Constrained Coding for Hardware-friendly Intensity Modulation

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Abstract: An advanced signal design for boosting the performance of binary-modulated IM/DD communication systems is presented. Multiple light sources are jointly modulated so that the optical signals superimpose at the receiver. The superimposed signal is of high rate. The switching sequences are constrained to match the physical properties of the transmit hardware. A graph-based representation is used to design a low-complexity block code, enabling the use of the binary superposition modulation scheme under investigation in a practical IM/DD setup. Based on this coded signal design measurement results on power consumption and simulation results on bit error rate performance are presented.

1 INTRODUCTION

Superimposing multiple binary-modulated light sources improves the performance of *intensity modulation and direct detection* (IM/DD) communication systems. This is a twofold effect.

On the one hand, the throughput is typically upper bounded by bandwidth limitations at the transmitter. An improvement of the maximum possible data rate can be realized by overlaying multiple binary intensities (Fath et al., 2013; Armstrong, 2013; Dobesch et al., 2014; Forkel and Hoeher, 2015) for forming a multilevel intensity modulated signal. Furthermore this receiver-side sum signal is possibly of higher rate then the state changes at the individual light sources (Forkel and Hoeher, 2016). The *constrained superposition intensity modulation* (CSIM) method under investigation exploits both techniques at the same time (Forkel and Hoeher, 2017).

On the other hand, the amount of power spent for modulation, i.e., for charging or discharging the capacities in the optical emitter and the driver circuitry, can be reduced by using the proposed superposition modulation scheme. This is possible by lowering the number of switching operations per source bit, compared for example to *on-off keying* (OOK) modulation.

The key contribution of this paper is a channel coding design which is matched to CSIM.

The overall work is organized as follows: In the next section we define a CSIM scheme to mitigate the physical limitation of the individual transmit LEDs by superimposing multiple low-rate sequences. We introduce a constrained capacity and evaluate the number of switching operations per source bit. Having derived a Moore-graph representation of the transmitter constraints, block coding is applied in Section 3. A *constrained superposition intensity coding* (CSIC) method allows CSIM sequences to be used for representing actual transmit data. Then simulation results comparing CSIC with OOK are presented. Finally conclusions are drawn in Section 4.

2 CONSTRAINED SUPERPOSITION MODULATION

The novel CSIC encoder, cf. Fig. 1, generates a vector $\mathbf{x}$ of integer numbers given a binary source data vector $\mathbf{u}$. The time duration of one vector element is denoted as one slot in the following. A mapper transforms the integer numbers $\mathbf{x}$ into switching patterns $\mathbf{s}_l \in \mathbb{G}_2^n$, $l = \{0, \ldots, L-1\}$, where L is the number of light sources. These switching patterns control the light sources, as shown in Fig. 2. Subsequently, we assume an illumination fixture where the LEDs are in close distance to each other (Mossaad et al., 2015). Correspondingly, all L light sources superimpose with equal weight on the channel. Therefore the channel gain H is the same for all light sources. Furthermore

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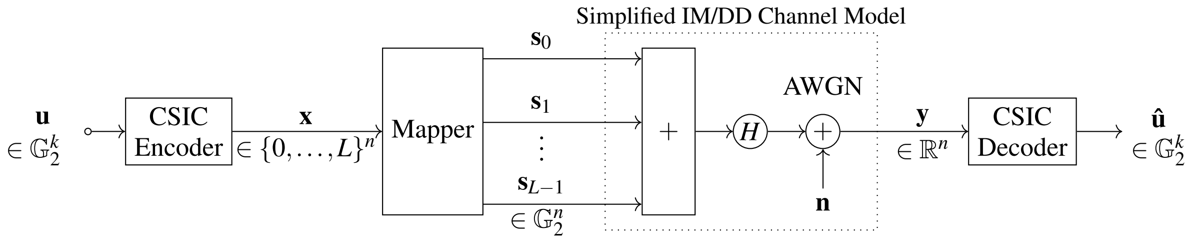

Figure 1: Proposed system model. The block lengths are denoted in the exponent of the variable names.

