Practical Space Shift Keying VLC System

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***Abstract*—This paper presents results of a practical implementation of a spatial shift keying (SSK) visible light communication (VLC) system. This is the first practical proof-of-concept real-time implementation of SSK to the best knowledge of the authors. The system uses four transmitter light emitting diodes (LEDs) to encode information, and four receiver photo diodes (PDs) to decode the spatial signatures and decode the incoming data signal. The achieved bit error ratio (BER) of less than 2×10^{-3} allows for error-free communication if forward error correction (FEC) is to be applied. The main challenge with practical implementations of SSK in VLC is identified, namely maintaining symbol separation in the received constellation, and solutions are proposed.**

I. Introduction

It is widely accepted that wireless data traffic is growing exponentially. It is expected that satisfying the increasing data rate demands of mobile users will be very challenging due to the limited available radio frequency (RF) communication spectrum [1].

One of the proposed ways to solve the aforementioned problem is to make use of the freely available visible light spectrum. Using visible light for communications can offer several advantages. The amount of bandwidth available is 10000 times more than that in the RF spectrum. It is currently unregulated and licence free. Both transmitter and receiver front end devices are simpler than their RF counterparts since no upconversion is required. The visible light spectrum does not generate any interference with sensitive electronic equipment. Last but not least, the communication functionality can be integrated in the already existing illumination infrastructure.

The above possibilities have lead to significant research activity in the field of visible light communication (VLC). Light emitting diodes (LEDs) are seen as one of the key components in VLC. Currently, they are incapable of being modulated at high frequencies due to the way they operate. Currently most commercially available white LEDs are made up of a blue LED and a yellow phosphor coating. The slow response time of the coating limits the usable bandwidth of the device to only several MHz [2]. This is perceived as one of the major challenges for the technology. It is possible to alleviate this problem by introducing an optical filter at the receiver that only allows blue light to pass through. This technique is capable of increasing the bandwidth up to 20 MHz [2]. There also are other additional pathways around this problem – equalization, higher order modulation schemes, as well as parallel transmission over several channels [2–4].

However, there is also a significant push to improve the performance of LEDs for communication purposes. Two examples of this research activity are resonant-cavity light emitting diodes [5] and μLEDs [6]. Using the aforementioned technologies, devices have been manufactured that are capable of supporting communication links of up to 3 Gb/s and 512 Mb/s, respectively.

Multiple input multiple output (MIMO) systems are also a focus of ongoing research within free space VLC. Both imaging and non-imaging approaches have been analyzed via simulation, and found to be capable of data rates up to 1 Gb/s [7]. Work has also been done on optimizing system parameters in a MIMO environment when using avalanche photo diodes (APDs) [8].

In this paper the first practical real-time implementation of a spatial shift keying (SSK) system for VLC is presented. The system is of low complexity and uses off-the-shelf components. The performance of this initial implementation is evaluated and the main challenges associated with its further development are identified.

The rest of this paper is organized as follows. The concept of SSK is introduced in Section II. The system set-up is described in detail in Section III. This is followed by results and discussion on the performance of the system in Section IV. Finally, the paper concludes with key findings and suggestion for future work in Section V.

II. Space Shift Keying

SSK is the simplest implementation of the concept of Spatial Modulation (SM) [9]. In general, SM introduces an additional, spatial, dimension to the constellation diagram, hence enhancing the achieved throughput without the need to either increase the power budget of the system or its bandwidth. SM is based on the fact that in a system consisting of a transmitter and receiver arrays, each transmitter and receiver pair enjoy a different channel compared to the others. This facilitates the ability of the receiver to decode which transmitter sent the received signal. SSK when applied in VLC is implemented as an intensity modulation, direct detection modulation scheme.

