Wireless optical system using amplitude modulation with GNU radio on a Raspberry Pi

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Abstract. Visible light communication system arises to create wireless links using light-emitting diode luminares. The literature reports multiple works in visible light communication using different development tools. However, most are based on signal processors, field-programmable gate Arrays and proprietary software to develop the algorithms. This paper presents a wireless optical communication system using amplitude modulation on both hardware and free software tools. An algorithm for amplitude modulation/demodulation in GNU Radio installed on the Raspberry Pi development card was created. Additionally, an optical transmitter based on a white light-emitting diode and a receiver with a solar panel was designed. Communication experiments were performed based on the distance of the system link. The results report that the optimal response of amplitude modulation/demodulation was achieved with a solar panel response of $-68 \text{ dBmV}$ at maximum distance of 3 m between transmitter and receiver at usual illumination levels, and the potential to use free hardware and software tools in the implementation and analysis of optical wireless communication systems.

1. Introduction
The increasing of wireless devices connected to the internet is causing saturation problems of the electromagnetic spectrum. Additionally, there are scenarios such as hospitals and airplanes in flight, where it is not possible to radiate radio frequency electromagnetic signals [1–3]. Visible light communication (VLC) uses visible spectrum for short-range transmissions and is a promising technology on indoor optical wireless communications (OWC) [1–3]. The VLC operates in a frequency band that does not require a license and allows the design of wireless communication links in application scenarios where it is not possible to radiate radio frequency signals, as proposed by the IEEE 802.15.7 standard [4]. Light emitting diodes (LEDs) and photodiodes are the foremost candidates for transmitter and receiver devices for OWC. However, many research papers using a solar panel in place of the photodiodes [5–9]. The solar panel is used to generate energy and recover data encoded by light, although low bandwidth limits the system in low data rate applications. However, the solar panel provides low signal saturation due to external lighting sources and electrical energy for the receiver circuits and that can be stored in battery banks [6,7,9].

Open source computing tools such as GNU Radio and Python programming language are being explored by researchers in the analysis and evaluation of VLC systems, due to their low cost and high computational performance [10,11]. Additionally, the low-cost evaluation hardware, such as the Raspberry Pi platform, allows the prototyping of VLC systems where its low cost is sufficient in many commercial applications research and development.
Regarding low-speed VLC systems, the transmission of audio signals is an application with multiple uses in different practical scenarios such as restaurants, museums, among others [12–15]. In VLC the distance between transmitter and receiver is critical parameter to designed experimental systems for different indoor scenarios.

In this research work, a visible light communication system is proposed for the transmission of audio signals. The system was implemented using two Raspberry Pi development cards on which GNU Radio was installed. A baseband amplitude modulation (AM) modulator/demodulator was designed, using the GNU Radio software. In the transmitter, the audio signal was amplitude modulated and transmitted through the audio headphone output to the VLC driver and in the receiver a solar panel was used to receive the optical signals. These signals were introduced through the microphone port to the Raspberry Pi card on which the AM demodulator algorithm runs for the extraction of the encoded audio signal. Experiments of transmission and reception of audio signals at different link lengths were performed, in order to have an experimental variation of the signal-to-noise ratio of the system and evaluate its performance. In our experiment we used a minimum distance at $\Delta x = 0.5$ m (with solar panel response at $-25$ dBmV) and we achieved maximum distance at $\Delta x = 5$ m (with solar panel response at $-80$ dBmV). However, the optimal response of AM demodulation was achieved with a solar panel response at $-68$ dBmV at a maximum distance of 3 m.

2. Materials and method

The implementation of the VLC based Raspberry Pi and AM was carried out in the Optics, Photonics and Artificial Vision Laboratory of the “Instituto Tecnológico Metropolitano (ITM)” of Medellin, Colombia. The light levels of the external light sources were not controlled, with the objective to evaluate VLC system performance.

