Electronic Shelf Labeling Employing Visible Light Communication Concepts

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Abstract— **This paper discusses the usage of visible light communication concepts for Electronic Shelf Labeling Devices (ESLD), using unmodified smart phones. Visible light communication enables novel and interesting approaches to the design of these devices, able to address application scenarios that have not yet been explored. Amongst these novel approaches, it is worthwhile highlighting the feasibility to offer easy integration of social networking concepts, and the inherent ability to explore communication means supported by the lighting installation. The achieved results show that these novel electronic shelf labeling devices are able to offer good quality of service support, with nearly optimal bit error rates under normal illumination levels.**

Keywords—Electronic shelf labeling; visible light communications; social networks; lighting.

I. Introduction

Efficient and error free price labeling represents an important requirement for large commercial areas. Product labels establish the primary connection between product sellers and consumers. These labels include product identification, general information (such as provenance and validity), and most relevant, product price. Common solutions to product labeling rely on fixed plastic or paper tags, which demand human intervention for verification and update. For large commercial areas, such as large supermarkets or electronic appliance stores, these labels need to be verified on a daily basis, requiring a huge human effort. Several approaches based on wireless radio technologies have been proposed to alleviate this problem. RFID tags can be used for labeling considerations, making the verification and updating tasks more resilient and fast [1]. Each tag includes an electronic display, a processing unit with storage capacity, and a unique identifier. However, RFID tags still require human intervention since tag programming must be performed individually, and in the vicinity of the device. Another possibility consists of wireless sensor network based labeling [2, 3]. In this approach, product information is relayed by a communication network to each individual device. Each sensor node has the means to identify the intended data, process it, and display it to consumers. Product information can be centralized and disseminated, without requiring human intervention. The sensor nodes may also include sensors to collect information about product integrity, product stocks and consumer statistics. These are important measures for internal store management. Another important measure would be to gather information about consumer preferences. However, this feature is not easily implemented with sensor networks relying on wireless radio communication interfaces.

Collecting information about consumer preferences is vital for proper product selection, but must be addressed at a very large scale. Social networks constitute a favorable approach to gather information about user preferences. In fact, this is a general trend that large suppliers are currently addressing. It is becoming quite common for large suppliers to implement loyalty measures for their customers. These measures often envisage personal information such as home address, email account, phone number, social network identifiers and even bank account. They aim at profiling consumer habits and preferences. ESLDs may play a key role in this scenario as future ESLDs should be able to allow consumer interaction, as a way of expressing preferences about a product and it's pricing, amongst others. In general, consumers will have communication devices such as a smartphone. Most of the current devices include a digital camera with a LED based flash. Thus, a suitable approach for user interaction would be to rely on visible light communication concepts based on the flash light. Smartphone's screens can also be used to send light signals [4, 5]. However, this requires more advanced optic receivers with higher processing capabilities, which increases the ESLD's complexity, power consumption and most importantly: cost. Moreover, from the perspective of usability, the LED flash is located in the back of the cell phone, allowing the screen to display real time information resulting from the interaction with the ESLD.

The concept of visible light based ESLD is not new. Some authors present ESLD design approaches supported on existing illumination infrastructures [6, 7]. This strategy presents several advantages over wireless radio solutions: i) it enables the design of low power, high autonomy devices; ii) explores an existing infrastructure for both lighting and communication means; and iii) improves energy efficiency, since it relies on LED as lighting devices. Moreover, the same communication concepts can be employed to establish the required interaction. This paper presents a new ESLD architecture based on visible light communication concepts. These devices are able to collect data sent by the consumer's smartphone, with the flash lights. Product information update is accomplished employing a visible light communication link between the ESLD and infrastructure illumination devices. ESLD status and information sharing is accomplished using an infra-red uplink, with the central controlling unit.