SSK uses the SM principle in its simplest form – data is encoded simply by turning on one transmitter at a time during the symbol period as illustrated in Fig. 1. Each transmitter is

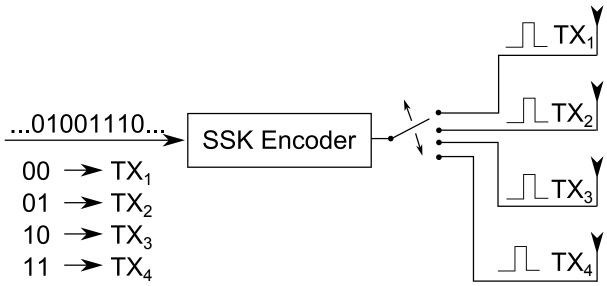


Fig. 1. Illustration of SSK operation

assigned a unique bit sequence. During data transmission, the different transmitter LEDs are turned on and off one after the other in order dependent on the data that is to be transmitted. Hence, M transmitters would allow the transmission of symbols that contain $\log_2 M$ bits of information.

This process can also be thought of as a combination of SM with on-off keying (OOK). OOK is known for its robustness against LED non-linearities but has low spectrum efficiency [10]. SSK combines the robustness of OOK against LED non-linearities with the ability to boost spectral efficiency by exploiting the spatial dimension. As shown above, the spectral efficiency scales with base two logarithm of the number of transmitter LEDs.

The bit error ratio (BER) performance of SSK systems in correlated Ricean fading channels has already been analytically treated [11]. The average bit error probability (ABEP) can be tightly upper-bounded by:

$$\mathrm{ABEP} \leq \frac{1}{N_t - 1} \sum_{i_1=1}^{N_t} \sum_{i_2=i_1+1}^{N_t} \mathrm{ABEP}_{i_2,i_1}, \quad (1)$$

where N_t is the number of transmit LEDs, ABEP_{i_2,i_1} for $i_1 = 1, 2, \cdots, N_t$ and $i_2 = 1, 2, \cdots, N_t$ is the ABEP of an equivalent $2 \times N_r$ SSK-MIMO system, which consists of only two transmit LEDs, *i.e.*, the LEDs with indexes i_1 and i_2, and N_r receive PDs. The ABEP of the equivalent SSK-MIMO system with only 2 transmitters and N_r receivers can be obtained from:

$$\mathrm{E}\left\{\mathrm{P_E}(h_1, h_2)\right\} = \mathrm{E}\left\{\mathrm{Q}\left(\sqrt{\frac{E_s}{4N}\sum_{n=1}^{N_r}|h_{2,n} - h_{1,n}|^2}\right)\right\}, \quad (2)$$

where $\mathrm{P_E}(\cdot,\cdot)$ is the probability of detecting the wrong transmitter index at the receiver, when conditioning on the channel transfer factors h_1 and h_2 of the links between the two transmitters and the N_r receivers.

An example received signal for the 4×4 SSK system discussed in this work can be found in Fig. 2. Since the system has 4 transmit LEDs, the number of bits per symbol transmitted is 2 and the number of symbols in the constellation is 4. The signal shown is the channel estimation part of a frame where the four symbols of the constellation are sent sequentially three times. In this particular realization, the four different receivers are well paired with the four different transmitters resulting in high distance between the different symbols.

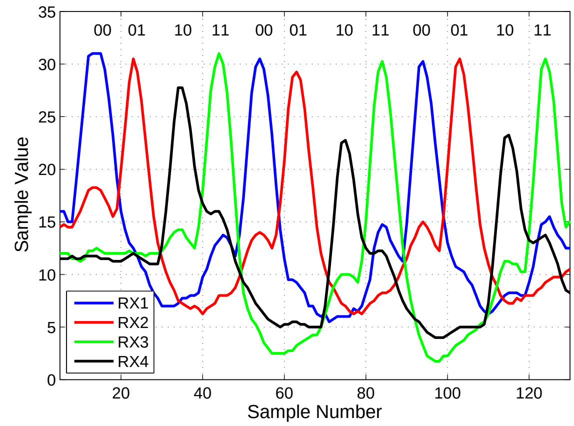


Fig. 2. Received SSK signal

In the context of VLC, SSK is envisioned to be relatively simple and straightforward to implement compared to the more traditional modulation schemes such as pulse amplitude modulation (PAM) and orthogonal frequency division modulation (OFDM). SSK requires that the transmitter LEDs are simply turned on and off dependent on the transmitted data stream – this greatly simplifies the LED driver circuitry and does not require the LED non-linearities to be taken into account.