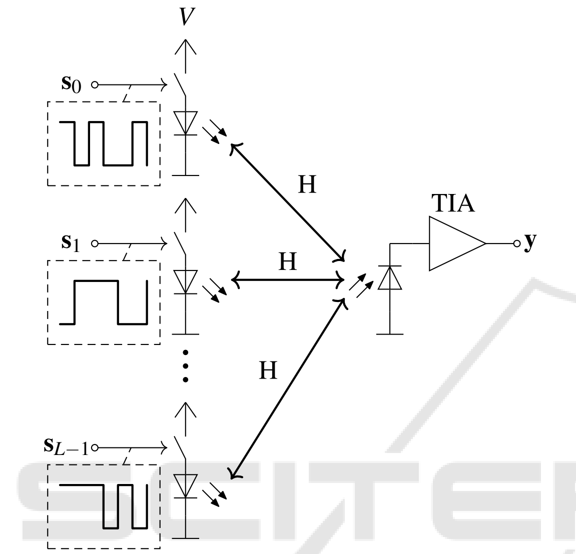

Figure 2: Transmitter configuration for binary intensity superposition modulation using L light sources and a single direct-detection receiver (represented by a photodiode with transimpedance amplifier). The optical signals superimpose at the receiver, weighted by the channel gain H.

additive white Gaussian noise (AWGN) is assumed:

$$\mathbf{y} = H \sum_{l=0}^{L-1} \mathbf{s}_l + \mathbf{n}\,. \tag{1}$$

In the field of mass storage technology it is common to match symbol sequences to the physical limitations of the storage hardware. Similarly we match binary sequences to the limitations of light sources, namely the restricted dynamic behavior caused by their junction capacities. Each individual LED sequence $\mathbf{s}_l$ is therefore constrained with $(d_0|d_1)$, where d_0 is the minimum number of slots the LED is hold in state "off" and d_1 is the minimum number of slots the light source has to remain in state "on". A corresponding graph is exemplarily given in Fig. 3. E.g. GaN-based LEDs (Kishi et al., 2014) exhibit high depletion capacities that lead to slower $1 \to 0$ than $0 \to 1$ transitions. This can be taken care of by setting $d_0 > d_1$.

In the following, we assume that each light source is individually binary-modulated employing a $(d_0|d_1)$ constrained sequence $\mathbf{s}_l$. The evolving superimposed signal is denoted as $(d_0|d_1)^L$ and a graph representation of permissible sequences $\mathbf{x}$ is exemplarily shown in Fig. 4. A corresponding signaling example is depicted in Fig. 5, including a measurement result for a receive signal using three LEDs and a single direct-detection receiver.

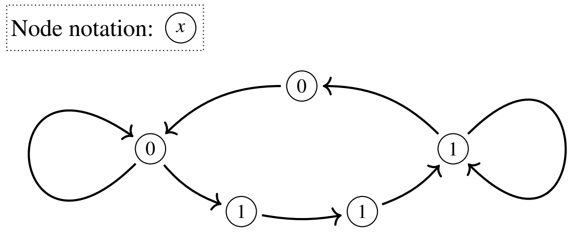

Figure 3: State diagram of a single $(2|3)$ constrained light source. The number of minimum "off" slots is $d_0 = 2$ and the minimum number of "on" slots is $d_1 = 3$.

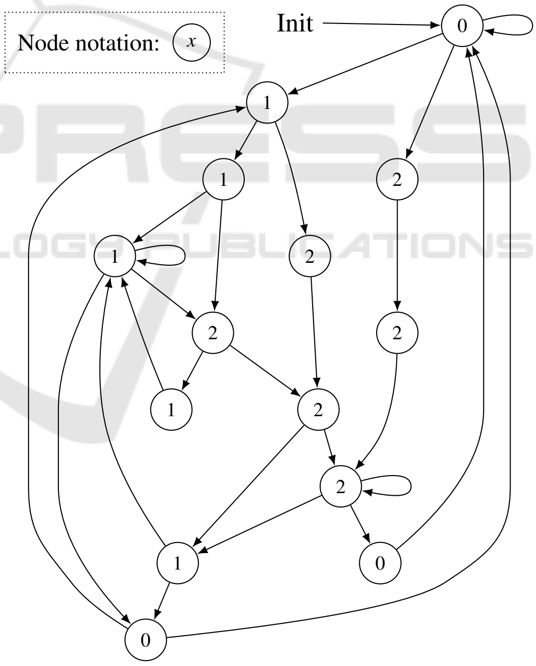

Figure 4: State diagram for $(2|3)^2$-CSIM, when superimposing two $(2|3)$ constrained sequences.

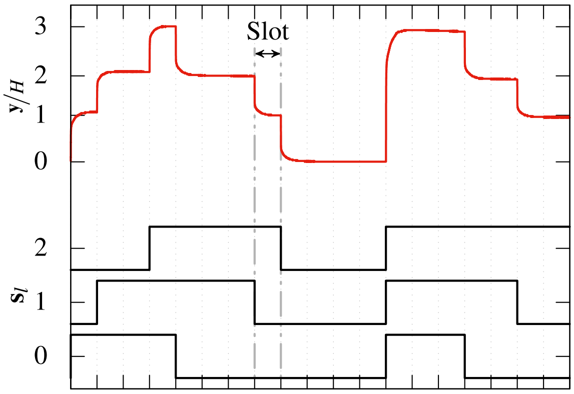

Figure 5: Example for $(2|3)^3$-CSIM signaling with individually constrained switching sequences $\mathbf{s}_l$, $l = 0, \ldots, 2$ and the measured receive signal $\mathbf{y}$ at a comparatively high signal-to-noise ratio.