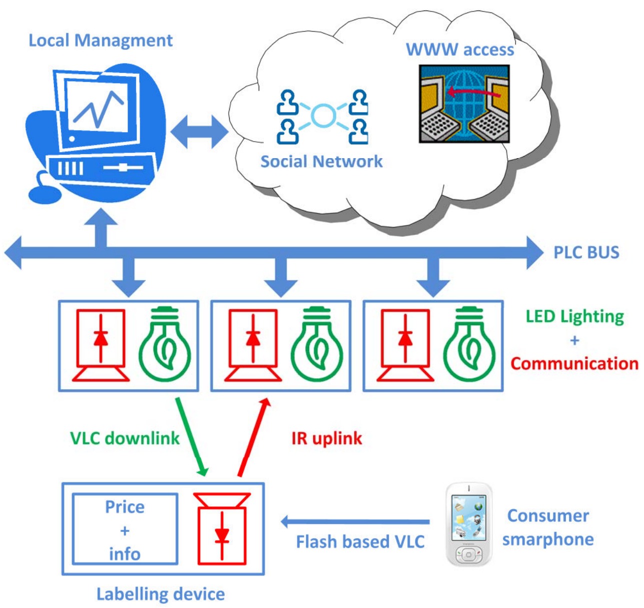

Fig. 1: System conceptual overview.

The paper is divided into five sections. Section II presents the system conceptual overview, discusses social network integration aspects, and compares the proposed approached with wireless radio based ESLDs. Section III presents the ESLD architecture and discusses ESLD design issues. Section IV presents the achieved validation results. Finally, section V draws the final remarks.

II. SYSTEM CONCEPTUAL OVERVIEW

As depicted in Figure 1, the integration of our system involves several actors over three actuation domains. Starting with the actuation domains, the complete system involves: i) the local store, where the action takes place; ii) the local management, where information decisions, data analysis and communication requirements are accomplished; and iii) the external connections, involving social networks, or other Internet based applications, and related internet access. The local management controls all the information exchange and ESLD programming tasks. Information exchange involves two communication links: the visible light communication (VLC) downlink supported on the lighting infrastructure and the infra-red (IR) uplink from the devices to the local management center. The VLC transmitter (the lighting devices) and the IR receiver are embedded on the luminaires. Both exchange information with the local management center using power line communications (PLC). The local management has also the responsibility to monitor illumination levels and implement energy saving strategies, dimming the light level for zones with reduced occupation. Conversely, light can be increased in particular zones in order to attract attention to products as part of marketing campaigns. LEDs are employed as lighting devices in order to enable the support of efficient light dimming and communication. This way, the lighting devices receive dimming and information from the PLC interface and transmit the information as modulated light pulses to the ESLDs under their illumination range. Each product on display has a unique ESLD attached. This device collects the information from the light, updates and displays that information to consumers. Consumers may interact with the ESLD using their smartphone's camera and flashing light. The camera is used to collect product information, such as through a (dynamic) QR code displayed by the ESLD. The product information can be constructed with the consumer information (number of likes, friends, social network ID, email address, local store ID, amongst others) and consumer's preferences and sent back to the ESLD using the smart phones LED flash. The ESLD collects the consumer information and relays it back to the local management center using the IR uplink, closing the cycle.

A. Social Network Integration

Social platforms are a priority vehicle for the promotion of products, and smart tags can play an important role in linking users and products. The use of the "like" feature in social networks such as Facebook allows users to advertise their preference for products, which acts as a recommendation. This is frequently used by advertisers to profile shoppers, but also for the purpose of increasing sales reach, through direct personal recommendation between users. Products are identified by their International Article Number (IAN), or as it frequently happens, by a carefully crafted webpage which further provides visitors with targeted information regarding the product. QR Codes have been the method of excellence as software can use the camera present in most smartphones to easily read them and post the "like". An application, with credentials to publish information into ones social circle acquires the IAN or URL and disseminates it to the social platform. A limitation of QR Codes is that they are limited in the amount of information they can provide and cannot be dynamically modified. Recent results on the usage of ePaper tags can be employed to overcome these limitations by allowing the use of dynamic QR Codes [3]. Still, QR Codes are limited in the amount of information they can carry, reading multiple QR Codes for the purpose of sending a higher amount of information is not easily accomplished, and most importantly, from the perspective of the seller, it hardens the task of tracking pre-sales product popularity.

ESLDs may be used for the purpose of providing novel advertisements schemes exploiting flash sales for individuals already present in the commercial space. Also, ESLDs may be used to redeem digital tickets and sales coupons available in the client smartphone. However, if customer presence at the product point of sale is to be forced (to exploit product placement tactics), it is required the transmission of information from the smartphone to the tag. Moreover, the method cannot present barriers, and in order to increase the reach of the technology, the communication interface should be as popular as possible so that every smartphone can be used.