Within this work, the decoding process of the SSK symbols is implemented as a maximum likelihood decoder. Each transmission frame starts with a sequence of known symbols that are used for channel estimation. The decoder operates by comparing the received signal to the received symbol signatures from the channel estimation part of the frame. Each symbol and symbol signature are represented by a vector of size N, where N is the number of receivers in the system. Each element of the vector represents the height of the signal pulse during the symbol period that the particular receiver experienced. The Euclidean distance between the received signal x and the signature of symbol y is calculated as:

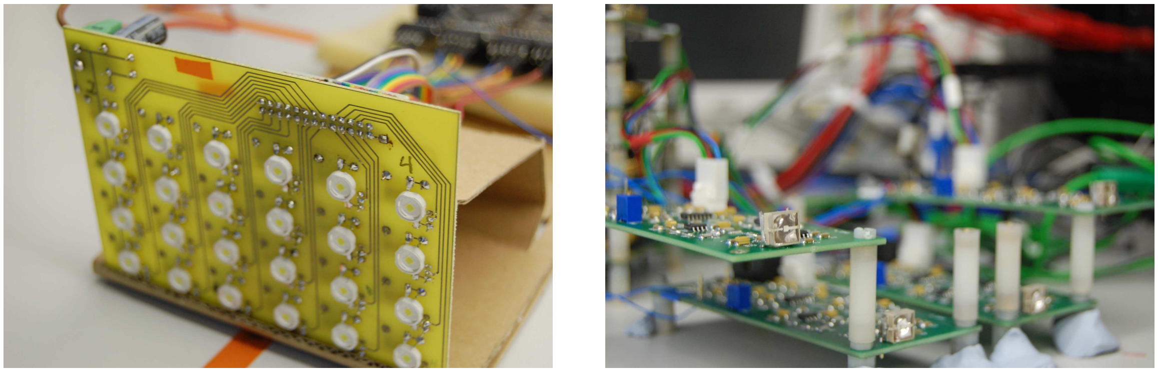
$$d = \sqrt{\sum_{i=1}^{N}(x_i - s_i^y)^2} \quad (3)$$

The symbol signature which has the lowest distance from the received signal is chosen as the correct one, and the associated bit sequence is passed as the output from the decoder.

III. System Set-up

For the purposes of an initial performance and feasibility evaluation, an SSK communication system has been constructed. The system consists of a transmission array of 4 LEDs and 4 photo diodes (PDs) and associated circuitry.

The system symbol rate is set at 500 KS/s. This results in a data rate of 1 Mbit/s. Such a low symbol rate is used to verify the operation of the system and prove that SSK is feasible in practice. Raising the symbol rate should be straightforward while it is done within the capabilities of the employed hardware. The only factor that could theoretically limit the data rate is the bandwidth of the LEDs and PDs used. The available commercial devices have only recently been manufactured for



(a) Transmitter (b) Receiver

Fig. 3. System Set-up

communication purposes and their bandwidth is still somewhat limited. Photos of the system set-up can be found in Fig. 3.

At this point it is important to address flicker, as it is commonly thought of as a problem for VLC systems. At the symbol rate the system operates, the human eye does not perceive the LEDs as flickering. In the case where there is no data to transmit, it is possible to set up the system to transmit empty frames, full of dummy data.

The following sections discuss the different aspects of the proof-of-concept system in more detail.

