# Experimental characterization of a new Software-Defined Radio-based DSP stage for VLC systems

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The deployment of visible light communication system is hampered by the presence of large amount of environmental noise caused by the use of artificial lighting and/or solar radiations, depending on the specific scenario, is one of the main challenges to be tackled to achieve a full fledged deployment of VLC in realistic scenarios. For mitigation of noise it is essential to design effective digital filtering stage to recover optical signal from background noise. In this paper we have presented a novel digital signal processing filtering stage based on Software Defined Radios. The SDR filtering stage is then integrated with a previously developed low cost Arduino DUE-based VLC system, in order to compare the performances of the two systems. The system employs standard low-power automotive white LED lamps, and it is tested for baud rates up to 1 Mbaud (OOK) Manchester. Our measurements, show that the DSP stage brings a 10-times improvement in intrinsic sensitivity as compared to the original system. This solution is effective for broad band light sources, like white LED, as it is not possible to exploit optical filtering in these scenarios.

Visible Light Communication (VLC) is a promising candidate for the development of innovative, pervasive wireless communication systems [1]. However, the presence of large amount of environmental noise caused by the use of artificial lighting and/or solar radiations, depending on the specific scenario, is one of the main challenges to be tackled to achieve a full-fledged deployment of VLC in realistic scenarios [2]. In order to overcome this issue, a suitable VLC receiver stage (RX) should be able to mitigate strong saturation effects due to large levels of background irradiation, as well as significant reduction of signal-to-noise ratio (SNR) in the received signal [3] as a consequence of large, time-dependent stray light components impinging on the detector. The harmful impact of such effects is considerably more severe in long VLC in outdoor scenarios, where sun irradiance at RX could exceed several hundreds of $mW/cm^2$, dominating over very small SNR levels. Consequently, it is crucial to include proper filtering stages in the RX to recover an adequate VLC channel quality and successful VLC communication. By exploiting the relatively narrow emission spectrum of LEDs or the monochromaticity of laser sources, optically-filtered photodiodes (PD) are the most widely adopted method for removing unwanted spectral components in the optical signal (OS) [4]. This method is also exploited to increase the bandwidth of a VLC system employing white LEDs with slow yellow-conversion substrates [5], allowing for Gb-class VLC communication systems exploiting the blue component of white LED [6]. However, optical filtering has the large disadvantage of decreasing by orders of magnitude the exploitable optical power of white LED sources [7], [8], and is not providing advantages in situations where ultra-large bandwidth is not necessary, as e.g., in most IoT applications [9], or outdoor VLC implementations [10]. Consequently, the employment of a suitable electronic filtering stage is a more appropriate approach when white light sources are employed as VLC transmitters (TX). Effective analog filtering stages have been implemented in [11] after the receiver's transimpedance (TIA) stage and software-simulated the performance of the system, while a static matched filtering stage is implemented between the PD and the TIA in [12] in order to eliminate the low-frequency noise. Authors of [13],[14] suggested a more sophisticated filtering setup that is based on automatic gain control (AGC) and real-time SNR analysis. However, the performance of the system is evaluated through simulations only. In this scenario, Software-Defined-Radios (SDRs), could represent a key element for developing and testing real-time active digital filtering stages. SDR technology was mainly developed for RF front-ends [15], but has gained attention from the scientific community also for VLC applications due to their versatile combination of hardware and software modules, also allowing a variety of modulation and coding schemes [16], [17]. In this research article, we present and characterize a novel Digital Signal Processing (DSP) stage based on Software-Defined-Radios (SDRs), representing the core of a VLC RX. The DSP filtering stage is based on an Ettus Research USRP-N210 SDR board, programmed using GNU Radio software [18]. The novel DSP block is integrated in a recently developed VLC system, based on Arduino DUE platform [19], in which a complete IEEE 802.15.7 compliant optical transmitter and receiver were designed and tested for safety critical ITS.

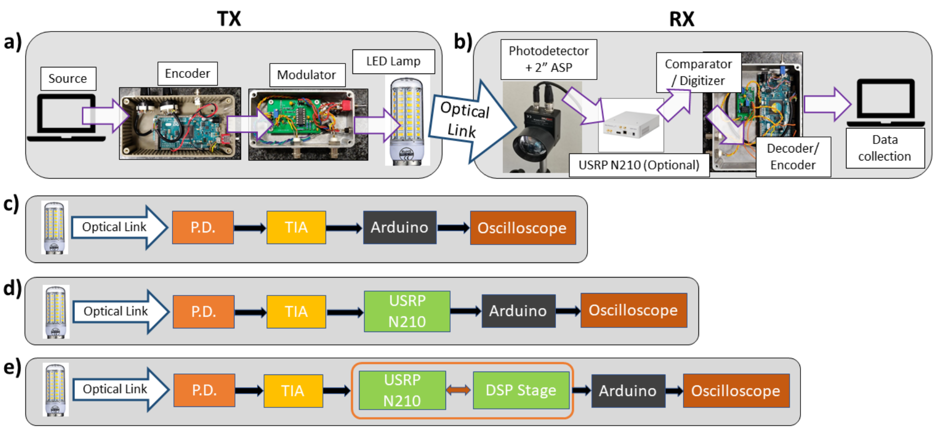


**Fig. 1. VLC hardware blocks of TX and RX system used: a) TX-modulator block provides the data packets and guides the LED Lamp, b) RX receives the data stream and performs a bitwise comparison. It follows VLC system block diagram for: c) *Direct Arduino* System, d) *Bridge* System, and e) *Full* System (description in text).**