With the CSIM construction it is possible to reduce the modulation bandwidth limitations of binary-type IM/DD modulation formats. Following Shannon's famous Mathematical Theory of Communication (Shannon, 1948), we can analytically derive the constrained capacity from the CSIM graph description. This is the capacity of a noiseless channel, where $N(T)$ is the number of admissible sequences of length T:

$$C = \lim_{T\to\infty} \frac{\log N(T)}{T}\,. \tag{2}$$

From now on we use a $(5|5)^5$-CSIM superposition modulation format with a constrained capacity of

$$C_{(5|5)^5\text{-CSIM}} \approx 1.55\,\text{bit}/\text{slot} \tag{3}$$

as an example, and OOK modulation as reference system. Regarding the light source switching requirements, OOK is thereby equalized to $(5|5)^5$-CSIM by setting the symbol duration of OOK to five slots, leading to a constrained capacity for OOK of

$$C_{\text{OOK}} = {}^{1}\!/\!{}_{L}\,\text{bit}/\text{slot} = 0.2\,\text{bit}/\text{slot}\,. \tag{4}$$

Thus the constrained capacity is increased by a factor of

$$\frac{C_{(5|5)^5\text{-CSIM}}}{C_{\text{OOK}}} \approx 7.75 \tag{5}$$

using the selected CSIM example.

In terms of power efficiency of the transmitter we use the number of switching operations necessary to encode one source bit as figure of merit. This is reasonable since the switching elements, typically *field-effect transistors* (FETs), exhibit no significant loss in DC operation when compared to the state transition phases. Additionally the junction capacities of the LEDs have to be charged or depleted for each state

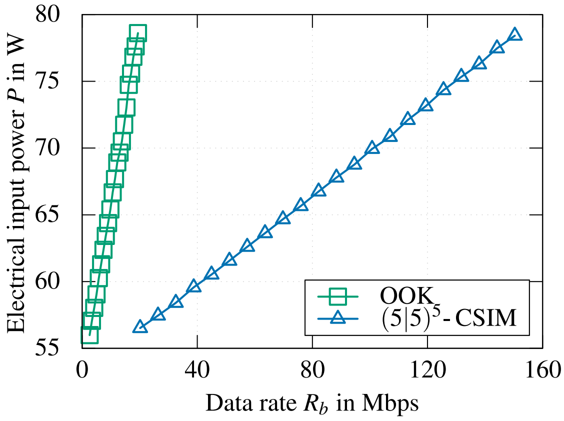

Figure 6: Measurement result on rate dependent transmitter-side power consumption.

transition consuming additional power. The power consumption of each switching operation is equal to the energy stored in the capacitors:

$$E = \frac{1}{2} C V^2\,. \tag{6}$$

Thus the overall transmitter-side power consumption is proportional to the number of switching operations per source bit. For a fair comparison, we assume the transmitter to consist of L light sources both for CSIC and OOK. In the case of OOK, with a probability of one half all light sources have to change their state to encode one source bit of an uniformly distributed random sequence, which leads to $L/2$ switching operations per bit. The analytic results show a reduction in the amount of required switching operations per bit from 2.5 for OOK to about 0.4 for CSIM, when $L = 5$ light sources are used. Effectively this is a reduction of the switching-dependent power consumption by a factor of approximately $2.5/0.4 = 6.25$ while preserving the data rate of the system.

Measurement results of the transmitter power consumption, supporting this reasoning, are shown in Fig. 6. In our lab setup we use five blue-colored LED arrays, each one supplied with 42.5 V at a current of 500 mA. The light sources are biased with 24 V to reduce the energy required for changing the output states. With this setup a reduction of the power consumption from 79.3 W to 56.5 W at a data rate of 20 Mbps (compare Fig. 6) is realized by using CSIM as replacement for OOK. This translates to a receiver-side SNR improvement of 2.94 dB in the electrical domain. By removing the static power-consumption of 52 W we can show that CSIM reduces the switching-dependent power consumption from 27.3 W to 4.5 W. This is a reduction by a factor of 6.07, and reasonably close to the analytic result of 6.25 and thus supports that power consumption in the transmitter is proportional to the number of switching operations per source bit.