B. RF Tags versus VLC Tags

Communication between smartphones and ESLDs can be achieved through a diverse set of channels. In particular because smartphones are by design, devices focused in communication tasks. Smartphones have several radio frequency interfaces, and may have optical interfaces as well. From the RF perspective, it is common to assume the existence of technologies such as WIFI, Bluetooth LE, and also Near Field Communications (NFC). However, not all are adequate for the purpose of communicating to a low power device such as an ESLD. Also, the availability of the different technologies in existing smart phones is not the same. The most common RF communication technology is Bluetooth and it is commonly used for the purpose of connecting wireless headsets, or to exchange information between devices. A serious drawback of Bluetooth lies in its design. While it supports low power operation, Bluetooth assumes the creation of a Personal Area Network (PAN), centered in a Master device. When a client wishes to connect to a Master it needs to scan for it and then complete an association process. In the scenario of a shopping center, where thousands of products are available, the use of Bluetooth is not reasonable. Bluetooth Low Energy (BLE) presents new interaction possibilities (e.g., the PXP profile), but still suffers from the lack of selectivity in a high-density scenario. WIFI is very different but also assumes the existence of a network (SSID) to which devices must connect (even in Ad-hoc mode). Another problem with WIFI is that it implies much larger power consumption than Bluetooth, and similar lack of selectivity. NFC technologies start to be available in modern smartphones and actually allow low power communications. From all RF technologies, NFC is actually the most promising, only suffering from the problem of reduced adoption by smartphone industry.

From the perspective of light based communications both Visible Light and Infrared (IRDA) approaches are valid. IRDA was a popular communication mechanism, which was almost ubiquitous in cellphones from the last decade. However, because devices now have much better connectivity mechanisms through WIFI, Bluetooth and even UMTS, the use of IRDA is now obsolete in smartphones, and almost no smartphone supports this technology. A novel communication mechanism is the use of Visible Light Communications (VLC). While cellphones have no dedicated interface supporting VLC, most devices have a camera and flash. In fact, as of April 2014 there are 1326 smartphone models available in the market with camera and flash, while only 285 models have NFC capabilities [8]. While we realize that VLC is probably not the best technology in terms of bandwidth, its advantages in terms of power consumption, receiver complexity and availability of devices, make it an attractive solution to overcome the major barriers to the adoption of smart ESLD.

III. ESLD Design Issues

This section discusses ESLD design issues. The discussion is focused on the device architecture, communication interfaces and their requirements.

A. ESLD Architecture

An ESLD must comply with several important requirements (see Figure 2): i) low complexity; ii) low power consumption; iii) high robustness; iv) high performance; v) small and lightweight; and obviously vi) low cost. As depicted in Figure 2, most of the existing ESLDs rely on: i) microcontrollers as central processing unit; ii) a wireless interface for communication means; iii) an electronic display (LCDs have been employed in the past. More recently electronic paper displays are replacing LCDs [3]); and iv) an energy harvesting unit. Evolved ESLDs may gather information about product integrity and availability using a dedicated ensemble of sensors.

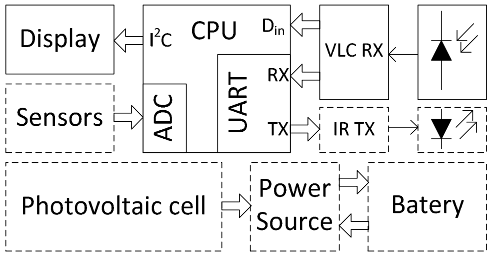

Fig. 2: VLC based ESLD architecture.

The proposed ESLD architecture employs optical communication means as wireless interface. The receiver front-end is shared for both information update (using a VLC link supported on the illumination installation) and consumer interaction (using a VLC link supported on smartphone flash lights). Information update is transmitted using the RS232 protocol through the microcontroller Universal Asynchronous Receiver/Transmitter (UART) receiving port (RX). Data rates for this link must comply with the microcontroller UART specifications. Consumer interaction occurs at very low data rates due to software constraints usually present in current smartphone in order to maximize battery efficiency. In general, these data rates are not supported by the UART and must be collected using a dedicated digital input (D_{in}). The uplink uses IR radiation in order to avoid the high interference levels present on the visible part of the spectrum due to illumination requirements. The microcontroller transmitting port (TX) is used for this purpose. The interface with the display uses I^2C protocol (available in several microcontrollers). Sensor interfaces connect directly to analog ports, thus facilitating sensor integration. The power source is based on a small photovoltaic cell able to collect energy from the surrounding illumination. The power source may also include energy storage means, able to improve autonomy. For the present proof of concept, the selected microcontroller was an 8 bit ATmega328, from ATMEL, clocked at 16MHz, and usually found in most Arduino platforms.