In Fig. 1 we report a sketch of the implemented VLC system. The TX box (Fig. 1(a)) can generate packets using NRZ-OOK modulation scheme at different baud rates in Manchester encoding. The generated set of data packets is sent to a custom made current modulator which provides DC and AC current to turn on a LED lamp source and modulate its intensity. The VLC TX source is a low-power V5W white automotive LED lamp. In our tests, we fixed LED and RX stage at the same height so as to achieve the line of sight (LoS) configuration. Fig. 1(b) shows the RX front-end: a modified Thorlabs PDA100A2 amplified PD [20] is used to receive the incoming signal. An aspheric condenser lens (ACL254160) is mounted on the front of PD to increase the optical gain and reduce the field of view [12], hence reducing the effect of environmental induced noise. After TIA, the SDR-based filtering system may or may not be activated, depending on the specific configurations chosen among the three described below. The signal is then discriminated by a single threshold Schmitt comparator and then analyzed by the Arduino DUE decoder stage, which also calculates Packet Error Rate (PER) by counting the correctly received packets in real-time for baud rates up to 5 MBaud. A received packet is considered as wrong when one or more bits are changed with the reference to the original message signal. As we send $10^5$ packets, the error-free threshold is PER $\leq 10^{-5}$. As mentioned above, we have implemented and tested three different configurations: Fig. 1(c) shows the block diagram of our traditional Arduino DUE based RX, named as *Direct Arduino* System. Fig. 1(d) shows the *Bridge* system configuration, where the SDR DSP stage is inserted between the PD and the input of the discriminator board. The input signal to the SDR is simply replicated on its output, and this configuration is used to quantify the noise figure introduced by DSP stage. Fig. 1(e) represents the system with complete filtering, named as *Full* System, in which SDR acts as a complete real-time digital signal processing system. In the latter configuration, the complex filtering process is done through Ettus Research USRP-N210 equipped with 30 MHz daughterboards by sampling the incoming signal at 20 Ms/s. As it is of critical importance to block the DC and low-frequency spectrum of the signal generated by surrounding stray light components, as first step in the DSP stage we implemented an efficient and controllable DC-block. This block takes advantage of the linear phase DC-Blocker algorithm [21]. With this approach, we compute the moving average of the signal and subtract that average value from the signal. The delay line element has a length equal to the mediator's group delay. This algorithm, compared to an equivalent FIR filter, produces a steeper low-pass filter for a smaller group delay [22], being at the same time computationally cheaper. An experimental characterization of the input bandwidth (BW) of the DC block stage was carried out as a function of the length of the sample used to dynamically determine the DC level, in order to choose the best configuration according to the baudrates used. Fig. 2 shows the results obtained by varying the length of the delayline. In particular, the black line corresponds to the system without DC-block filter. The red curve represents the input BW for a delay time of 20 samples. In this case the observed low-frequency cut is about 300 kHz. This configuration is optimal for baud rates ≥ 2.5 MBaud. For lower baud rates, higher delay lines should be used. The green line represents the input BW with a delay length of 200 samples, which is optimal for baud rates starting from 500 kBaud. For very low baud rates, it is more convenient to use large delay length. The orange line represents the input BW for a length delay of 2000 samples, which can be used for 115 kBaud. In all cases the high frequency cut (-3 dB) corresponds to the physical BW of the Daughterboards (4 MHz, actually lower than the nominal BW of 30 MHz) and it is not affected by the DC-block settings.