A. Hardware

The user terminals at both ends of the system, receiver and transmitter, are a combination of digital and analog blocks. No optical filtering is employed to keep the complexity of the system as low as possible.

The transmitter is made up of a a system on a chip (SoC) in the form of the Texas Instruments (TI) BeagleBone connected to a field programmable gate array (FPGA) board – the ValentFX MARK-1. The FPGA is used to digitally control the analog front end which features 24 LEDs (only the corner 4 are used for communication currently, the rest are kept off). The analog front end is purposefully kept simple – each LED is connected to a current limiting resistor and a transistor which enables the digital on-off operation by the FPGA. The LEDs used are the Avago ASMT-AW00-NSU00, and each LED draws approximately 1 W of power.

The receiver consists of the same BeagleBone and MARK-1 combination, but in addition it also has 4 TI TLC5540 analog-to-digital converters (ADCs), as well as four separate analog receiver boards. Each receiver board consists of an Outstanding Technology LEC-RP0508 pin PD followed by a trans-impedance amplifier, a Sallen-Key low pass filter, a voltage-controlled amplifier (VCA) and a set gain non-inverting amplifier. Although a VCA is present in the system, no automatic gain control is implemented. Pin PDs are used instead of imaging receivers for their larger bandwidth as well as significantly lower cost.

The ADCs are capable of outputting an 8 bit digital representation of the input signal at speeds of up to 40 MHz. However, only 5 bits are used due to the number of input pins available on the FPGA. The sampling rate is set at 5 MHz. The clock signals are generated by the FPGA.

The only problem encountered during the hardware implementation was a mismatch between the impedances on the ADC clock output from the FPGA and the clock input on the ADC side. The mismatch resulted in a significant level of noise on the line, which caused the ADC to occasionally not convert the analog values correctly, and output a zero instead of the correct level. The addition of a resistive and capacitive load to each of the clock lines solved the issue.

B. Firmware

The FPGA boards feature the Xilinx Spartan-6 FPGAs. All the processing in terms of encoding and decoding the transmission data is performed on them.

The transmitter FPGA interfaces with the BeagleBone SoC Linux system by using the general purpose memory controller (GPMC) interface. The data stream from the user terminal is inspected and encoded to the different transmitter LEDs. Channel estimation symbols are added in the beginning of every frame. Each frame consists of 12 estimation symbols, 3 of each used symbol, followed by 188 data symbols. Synchronization is currently performed over a wire interface – a frame synchronization as well as a clock signal are passed on to the receiver. A wire interface is used to make sure that synchronization is perfect and the system performance only depends on the used modulation technique – SSK.

On the receiver side, the FPGA receives the four data streams from the receivers as well as the synchronization signals from the transmitter. It then applies a digital low pass filter in the form of a 4 point running average to reduce any high frequency noise components, and then applies the maximum likelihood decoding principle and (3). The decoding process runs in realtime. Therefore, the system is capable of streaming real-time data. Possible applications for it would be the transmission of telemetry data or sensor data.

C. Software

A real-time Linux driver on both the receiver and transmitter sides governs the communication between the BeagleBone and the FPGA. Random bit sequences are generated, transmitted and received for the purpose of evaluating the system performance.

IV. Performance Results

To illustrate the performance of the system, measurements are taken to gauge its BER.

A. Measurement Setup

Measurements are taken with the transmitter and receiver being collinear with each other and varying the distance between them from 5 cm to 35 cm in 5 cm steps. The BER is measured as a function of the minimum Euclidean distance between the symbols in the received constellation. This is in line with (1) and (2). The equations are based on the distance between channels, which is equivalent to the distance between symbols in the implemented SSK system since a symbol is a pulse transmitted from a particular LED. The distance is measured with the use of (3). The results are unit less as the values used in the calculation are obtained from the outputs of the analog to digital converters.

No attempt is made to compare the theoretical results from [11] to the practical results presented here. The practical implementation is not optimal due to hardware constraints. This renders the comparison meaningless as the performance of the practical system is significantly lower than the theoretical maximum. Instead, this paper focuses on showing that using SSK for practical communication is indeed possible.