B. Information Update Dowlink

The UART module, available in most microcontrollers, was selected for the data link layer, thus relying on the 0-5V RS-232 TTL signals, to transmit 8 bit data packets to the ESLD, with a user selectable baud rate. To actually program the ESLD, the received bytes should be interpreted as being part of a frame containing complete information for every label, as the one described in [2]. Although the RS232 standard is based on NRZ line coding, this may have an undesirable side effect – LED flickering [10]. A possible solution to overcome this problem relies on the usage of a 1B2B line code instead, such as a Manchester code. This approach avoids the presence of long chains of zeroes or ones, during which light flickering effects are apparent, impairing illumination comfort conditions. In fact, the IEEE 802.15.7 VLC standard [9], suggests the use of variable Pulse Position Modulation (PPM) formats, able to combine dimming rules and data transmission. Variable PPM can be regarded as a combination of Manchester coding with discrete Pulse Width Modulation (PWM), in which the Manchester pulses have variable length within the bit period.

Given this, it is necessary to adapt Manchester-PWM formats to NRZ by following two possible approaches: i) using

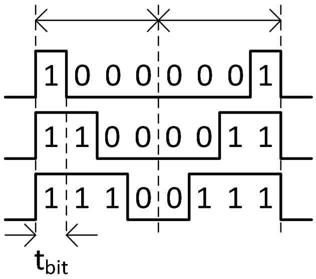

Fig. 3: Manchester-PWM recovery.

a dedicated Manchester-PWM to NRZ recovery circuit (see Figure 3), implying the usage of more dedicated hardware and consequently, raising the overall cost; or ii) using the microcontroller UART and relying on signal's post-processing. A simple solution consists on the direct interpretation of the Manchester-PWM symbol as a sequence of N NRZ bits, transmitted with a fixed bit duration t_{bit}. Each complete Manchester-PWM symbol has symbol duration Nt_{bit}. The number N establishes the dimming resolution where very precise dimming control requires a large N. However, for a large N the overall transmission rate will be N times less than the UART transmission rate, implying a tradeoff between dimming resolution and transmission speed.

After receiving the Manchester-PWM symbols, data processing must decide upon the reception of a bit 1 or a bit 0. If $D \in \{1, 2, .., N-1\}$ represents the dimming level, then a NRZ 1 corresponds to a Manchester-PWM symbol consisting of a 1 bit, succeeded by N-D-1 zeros, while a NRZ 0 corresponds to a 1 preceded by N-D-1 zeros.

C. Consumer Interaction Downlink

Smartphones can also use their VLC capabilities in order to transmit small amounts of information to the ESLD. However, due to the level of control over the flash is limited, it is impossible to rely on Manchester-PWM encoding. The flash device in smartphones typically provides no control over its output power. However it is still possible to modulate the duration of the pulses emitted with some accuracy. Therefore, the solution is to rely on a pure PWM scheme for low rate communications from the smartphone to the ESLD. This scheme is compatible with the Manchester-PWM scheme used for higher speed communications and effectively allows the coexistence of both communication methods.

As illustrated in Figure 4, an interval t_B or Nt_B is used to modulate the two possible values of a bit 1 or 0, respectively. Symbols are separated by an interval t_D. Both, t_D, t_B and Nt_B can be supported in a smartphone by means of simple (yet accurate) delays. Because we are modulating the LED flash from user space in a multi-tasking operating system, data signaling is also characterized by the setting times t_{s0} and t_{s1}, whose magnitude is very relevant, and are one of the factors limiting the performance of any similar system.

D. Front-End Design Considerations

Figure 5 depicts the front-end receiver used for VLC signal detection. This front-end comprises: i) the photo-detector employed to convert the detected optical signal into an electrical current; ii) a transimpedance gain stage, used to amplify the detected signal and perform current-to-voltage conversion; iii) a level detector, to extract the signal average;

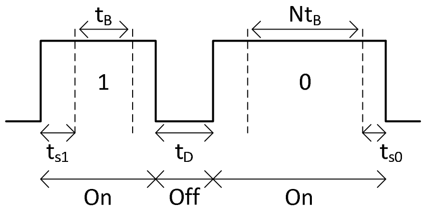

Fig. 4: Smartphone Flash data specifications for VLC transmission.

