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Walsh-Coded Orthogonal Chaotic Shift Keying for key distribution in Visible Light Communication Systems

TIAGO SILVÉRIO,[1,2] GONÇALO FIGUEIREDO[1], RUTE A. S. FERREIRA,[1,**] AND PAULO ANDRÉ[3*]

[1] *Physics Department and CICECO-Aveiro Institute of Materials, University of Aveiro, Aveiro, Portugal*

[2] *Instituto de Telecomunicações, University of Aveiro, Aveiro, Portugal*

[3] *Department of Electrical and Computer Engineering and Instituto de Telecomunicações, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*

***rferreira@ua.pt, * paulo.andre@lx.it.pt*

Abstract: In contemporary society, secure communications employing chaotic communication schemes have opened new challenges. Chaotic communication schemes in which signals are spectrally spread, with low power spectral density, become useful to improve resilience against multipath fading, making them increasingly important for indoor applications in the framework of visible light communication (VLC). Here, we will explore the 16-QAM orthogonal shift key in combination with Walsh coded chaotic basis for application of a secure VLC link, used simultaneously for illumination and security-enhanced data transmission. The experimental results are carried out for a 12 Baud symbol rate, indicating a symbol error rate below the FEC hard threshold limit for an optical irradiance higher than 25 mW/cm^2, covering a 1.4 m^2 operating area.

Keywords: visible light communication, Orthogonal Chaotic Shift Keying

1. Introduction

In recent years, secure communications have attracted considerable research interests due to growing awareness of malware issues, especially involving critical mobile devices. Secure communication is established when two entities can communicate and a third party in unable to intercept the message. This level of security can be guaranteed by encryption in which data is rendered hard to read by an unauthorized party [1]. One solution to implement secure links, at the physical level, is to employ a chaotic encryption communication scheme, as described in [2] and references therein. These chaotic systems use segments of chaotic waveforms as samples, which are stable but oscillate non periodically, making them naturally difficult to identify and predict [3]. These signals are characterized by a large bandwidth and low power spectral density, resulting in improved resilience against multipath fading [4], which is especially relevant for indoor applications where the spectral constraints are reduced.

Nowadays, indoor communications have an increasing demand in terms of connections and data rate, as there is a continuous growth of data transmission due to the development of self-sustainable smart houses and Internet of Things (IoT) devices [5, 6]. To improve data transmission capacity in these environments, a possible solution is to employ visible light communication (VLC) links, recently proposed as a research spotlight in the scientific community. Unlike typical Wi-Fi communication, VLC offers unique advantages, such as license-free channels, high electromagnetic immunity, high modulation bandwidth, and a wider spectral region of available channels, which can dramatically increase the system capacity [7-10]. Additionally, as VLC can use existing lighting infrastructures and detection systems, the carbon footprint associated with manufacturing and deployment is low, which contributes to the achievement of United Nations sustainable development goals [8, 11].

Several studies have explored the use of VLC-based systems as a sustainable and environmentally friendly method of communication. Employing a low complexity on-off keying system was possible to achieve 96 Mbps, showing that a low complexity modulation scheme could achieve bitrates comparable to Wi-fi [12]. Outlining a use on IoT applications, employing low power wide area networking with high scalability and optical amplification, was achieved with binary intensity modulation solution with 2 kHz bandwidth, bitrate of 62.5 bps, and 5.9 dB optical gain provided by photoluminescent waveguides, allowing an increase of the coverage area beyond 200 % [13].

VLC is also suitable for high order modulation techniques, as QAM-OFDM (quadrature amplitude modulation with orthogonal frequency division modulation) reported in [14], with the bit rate of 9 Gbps while operating with a BER bellow of 3.8×10^{-3}. In this case, the utilization was focused on a particularly challenging communication channel, undersea application, with a 5-meter link. VLC is also being developed towards a newly designed 5G radio system, as reported in [15]. Using a QPSK (quadrature phase-shift keying) mapping, this approach was able to achieve 14.4 Mbps while maintaining an error vector magnitude of 4.78% for a 55 cm free space transmission span. A MIMO (multiple inputs multiple outputs) approach system was also introduced in [16], using 16-QAM along with a machine learning routine to maximize the capacity of such systems, resulting in a transmission rate of 750 Mbps over a 1.3 m line of sight trial with a BER bellow 10^{-3}. As for cryptographic key distribution allied with VLC systems, in [17], was reported towards a low-cost implementation of an indoor VLC system using a continuous-variable quantum key distribution protocol and obtaining a quantum error-rate below 10^{-3}, at 1 Mbps.

