angle at which the optical radiation from the LED no longer resembles the desired signal, and the maximum angle at which photons impinging upon the photodiode generate current above the dark current. Both parameters are design considerations that can be tailored to fit individual systems. To adjust these values, both LEDs and photodiodes can be fitted with lenses to focus or diffuse the light. In addition, photodiodes with larger areas can be used in low lighting situations. The current system only uses the lenses that come already mounted on the LED and photodiode, and testing was performed using only one model of photodiode. With these default parameters, the tested system can receive the transmitted signal with an LED nearly 90° to the photodiode at 1 m, as long as as an angle of less than 21° is maintained between the photodiode and light source.

IV. FUTURE DESIGN DIRECTIONS

The final hybrid transmitter envisioned pushes power consumption outside the LED to minimal levels. However, at the end of the day, these changes are modifications of a topology with inherently unattractive power dissipation properties. Here we present groundwork for potentially leveraging RF power amplifier techniques for LED modulation. For more detailed information about RF power amplifier topologies, the interested reader is directed to [17].

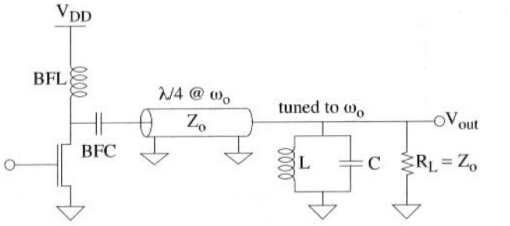

Fig. 6: Class F amplifier schematic from [17]

The class F topology is most interesting for use in VLC applications. We go into slightly more detail of operation here as a result. Figure 6 displays a class F amplifier. The effect of the $\lambda/4$ line is to provide a short to the drain of the transistor at even harmonics of the center frequency ω_0, and an open circuit at odd harmonics. Fourier analysis tells us that a square-wave voltage results at the drain. The drain current is ideally exactly out of the phase due to the $\lambda/4$ line action, and is a sinusoid due to the filtering action of the LC tank. The closely related F^{-1} topology forces a square current waveform through the drain and has a sinusoidal drain voltage characteristic. Finally, for modification of this topology at lower frequencies, we may replace the transmission line by tuned LC tanks. Empirical results suggest that two series tanks at ω_0 and $3\omega_0$ suffice for acceptable performance.

If we may imagine using some small dummy load resistor in the topology, then placing the LED in series with the drain would allow for the general type of current signal through the LED that we wish to achieve. Unfortunately, time only permitted the development of a simulated class F amplifier with no LED. The schematic and traces are displayed in figure 7.

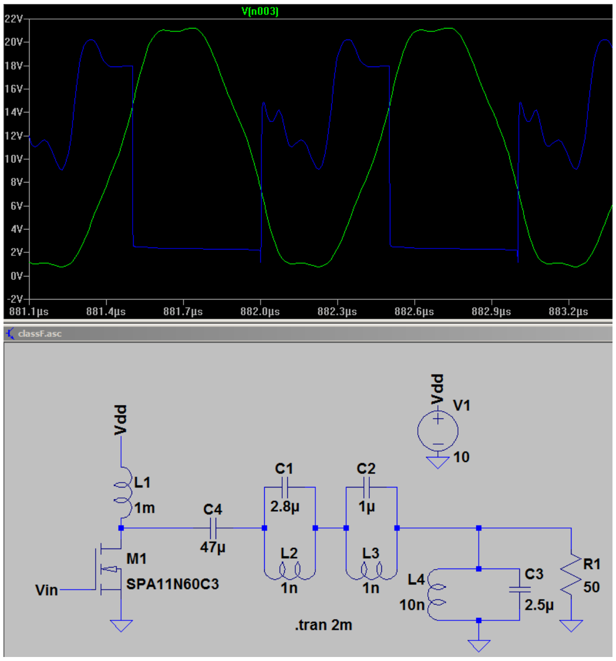

Fig. 7: Simulated class F amplifier

It is immediately clear that the traces seen do not match the ideal half-sinusoid current and square drain voltage waveforms described above. However, these results do match those seen in the literature [18]. Moreover, the LED itself will introduce extra complications due to the low-pass effect of the LED response. At the very least, this is a direction that should be investigated moving forward in order to enable elegant, power-efficient driving of the LED.

Future improvements in receiver design will mostly come from the adaptation of current methods used in other communications systems. Single photodiode receivers can be arranged to form an array that uses MRC or some other form of combining to increase the spatial performance of the system. More advanced antenna combining schemes, e.g. beamforming, could also be adapted to add functionality to the receiver.

V. CONCLUSION

The objective of this project as laid out in the beginning of this year was to develop VLC hardware for researchers to use in developing VLC technology at higher levels of abstraction. We have achieved this through the construction of proof-of-concept hardware that has been interfaced to the USRP2 software defined radio platform, and that needs only minor modifications to be used in other, more general systems. We have demonstrated that the system is capable of generating light output in a power-efficient manner at levels suitable for home lighting deployment, and that the system can function in the low MHz region, with functionality in tens of MHz theoretically possible given proper component choice. The system is also capable of functioning at distances comparable to the distances between workspaces and overhead lighting. With respect to the IEEE 802.15.7 standard, the ground-level speeds available in the circuitry allows for straightforward compatibility with PHY I OOK. Though performance demonstrated falls just short of compliance with PHY II OOK, the limitation not a fundamental one, and is due rather to component choice.

Though the hardware can be used by other academic groups as is, there is certainly room for improvement: the aforementioned extension of bandwidth, the full integration of a switchmode current source at the transmitter, and establishing the functionality of the designed diversity receiver cells are the next logical steps to take.

As mentioned above, RF power amplifier topologies demonstrate an interesting potential to be leveraged for power-efficient LED driving. Though we were only able to submit proof-of-concept simulations in this work, future work should include an in-depth investigation into the feasibility of using such topologies for VLC applications.

VI. ACKNOWLEDGEMENTS

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