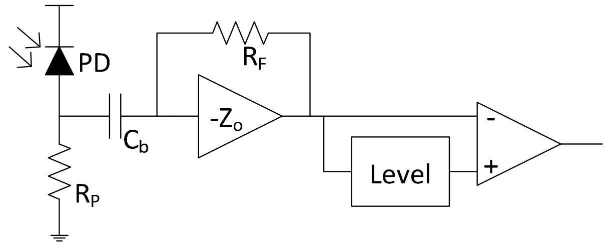

Fig. 5: Front-end for VLC signal detection.

and iv) a threshold comparator, which compares the amplified signal to its average a decides upon the detection of a 1 or a 0.

The design of the transimpedance amplifier does not pose stringent design considerations, since the target bandwidth is limited by the microcontroller data rates. For the present case, using the ATmega328's hardware UART, with a clock of 16MHz, the supported data rates are below 50kbit/s. Thus, the important parameters for the design of this front-end amplifier were: the photo-detector area; the transimpedance gain; and the inferior cut-off frequency. The photo-detector consisted of a VTH 2091 EG&G VACTEC PIN photodiode, with 9.2x9.2mm active area and nearly 150pF intrinsic capacitance (when biased with -10V). The amplifier employs a LMH6724MA integrated transimpedance amplifier, configured with a feedback resistor of 75kΩ. The inferior cut-off frequency is configured by the combination of the amplifier's input impedance and the C_b. For the present case, C_b took the value of 100nF and the cut-off frequency was below 100Hz, allowing the detection of smartphones flash signals. This unusually low value of the inferior cut-off frequency has its implications on system performance. On one side, it implies more flicker noise impact. On the other side, it will make the detection prone to slowly moving objects in the range of the photo-detector. The impairment of slowly moving objects can be reduced resorting to differential front-end topologies, with high degree of immunity to common mode signals.

E. Uplink Design Options

The present proof of concept ESLD aimed at the demonstration of the possibility of using light to transmit information, in particular, targeting the possibility to exploit VLC with the smartphones' LED flash. The complete scenario discussed in sections II and III demand additional hardware resources and social network integration. The additional hardware resources include: i) the sensors for product monitoring; ii) the power source and associated photovoltaic cells and storage means; and iii) the uplink, to transmit sensor and consumer data to the local management center. VLC concepts cannot be applied for the uplink, since it would imply the usage of a high power LED transmitter and high sensitivity receivers, to face the environmental optical power due to illumination. Instead, it will be adequate to use an IR

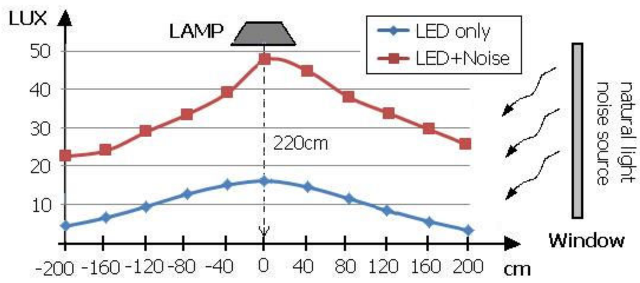

Fig. 6: Setup for data link layer evaluation.

communication uplink. This will consist of low power transmitters and optical receivers with high sensitivity to IR spectrum. Because of the high-density scenario, where many tags exist in a single corridor, receiving stations must be placed so that each station only receives information from a limited number of corridors. Effective communication is achieved by means of a stop and wait mechanism, and retransmissions with exponential backoff intervals. Given the supported data rates (see section III-B), the design of the uplink is not very challenging, as discussed previously. Moreover, while ESLD density is high, communication through the uplink channel is driven by user interaction, with intervals between interactions of the order of tens of seconds.

IV. Experimental Results

This section presents the achieved results. The first trial tests aimed at the demonstration of the device capability to receive programming information from the illumination devices and also to collect information from smartphones.