In this work, we propose the use of M-ary modulation, with a low-cost luminary system, to grant security through the use of chaotic sequences to encode the information [18]. This innovative VLC system based on orthogonal chaotic shift keying using Walsh basis, assure a secure optical link for cryptographic key distribution aiming the indoor implementation in mobile phones and computers.

2. Methodology

The proposed VLC system is implemented recurring to the direct modulation of a LED lamp (array of LEDs) operating in the visible spectral region and to a correlator-based detector. The transmitted binary data is firstly encoded with an orthogonal chaotic basis in conjugation with Walsh functions, using a Gray coded 16-QAM scheme [19]. The considered figure of merit used to describe the overall performance was the Symbol Error Rate (SER), discussed as a function of the signal-to-noise ratio (SNR) [20]. In this configuration of orthogonal chaotic shift keying, the digital signal is used to switch the transmitted signal between the combination of two orthogonal, statistically independently, chaotic bases. For the chaotic basis generation, it was employed a Chebyshev logistic map, describe by:

$$x_{k+1,i} = \cos(h \cos^{-1}(x_{k,i})), \tag{1}$$

where $h \in [0, 1]$ is a constant key parameter and $x_{k,i}$ is the *k*-th value generated by the *i*-th $\in \{1, 2\}$ basis [21]. The Chebyshev logistic map generation implies prior knowledge of the key values $(h, x_{1,i})$, so the unpredictability of the sequence is guaranteed assuming the pair of values to be unknown. These values, $(h,x_{1,i})$, are randomly and accurately generated and, both the transmitter and the receiver know these values to perfectly reconstruct the basis of the signal. While the transmitter sends the chaotic basis, at the receiver the message is recovered by coherently correlating the received signal with the orthogonal basis, which will result in the corresponding reconstructed message. However, the modulation basis values must obey the function domain restrictions, namely, that the codomain of the Chebyshev polynomial is coincident with its domain ([-1, 1]). Ensuring that $h > 1$ [21], the Chebyshev logistic map is characterized by a null mean value and a probability density function described by Eq. (2).

$$\rho(x) = \frac{1}{\pi\sqrt{1 - x^2}}. \tag{2}$$

Under these circumstances, the logistic map presents a normalized correlation values of $R_x(\tau=0) = 0.5$ and $R_x(\tau) = 0$ for $\tau \neq 0$. Furthermore, for any two different initial values, the normalized cross-correlation function for the two generated sequences is null, $R_{x1,x2}(\tau) = 0$. However, this is only true for an infinite length sequence [4]. Therefore, a problem of orthogonality within the basis arises as a consequence of this cross-correlation drawback, creating a dependence between the performance of the system and the number of chaotic samples used to represent each symbol. To further address this point, the orthogonality of the basis's functions can be guaranteed by combining the Walsh functions with the chaotic logistic map signals. Each basis function has two segments called the reference and information-bearing chips [4]. Resulting in the following two bases functions ($g_I(t)$ and $g_Q(t)$):

$$g_{I,(Q)}(t) = \begin{cases} +\dfrac{1}{\sqrt{E_s}} c_{1,(2)}(t), & 0 \leq t < \dfrac{T_s}{2} \\ +(-)\dfrac{1}{\sqrt{E_s}} c_{1,(2)}\left(t - \dfrac{T_s}{2}\right), & \dfrac{T_s}{2} \leq t < T_s \end{cases} \quad (3)$$

where t represents the time, T_s is the symbol period, E_s is the symbol of energy and $c_{1,(2)}(t)$ are the chaotic waveforms.

This methodology allows orthogonality to be assured even for a finite duration signal due to the symmetry proprieties within each symbol while conserving the chaotic nature of the message throughout the communication. These bases g_I and g_Q, compose the vectors for the 16-QAM constellation.