Since no automatic gain control is present in the system, the minimum distance between symbols is varied by changing the distance between receiver and transmitter. This leads to a reduction in the magnitude of the pulses received which in turn reduces the distance between the symbols in the constellation due to the limited precision with which computation is carried out. The increase in distance between transmitter and receiver also increases the correlation among channels between the different transmitter and receiver pairs. As the channel correlation increases the Euclidean distance between symbols in the received constellation diminishes.

B. Results

The BER versus minimum symbol distance in the receiver constellation can be found in Fig. 4. The x-axis is quantified in terms of the distance d presented in (3). The BER exhibits similar behavior to that expected of traditional BER versus SNR curves after a rapid initial decrease for distances between 4 and 5. The BER decreases as the minimum Euclidean distance between the received symbols increases. The maximum theoretical distance possible between two symbols is 62. This is the distance between an all zero signal on all 4 receivers, and one that has the maximum possible amplitude, 31, on all receivers. However, in practice minimum symbol distances in the received constellation over 31 are very difficult to achieve due to the number of symbols in the system as well as the the number of bits per sample the ADC outputs.

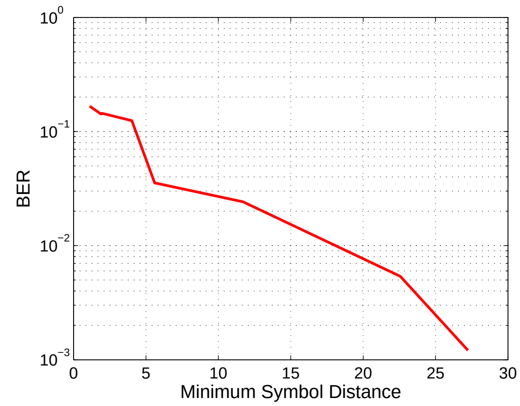


Fig. 4. BER as a function of minimum symbol distance

BER performance under 2×10^{-3} falls within the capability of forward error correction (FER) codes to achieve error-free communication in practice $[2, 12]$. The addition of the FER code leads to a 7% overhead $[2, 12]$, which reduces the achieved data rate to 0.93 Mbps.

The best BER performance in the above graph is achieved at a distance of approximately 15 cm. This distance can be increased if the gain in the receiver analog circuitry is calibrated for a larger one. However, as the physical separation increases, the channel difference between the different transmitter and receiver pairs will decrease as the propagation paths become more collinear. This effect can be combated by introducing a larger spatial separation between the different transmitter LEDs.

C. Challenges

From the above results it emerges that the main challenge for SSK in VLC is preserving the minimum distance between the symbols in the received constellation under different conditions.

Increasing the distance between receiver and transmitter decreases the distance between symbols due to the overlap between the field of view of the different PD receivers increasing. There are several ways to combat this effect. A power imbalance can be introduced at the transmitter to allow better distinction between the different symbols. Other hereby proposed methods are using polarization filters at both the transmitter and receiver, and using special geometrical placement of the PD receivers as well as transmitter LEDs to minimize the overlap in field of view.

V. Conclusion and Future Work

A working practical implementation of real-time SSK in a VLC setting is presented. BER results as function of the minimum distance between symbols in the received constellation are presented. The best achieved BER allows for error-free communication provided FEC coding is used. The main challenge associated with the implementation of the system is identified – namely preserving the minimum distance between symbols in the constellation under varying conditions.

Future work is to include an improved system in terms of higher symbol rate. Further investigation will be carried out to assess the benefits from polarization filters and particular transmitter and receiver geometries that enhance the channel separation between different transmitter and receiver pairs. Moreover, generalized SSK will be investigated as well, where more than one LED is turned on at a time to generate a higher number of spatial symbols than available LEDs in the system.

VI. Acknowledgment

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