A. LED Lighting VLC Data Transmission

The setup represented in Figure 6 was used to evaluate the LED Lighting VLC data link performance. The light source was placed 220cm above the floor and configured to a minimum light emission. Although the lamp incorporates 10 white LW-W5SM Golden Dragon LEDs, with a maximum current consumption limited to 250mA, they were dimmed to consume only 120mA in order to simulate a worst case scenario, with lower signal-to-noise ratio. The ESLD bit error rate (BER) and packet error rate (PER) was evaluated along the represented axis, within a range of ±200cm from the best position (perfect alignment with the light source).

The light levels presented in this figure were measured with an EXTECH HD-450 lux meter (calibrated for human photopic vision). The blue curve corresponds to the light level reaching the tag from the lamp only, while the LED's were being modulated. The red curve corresponds to the total light level reaching the tag (lamp plus natural light).

The LEDs were modulated with 8-bit data packets, generated by an 8 bit pseudo-random binary sequence generator (PRBSG), at 19200 baud. To minimize the impact of systematic interference, data packets were transmitted with random time intervals between them, selected from a range between Δ and 2Δ, where Δ represents the time required to transmit a single data packet.

A bit and packet error rate meter was implemented, using a Spartan-3E FPGA from Xilinx, to evaluate the ELSD's performance. This error rate meter, includes an UART receiver, similar to the one incorporated in the microcontroller, followed by the BER and PER evaluation modules. Due to the relatively low data rate, and to keep evaluation time under reasonable limits, we measured BER and PER parameters with a resolution of 10E-5.

Results have shown this system to be quite robust to white noise (natural light sources) with virtually no errors in the area under the range of the lamp. In the worst case scenario, with natural light (red curve in 6), the ESLD's performance was virtually exempt from errors (BER=0) in the range [-160:160] cm. However, at ±200cm, the observed error rates reached 5.3E-3 for PER and 16.7E-3 for BER. Results with other levels of natural light and LED lighting were similar, demonstrating that the system's performance depends very abruptly on a signal to noise ratio threshold. Above it, there are no errors and bellow it, errors increase sharply. This shows that, for situations falling inside the illuminated range, the ESLD performance is virtually free from errors. In a real case scenario, the required illumination levels are well above the values used for this test case (according to ISO/CIE recommendations, the luminance level for indoor spaces with normal visual requirements should lie between 500-1000 lux [10]), thus system's error resilience is expected to improve.

B. Smartphone to Tag Communication Link

Communications from the smartphone to the ESLD was implemented using an iPhone 4S, with iOS 6.1.1. This smartphone is built around a Dual-core 1GHz Cortex-A9 processor, clocked down to 800MHz. An application capable of sending arbitrary strings by modulating the individual bits using the LED flash was implemented. In this case, it was considered t_B to be variably adjusted, starting at 1ms, and N to take the value of 2. Before each stream was transmitted, a sequence `01010101` was sent for the purpose of allowing the receiver to determine the constant t_B. It was observed that performance was dependent on t_B accuracy. However, as t_B decreases, it was observed that the accuracy decreased. Table 1 shows the actual interval as a function of different target values of t_B, as measured inside the smartphone. All values have a confidence of 95%, with errors off less than 0.15%.

Table 1 clearly shows that the capability of setting accurate t_B values to modulate a flash device is limited to bitrates not much higher than 1000bps, which results from limitations of the hardware, as well as the abstraction provided by the Application Programming Interface (API) of this prototype. Another important aspect to consider when modulating a signal through the LED flash is the delay between issuing the commands and the actual triggering of the LED flash. From a hardware perspective, since the flash is a LED it may be kept constantly on and toggle with great accuracy. However, manipulating such hardware device from a very high layer API reduces the programmers' control over timings. In this case it was observed that setting the flash to ON would incur in a constant delay of 8.4ms ±0.015%, while setting it to OFF

Table 1: Flash light timing control accuracy

Target t_B	Measured t_B	Deviation from Target
1ms	1.224	22.5%
5ms	5.659	13.2%
10ms	10.988	9.9%
20ms	21.032	5.2%
40ms	40.995	2.5%