3. Simulation description / Experimental details

To further evaluate the proposed scheme, a VLC system was designed and implemented experimentally and in a numerical simulation environment, Fig. 1. The chaotic/Walsh basis is generated for each component of the QAM system, according to Eqs. (1) and (3). Data was described with random data and encoded in a serial/parallel converter before multiplied by the basis, resulting in the output optical signal, *s(t)*. In the simulation environment, an additive white Gaussian noise model has been used to emulate the effects of the multipath fading and the electro-optical-electro conversions in the transmitter and receiver. To demodulate the data, the received message, $r_m(t)$, is correlated with the original chaotic/Walsh basis, forming the two orthogonal components: $z_1(t)$ and $z_2(t)$. This response is processed with Cluster Analysis applied to the constellation diagram to determine the boundaries of the symbol for optimum decision.

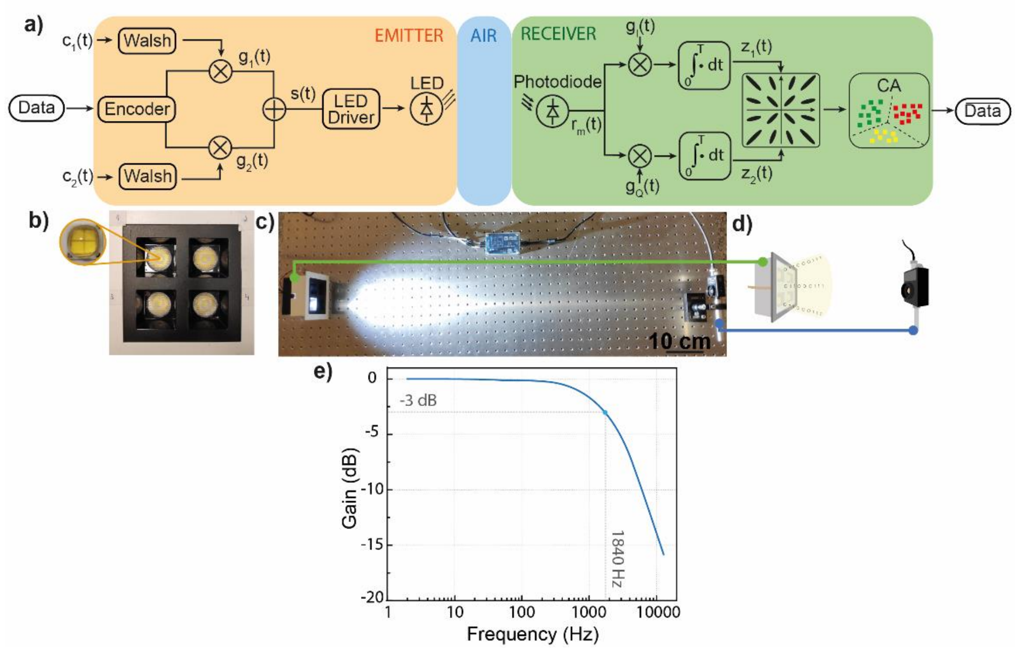

Fig. 1 a) Scheme of the set-up used for chaotic shift keying VLC system. Photos of the b) Codex-E Lamp and the LED modules and d) experimental implementation; c) illustration of the transmitter and a receiver. e) Frequency response of the Codex-E Lamp luminary (highlighted the -3 dB bandwidth of ~1840 Hz).

In the modulation, each symbol was codified into *N* samples (typically 100) of the chaotic basis. Along the description of this implementation the following logistic map parameters were used: h = 3.900; $x_{1,1}$ = 0.4500 (I component) and $x_{1,2}$ = 0.5000 (Q component).

The data transmission was performed on the chaotic VLC system shown in Fig. 1d), employing a commercial luminary (Codex-E Lamp; Lightenjin) operating simultaneously as an illumination point and data source. The luminary comprises four lamps, each one with four white emitting LEDs, and presents a luminous efficiency of 80 lm/W and luminous flux up to 4000 lm when operating at the nominal electric power of 50 W. Each lamp has a radiation diagram with a –3dB beam aperture of 60º. The system characterization was performed using one lamp at 20% of its nominal power (current of 0.240 A), presenting a modulation bandwidth of 1840 Hz, as illustrated by Fig. 1e), for a distance of 0.5 m between emitter and receiver and an optical irradiance, obtained with OP-2 VIS power meter (by Coherent), of 97.0 $\pm$ 0.1 mW/cm^2. Although the available modulation bandwidth is 1840 Hz, the considered sampling rate of the chaotic symbols was 850 Hz. In the experimental implementation, the ADALM1000 board (Analog Devices) was used as an I/O interface, which has a sampling rate adequate for the demonstrative proposal of this work. The modulation signal was applied to the LED through a current source (T-Cube LED Driver; Thorlabs) and the detection was realized with a-Si photodiode, Det10A (Thorlabs).