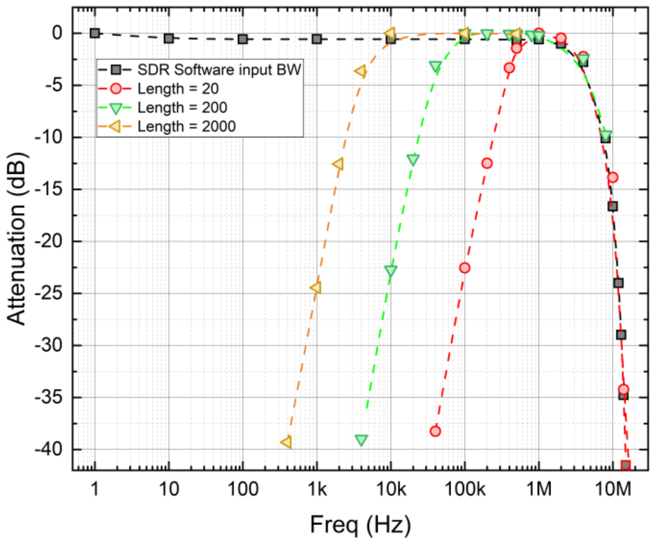


**Fig.2. Input BW: results obtained by varying the length of the delay line in DC-block algorithm.**

At the second stage of our DSP architecture, a fast Automatic Gain Control (AGC) block is implemented, with 1 ms update rate and maximum gain = 10000, to dynamically keep the signal level in a certain range. The set reference level is 1 V. AGC is of fundamental importance especially for outdoor scenarios, where the signal levels can considerably vary due to the different relative distances between the various communication nodes, or due to partial saturation effects of the RX stage caused by strong solar irradiance. A first-order low-pass filter block with cut-off frequency of 4 MHz (Hamming windowing function) is then used to further remove high-frequency noise. The signal is then digitized by a software discriminator block with adjustable threshold, generating a [0-1]V logic signal which is then passed to the SDR output.

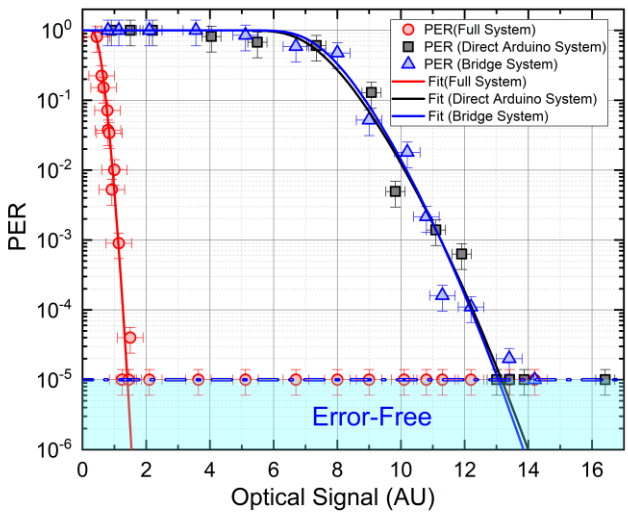


**Fig. 3. PER as a function of the optical signal for the three experimental systems used (see text).**

In Fig. 3 the filled data points show the PER for all three systems in terms of the received optical signal (OS), for OOK 1 MBaud Manchester, respectively for the *Full* (red), *Bridge* (blue) and, *Direct Arduino* (black) systems. OS was varied by changing the relative position between TX ad RX so as to vary the signal intensity. For reference, OS=1 approximately corresponds to a TX-RX distance of 7.5 m. Solid lines represent the best calculated fit. The fit, with free parameters, is performed considering the relationship between PER and SNR reported in [20], assuming a uniform distribution of the error bits on the incorrect received packets and the Additive White Gaussian Noise (AWGN) approximation. Blue data points, representing *Bridge* system that simply replicates the input signal from PD towards the input of discriminator stage, show that SDR does not induce appreciable excess noise to the original system. The comparison between *Full* and *Direct Arduino* systems lines shows a very pronounced improvement in the systems performance by adding the SDR filtering stage, as it allows Error-free communication for an OS which is 10 times lower than the original value. On the other hand, if we consider as FEC limit PER = $10^{-3}$, from Fig. 3 it can be seen that with OS $\simeq$ 1 we get the same performance as the *Direct Arduino* system with an OS $\simeq$ 11. Table 1 summarizes the minimum OS values necessary to obtain error-free and PER ≤ $10^{-3}$ (FEC limit) performances, for the three analyzed configurations.

| | **Direct Arduino** | **Bridge** | **Full** |
|---|---|---|---|
| **PER = $10^{-5}$** | OS = 13.2 | OS = 13.2 | OS = 1.4 |
| **PER = $10^{-3}$** | OS = 11.3 | OS = 11.3 | OS = 1.1 |

**Table 1: Recorded OS (arbitrary units) for the three configuration investigated for: PER = $10^{-5}$ (Error-free threshold), and PER = $10^{-3}$ (FEC limit)**

In this work we have presented a SDR-based filtering stage for the active and dynamical removal of ambient background noise in VLC systems, aimed at use in both outdoor and indoor realistic scenarios. Specifically, we provide details on the building blocks of our DSP stage. The SDR filtering stage is then integrated with a previously developed low-cost Arduino DUE-based VLC system, in order to compare the performances of the two systems. Our measurements, performed at the baud rate of 1 MBaud (NRZ-OOK), show that the DSP stage brings a 10-times improvement in intrinsic sensitivity as compared to the original system, thus requiring 1/10 of the optical signal required by the conventional Arduino DUE-based RX, to achieve the same communication performances. As future perspectives, our novel SDR-based DSP stage will be experimentally analyzed indoor in the presence of strong unwanted light components, such as variable AC-lights, and outdoors to test the strong reduction of shot noise due to the presence of high solar irradiance.

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