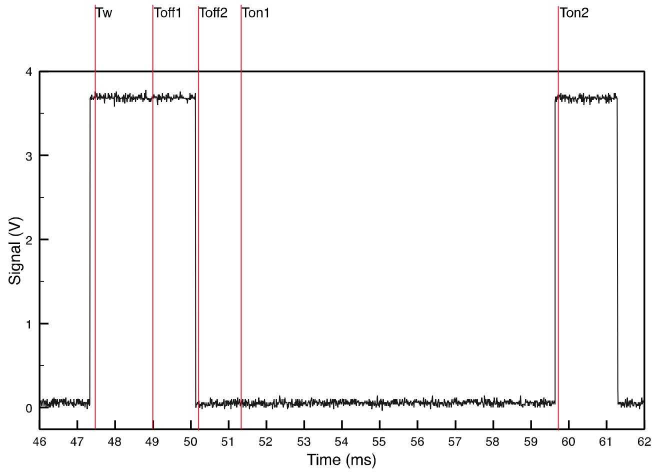

Fig. 7: Effective LED behavior when transmitting 2 bits.

would take 1.595ms ±0.189%. It should be noticed that setting the flash state implies acquiring a lock for configuring the device, changing its configuration, and then committing it.

Changing state takes 8.4ms (OFF to ON), but from a programmatic perspective there is no feedback regarding the instant when the flash actually started emitting light. Characterizing this behavior is important to know the communication limits of the system. Figure 7 depicts the impulses detected by the VLC receiver when the smartphone transmitted two bits (01) using t_B=500us. The modulation scheme adopted is able to provide distinct impulses for the different symbols being transmitted. Taking into consideration the switching times, as well as the actual delays considered, it is possible to determine the behavior of the smartphone when commanding the flash. Figure 7 displays several time instants, namely T_w, T_{off1}, T_{off2}, T_{on1} and T_{on2}, which satisfy the timings observed previously. At instant T_w, the flash is ON, initiating a wait period of 2t (1ms), which in practice implies a little more than 1.2ms. When T_{off1} is reached the flash is turned OFF, which actually happens, 1.6ms later, at instant T_{off2}. Instant T_{on1}, marks the start of the next bit with value 1. As identified, turning the flash ON implies a much higher latency, and only after 8.4ms the flash is actually enabled, at T_{on2}.

Taking into consideration the results obtained, and considering that the actual communication rate will be limited by two main factors: switching delay and timing accuracy; we conclude that the maximum symbol rate for this system will be ~91 symbols per sequence, for a sequence with duration of 1s (reasonable for consumer interaction). In this case, each bit will consist of a period of at least 1ms plus 8.4ms OFF and 1.6ms ON. Considering using 4 symbols (0ms, 0.8ms, 1.6ms, 2.4ms), the total bitrate should be between ~208bps and 272bps. As some hardware (e.g., HTC Desire) allows setting the intensity of the LED flash to 4 different levels, we assume to expect a capacity of 1091bps for this system if intensity modulation is considered, which we plan to pursuit in a future work.

To further validate the proposed approach the VLC receiver was connected to an Arduino Uno, with an ATmega328 microcontroller. It was developed a decoding algorithm capable of measuring the time of the impulses sent by the VLC receiver. An application running on an iPhone 4S modulated an arbitrary string using the flash, and according to the timing constrains previously discussed. Figure 8 depicts a simple

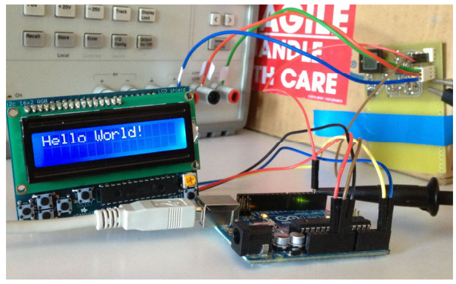

Fig. 8: Smartphone to ESLD setup.

demonstration setup, as well as the string “Hello World!” which was transmitted from the smartphone.

V. CONCLUSIONS

This paper discussed the conceptual design of ESLD based on VLC communication able to support social network integration. Key design issues concerning the deployment of low complexity and low cost hardware systems suitable for ESLD design have been discussed. The achieved proof of concept system supports VLC communication based on both LED lighting installations and smartphone’s flash lights. This is a proof of concept exploiting the possibility to establish low bit rate VLC communication using smartphone’s LED flash, based on PWM. System performance metrics have shown promising results, with high immunity to electrical noise sources. On the other hand, results have shown that system performance becomes impaired by slowly moving objects, due to the unusually low frequency system operation

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