4. Results and Discussion

The focus of the experimental implementation was to demonstrate the feasibility of the chaotic key distribution when applied to VLC systems, where the main impacting factors are the bandwidth of emitter and receiver and the indoor environment multipath propagation. In Fig. 2a) there is a representation of a fraction of the signals sent and received, in the electrical domain, highlighting the transmission of the different symbols.

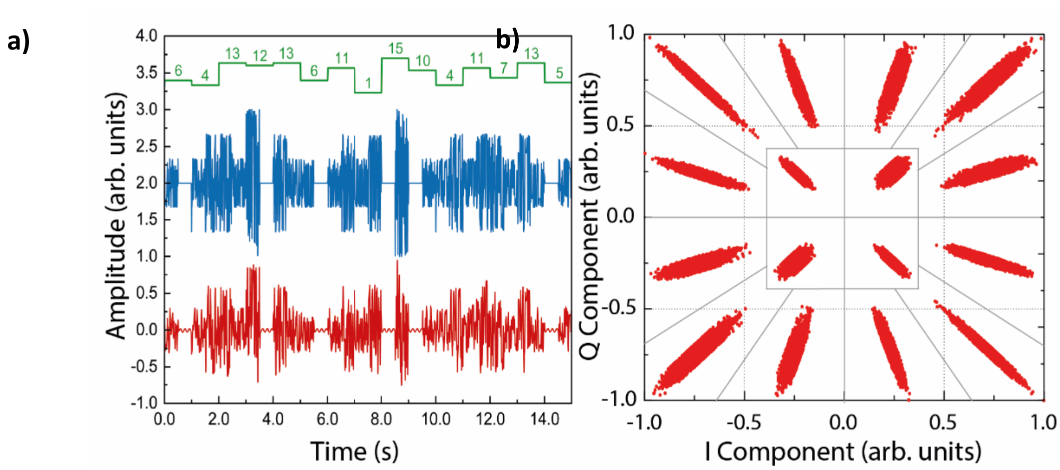

Fig. 2 a) Sample of the transmitted symbols (top, green), modulate chaotic signal waveform (middle, blue), and chaotic signal received (bottom, red) measured in the electrical domain. b) constellation diagram for the transmission of 10^5 symbols at 1 kBaud. The number of chaotic samples per symbol was 100 and the optical irradiance at the receiver was 35 mW/cm^2.

The maximum symbol rate is experimentally defined by the number of chaotic samples used per symbol (*N*). A low symbol rate solution was implemented, for illustrative proposes, but perfectly compatible with secret key distribution systems. The constellation diagram can be seen in Fig. 2b), where a constellation diagram is presented with 10^5 symbols, for an optical irradiance of 35 mW/cm^2 and1 kBaud (N = 100 samples/symbol). The symbols are well decoded with the illustrated decision regions, defined using $Q = k \cdot I$ lines, where k is defined using the K-means algorithm for Cluster Analysis to classify the optimal intersymbol boundaries. These decision areas are constructed to minimize the errors in the demodulation of the signal and have the advantage of being system-dependent. For each finite sequence of transmission, these areas can change to improve the performance. The symbol dispersion is not coincident with this trend, being attributed to the noise channel, while the dispersion around $Q = k \cdot I$ lines is a match to the basis cross-correlation drawback. The higher the number of chaotic samples per symbol, the lower is this dispersion which illustrates that the decrease in correlation between the two components of the basis describes the importance of keeping this drawback in check.

The symbols centroid position in the constellation must be determined while performing the communication, using the clustering analysis to determine the most probable centroid position for each symbol based on K-means using City Block distance. This algorithm computes the sum of absolute differences and was chosen based on its performance with various types of transmissions over several tests. After the decision boundaries being defined, the performance using the different parameters of the transmission can be analyzed. As previously highlighted, due to a finite number of chaotic samples in each symbol, its cross-correlation different than 0 which is directly responsible for not only increasing the dispersion in the constellation diagrams but also moves the symbols towards the central point since the two bases are no longer perfectly orthogonal. Fig. 3a) shows the relationship between SER and the number of chaotic samples per symbol, obtained experimentally and in the numerical simulation.

a) b)