3 CODING ON CONSTRAINED SEQUENCES

Having introduced a graph-based representation of the constrained optical superposition transmitter, we now adapt a block coding scheme originally developed in the mass storage community. The recursive elimination algorithm by Franaszek (Franaszek, 1968; Franaszek, 1969) provides a mapping from the binary input sequences $\mathbf{u}$ to the modulation sequences $\mathbf{x}$. The algorithm is able to identify a subset of the original system states, called *principal states* q_i, $i = 0, \dots, Q-1$, given the CSIM state-transition matrix D^n. The requirement for a valid code is that each code word set $W(q_i)$ contains $\geq 2^k$ code words of length n. If a state does not satisfy the condition, it is eliminated and the condition gets rechecked, until either all states have been eliminated or until a valid set of principal states has been found. If more than 2^k codes are in one set we remove the code words with the worst Euclidean distance profile in an iterative process. The resulting CSIC code is state-dependent. The code rate k/n is defined as the number of source bits k mapped to one symbol block with a duration of n slots. It is smaller or equal than the CSIM constrained capacity.

We have chosen a coding scheme with rate $1.25\,\mathrm{bit/slot}$ for the $(5|5)^5$-CSIM example, mapping $k = 5$ source bits onto $n = 4$ symbol slots. The short block length results in some rate degradation compared to the maximum possible capacity of approximately $1.55\,\mathrm{bit/slot}$ for CSIM, but it offers encoding/decoding with relatively low complexity and low memory footprint with a requirement of $Q = 1680$ principle states and $2^k = 32$ admissible code words per state.

Mapping the code words, i.e. the output symbols $\mathbf{x}$ to switching sequences $\mathbf{s}_l$, is done by symbol-wise evolving the light sources output states while following the per light source constraints. For performance reasons $\mathbf{s}_l$, $l = 0, \dots, L-1$, can be computed offline and used in the transmitter as replacement for the code words $\mathbf{x}$, effectively joining the CSIC encoder and the mapper. By this method, we are able to implement a purely lookup-table based encoder.

Decoding is performed using maximum-likelihood (ML) decoding according to

$$\hat{\mathbf{u}} = \underset{\mathbf{u}}{\operatorname{argmax}} \left(y - W_{\mathbf{u}} \left(q_i \right) \right),$$

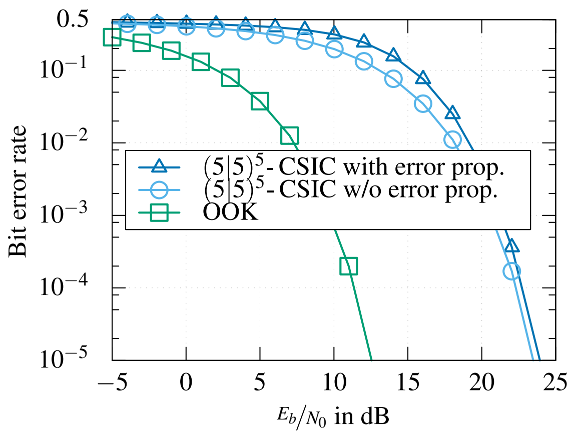

Figure 7: Simulation results using five constrained light sources. The triangle-style CSIC curve represents the “real-world” decoder performance (including error propagation effects), while for the circle-style CSIC curve perfect receiver-side knowledge of the system state q is assumed.

were q_i is the previous system state and $W_{\mathbf{u}}(q_i)$ is the code word from the set $W(q_i)$ assigned to the source word $\mathbf{u}$. This typically leads to error propagation due to the state dependency. The *bit error rate* (BER) results in Fig. 7 show that both curves with and without the error propagation are converging at low BER values.

Finally we use the Monte Carlo simulation results to evaluate the performance of CSIC. Specifically we compare the developed $(5|5)^5$-CSIC system to OOK. We have shown before that CSIM is superior to OOK in terms of constrained capacity and transmitter-side power consumption. As penalty, power efficiency is reduced by 11.4 dB at a bit error rate of 10^{-5}, cf. Fig. 7. This degradation is partly mitigated by the transmitter-side power savings.

4 CONCLUSIONS

In this work, we present a superposition IM/DD scheme, where multiple binary-modulated light sources are combined to boost the data rate. For this superposition of individually constrained switching sequences a graph-based representation is introduced. Based on an example using five light sources we achieve a capacity boost of almost factor eight, and at the same time we are able to reduce the transmitter-side power consumption by a factor of six. Noteworthy the transmitter-side power savings are of particular importance in practical *visible-light communication* (VLC) scenarios, where high optical output powers are required for the purpose of illumination. The receiver-side SNR penalty may be of minior interest in many scenarios. Furthermore, a block coding scheme is adapted to this communication scenario and its feasibility is supported by bit error rate simulations and measurements.

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