A block diagram of the proposed experiment VLC system is shown in Figure 1. We vary the distance $\Delta x$ between transmitter and receiver from a dominant line of sight (LOS) path and we do not consider the reflections or diffusion of light from various physical objects, because a dominant LOS path exists between LED transmitter and receiver. The transmitter is composed of a Raspberry Pi 3 model B+ with 64-bit quad core processor running at 1.4 GHz, 4 pole stereo output, one full size high-definition multimedia interface (HDMI) to connect the computer monitor and others. We installed GNU Radio on Raspberry Pi and we developed an algorithm in the Python programming for baseband AM and demodulation to encode/decode binary data. The AM was configured with the sampling frequency 48 kHz, because we used audio signal as data (bandwidth between 20 Hz Hz and 20 kHz). The audio file (filename extension .wav) was stored on memory card of the Raspberry Pi. In the transmitter, we used the audio output on headphone jack to apply the audio signal AM through the digital-to-analog converter (DAC) to driver VLC. Then, the driver VLC based on power MOSFET IRF630 uses the DAC signal to control forward current of white LED (with optical power 9 W and 120° full emission at half maximum intensity). The direct voltage (1 Vdc) component is used to forward voltage of LED to guarantee a minimum optical power. The commercial phosphorescent white LEDs emits the wavelengths from yellow color to blue color, due to phosphorus material. The light signal travel different free space transmission distances and is detected by a solar panel. The solar panel is commercially available with $V_{op}/I_{op} = 6V/167 mA$ and dimensions $110x60x2$ mm. A coupling capacitor (0.47 $\mu$F) is added in series with the solar panel for block DC component and allows only AC signal (audio signal received by the solar panel). Then, the solar panel was connected with the microphone input on external hardware USB 3D sound card expansion board for Raspberry Pi. The electrical signal from solar panel is converter to digital signal with analog-to-digital converter (ADC) on USB 3D sound and waveform can be transferred to the baseband AM demodulation on Raspberry Pi to recovered original information (audio signal). We used AM demodulation technique based on enveloper detector (implemented by code on GNU Radio) because is low cost and it does not require synchronization signals. The amplitude of recovered signal is analyzed as a function of the VLC link for different distances $\Delta x$ between transmitter and receiver. Finally, the demodulated signal is transferred to operational amplifier (OP-Amp) via audio output on headphone jack of the Raspberry Pi.
3. Results and discussion

The main objective of visible light communication is to provide optical wireless link without affecting the general illumination of the indoor environment. In our experiment we considered as primary parameter the optical power levels on the solar panel.

The measurement was thus performed varying the optical power level, simply adjusting the distance $\Delta x$ between transmitter and receiver. In our experiment we used a minimum distance at $\Delta x = 0.5$ m (with solar panel response at -25 dBmV) and we achieved maximum distance at $\Delta x = 5$ m (with solar panel response at -80 dBmV as shown in Figure 2. The maximum distance is due to high optical power LED, low signal-to-noise ratio (SNR) and AM technique benefits (long distance propagation). The experimental SNR estimation for transmission distances were made in Matlab for offline signal processing, where the SNR expression is defined as $\text{SNR} (\text{dBmV}) = 20 \log_{10} \frac{\text{solar panel voltage}}{\text{noise voltage}}$. We consider that in a practical scenario, when the used several LEDs, the distance can be easily improved. Some signal fluctuations from solar panel response for several distance (>3 m) it may be due to the influence of the luminaries on the ceiling. However, the optical power of the luminaries affects only the DC level and not the audio signal (AC). In this case, the coupling capacitor works well. We can say, that the solar panel received used in this experiment has a limit of -80 dBmV at maximum distance of 5 m.

In terms of achievable real VLC system based on AM, the low solar panel response voltage is critical for the AM demodulation signal. Therefore, the optimal response of AM demodulation was achieved with a solar panel response of -68 dBmV at a maximum distance of 3 m. The low distance is due to
limited optical radiation on the surface of the solar panel used as VLC receiver. Note that we do not use an amplifier to condition the voltage signal from the solar panel. However, we believe that this distance (3 m) between solar panel to LED is enough for sending audio streaming or low data rate information in some application scenarios indoors.

4. Conclusions
A visible light optical wireless communication system based on Raspberry Pi, amplitude modulation and solar panel as a receiver has been reported. In addition, the solar panel is a passive VLC receiver and it does not require power supply to operate. We demonstrated 3 m maximum distance communication link with a solar panel response $-68$ dBmV. To achieve these results, we adopted an AM modulation and demodulation based on a technique envelop detector, implemented by code on GNU Radio. This way of detection is suggested for audio streaming or low data rate application scenarios (indoor location, sensor networks, VLC-ID systems) because the limited distance of the system, which is less than 4 m. This system could integrate with wearable device providing audio streaming or data communication with low cost. Further improvements may be implementing an automatic gain control for improve the solar panel response and increase distance between transmitter and receiver, maintaining the energy efficiency of the white LED.

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