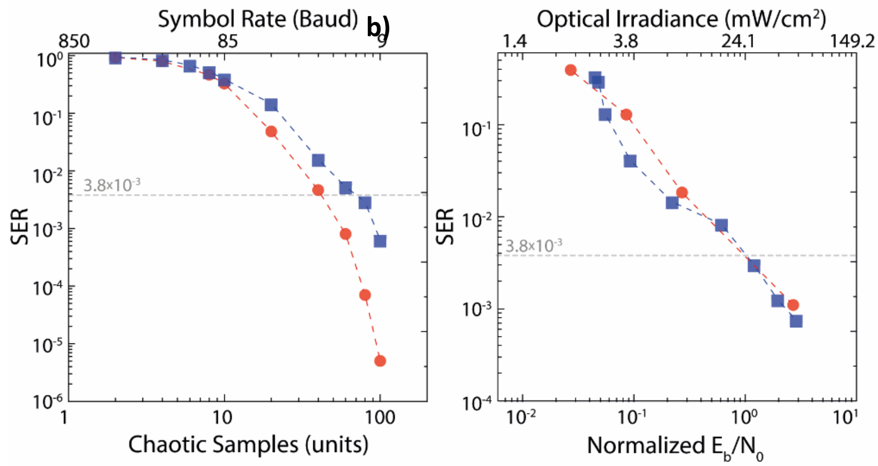

Fig. 3 a) Simulation and experimental results for SER as a function of the number of chaotic samples per symbol; b) simulation and experimental curves for SER as a function of the normalized E_b/N_0 at the SER limit. The blue stars are experimental results, the red circles are simulated results while the dashed line represents a visual guide of the trend. The used system parameters are a sampling rate of $\cdot 10^5$ samples/s and an optical irradiance of 35 mW/cm^2 in a) and 100 chaotic samples per symbol in b).

Increasing the number of chaotic samples per symbol results in the decrease of the achieved SER. The differences between these curves arise from the impairments of the experimental implementation, namely symbols distortion resulting from the limited bandwidth or optical signal multipath fading. To further quantify the performance, an SER threshold of 3.8×10^{-3} (corresponding to the 7% hard-decision forward error correction, HD-FEC [22]) was considered as the low bound operation value. The orthogonal chaotic shift keying proposed, for the considered SNR can operate below this limit when the number of chaotic samples per symbol is larger than ~70 and ~45, in the experimental and simulated environments, respectively. With this condition, a restriction of the symbol rate can be established as a maximum of 12 Baud for the described experimental deployment. Another similar analysis is made regarding SER as a function of the E_b/N_0 (Fig. 3b), showing a good agreement of the experimental and simulation results and providing a good indicator for the use of simulation models to design and optimize experimental deployments.

To analyze the feasibility of the proposed system, the performance was attained in a realistic environment, Fig. 4a. The transmitter was placed in a vertical configuration, at 1 m from the receiver (typical distance between a handheld device and the ceiling lamp) while operating at nominal conditions using four lamps, modulated with a maximum current of 1.2 A, with a maximum optical irradiance at the receiver of 877 ± 1 mW/cm^2. The irradiance map of the LED lamp emitting to an XY projection plane has a circular symmetry distribution of the optical power with a central area of, approximately, 1.4 m^2 where the secure data transmission is feasible, i.e., where the SER is lower than the considered hard FEC limit (Fig. 4b). The SER was estimated to be below 10^{-9} in the point vertically below the lamp.

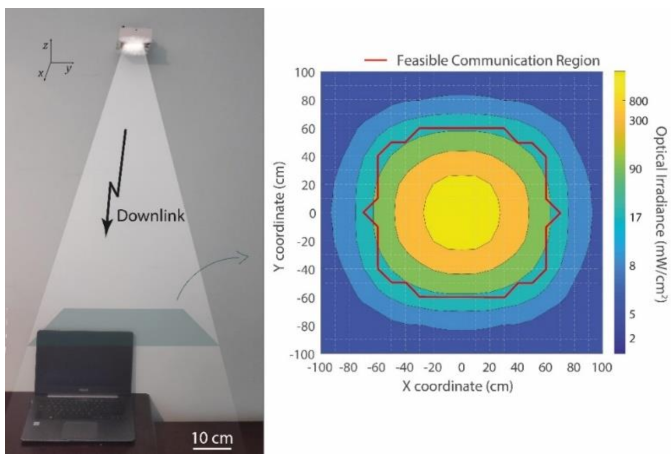

Fig. 4 a) Photo the proposed chaotic VLC system; b) Optical irradiance map of the LED lamp operating in nominal conditions placed at 1 m from the transmitter.

5. Security Analysis

To ensure the security of the proposed system, statistical tests were made to guarantee that the chaotic sequences generated a bitstream considered to be random. The tests applied were developed by NIST, [23], and were run at a significance level of 1% (i.e. there is a 1% probability that the sequence was considered random while being non-random), which is the standard approach in cryptographic applications. The number of runs performed for each test was 10^4, each evaluating a bit-sequence of 1024 bits, giving a total of, approximately, 10^7 samples appraised by each type of statistical test. To certify the representativity and test independence of these results, the chaotic sequences were generated for 9 different statistical tests based on different h values, inputted in Eq. (1), giving a total of $10^{7\times9} \approx 2^{210}$ samples generated. The results of the 9 NIST statistical tests performed are summarized in Fig. 5, highlighting the approval rate of the chaotic sequences for each one of them.

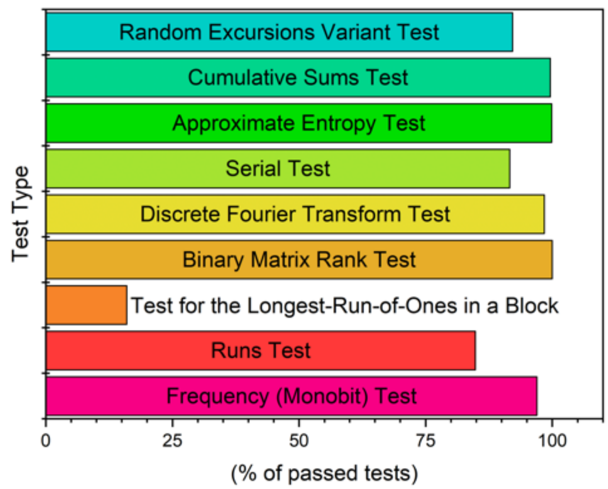

Fig. 5 NIST statistical tests, using the guidelines established in [23]. The results attained described the approval rates for a total of 2^{210} chaotic samples generated by the Chebyshev logistic map.

The results provide evidence of the randomness of the bitstreams generated, despite the test for the Longest-Run-of-Ones in a Block prevent a high pass rate. Moreover, as detailed above in Eq. (1), the cryptographic key of the proposed system is expressed as a combination of the system values $(h, x_{1,i})$. Most likely, these values are not known by an attacker, and, given the chaotic nature of the Chebyshev logistic map, by failing to input these values correctly, the sequence obtained is completely different, as pointed in [21]. To ensure attack-resistant keys, both key parameters are generated using a scale fixed-point format with 15-digit precision for double precision. According to the IEEE floating-point standard [24], the computational precision of the 64 double-precision number is approximately 10^{15}, [25]. Therefore, the keyspace is approximately given by $\text{key} = 10^{15\times2} \approx 2^{100}$, which is large enough to efficiently resist brute-force attacks.

6. Conclusion

We reported the experimental demonstration of Walsh coded orthogonal chaotic shift keying in VLC systems. The modulation parameters were studied and optimized, indicating that the Chebyshev logistic map is a good candidate to be used in the generation of the orthogonal basis and the adequate number of chaotic samples used per symbol was found in 70.

The experimental deployment can achieve a symbol rate of 12 Baud, satisfying the FEC limit with an optical irradiance of 25 mW/cm^2. The results of the case study showed that, in a realistic environment, a commercial luminary can operate at these irradiance values and illuminate an operating area of 1.4 m^2. Although this area may not be enough for a realistic widespread implementation, modifications in the luminary structure could be made so that the beamwidth could be increased and, thus, increasing the region of operation.

Increasing the baud rates of this system while maintaining optimal performance will require some additional steps, feasible with the proposed modulation scheme, namely, using higher-order modulation schemes, using luminaries with higher bandwidth, and increasing the nominal operating power of the LEDs. Furthermore, imposing these adaptations to the existent LED-based illumination system can have a meaningful impact on its operation, with a cost-effective network solution. Nevertheless, a low baud rate implementation of the proposed system is a cost-effective solution for maintaining a secured channel for either user authentication protocols or cryptographic key distribution.

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