Cyclic code-shift extension keying for multi-user optical wireless communications

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Cyclic code-shift extension keying for multi-user optical wireless communications

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An optical code-division multiple access (OCDMA) scheme based on cyclic shift extension of a base code is proposed to enable asynchronous multi-user optical wireless communications for very populated scenarios. This multiple access method is convenient for low–medium data rate communications of a large number of simultaneous transmitters. An expression to obtain a tight upper bound of the bit-error probability of the new scheme is provided which is also confirmed by experimental results. A variant of the proposed communication method which allows the encoding of several bits per symbol is also presented, although its analysis demonstrates that the first simpler strategy reaches similar performance with a significantly lower receiver complexity.

Introduction: In the past years, many research efforts on visible light communications (VLCs) have been oriented to the multi-user communication issue [1–4]. The preferred multiple access methods for VLC are frequency-division [1], colour-shift keying [2] and optical code-division multiple access (OCDMA). However, the implementation of the first two schemes is usually complex and/or they are only feasible for a limited number of users. OCDMA is inherently simpler and it is able to accommodate a large number of users [3, 4].

In [3], an OCDMA scheme which provides high-data rates by multi-level signalling in a synchronous scenario is presented mainly for the VLC downlink. When synchronous transmission is infeasible or impractical, a system which can deal with asynchronous communications is required. In [4], a very simple OCDMA scheme based on random optical codes [5] is proposed for asynchronous multi-user communications for low–medium data rates. Asynchronous communications are enabled by incorporating a synchronisation preamble prior to transmitting data. However, from [5] we can see that a bit-error rate (BER) below 10^{-4} requires code lengths $L > 10 \times s$, where s is the number of simultaneous users and L is the number of slots (chips), in which the bit-transmission interval is divided. Moreover, effective synchronisation preambles must last $m \times L$ chips, with $m \geq 3$ [6]. Therefore, a large number s of users requires a large L with an increasing synchronisation complexity. Additionally, any subsequent chip-desynchronisation or bad synchronisation would make the system incur an uncontrollable burst of errors. In this Letter, we propose a new codification method which works with shorter codes and enables improved performance by extending the base code with cyclic shifted replicas of itself. This cyclic code-shift extension (CCSE) also provides auto-synchronisation capability, thus preventing bursty errors. A multi-bit variant is also evaluated to enable higher data rates.

System description: In typical OCDMA schemes, each user is assigned a different code where only w out of L positions is occupied by pulses. The parameter w is the weight of the code and L its length. Note that each pulse lasts $T_c = T/L$ in the bit-transmission interval T. When a specific user needs to transmit a bit '1', it sends its code, whereas no signal is transmitted for data bits '0'. There exist good optical codes, such as orthogonal optical codes [7], with good correlation properties but whose implementation is difficult for a large number of users. However, random optical codes [5] are easily generated and their poor correlation properties can be combated by the CCSE method as detailed below.

An error detection is caused when the w specific positions of a user code are occupied by pulses from other interfering users although it had transmitted no signal (data bit '0'), thus making its corresponding receiver erroneously demodulate a data bit '1'. However, if the base code is extended by a cyclic shifted code replica, where this shift (number of chips to cyclically shift) is different for each user, the interfering pattern would not be likely to affect the new w positions of this extension, thus avoiding the error detection. Annexing additional code extensions, each with a different shift, makes the OCDMA scheme even robuster. The proposed CCSE keying and its ability to avoid erroneous decoding when the desired user 1 transmits either data bit '1' or '0' is depicted in Fig. 1. Each new code extension is cyclically shifted $i \times l$ chips with respect to its preceding extension for the ith user and the lth CCSE($1 \leq i \leq s$, $0 \leq l \leq E$ where $l = 0$ corresponds to the base code and E is the number of applied code extensions). The length and weight of the new code sequence are now $(1 + E)$ times those of the base code. As illustrated in Fig. 1, the sequences are demodulated by a synchroniser composed of a shift register which looks for the specific $w \times (1 + E)$ positions of the code sequence by evaluating the last $L \times (1 + E)$ received chips. Therefore, totally asynchronous transmission is supported and, moreover, the receiver automatically synchronises with its corresponding transmitter after each new data bit '1' is received.

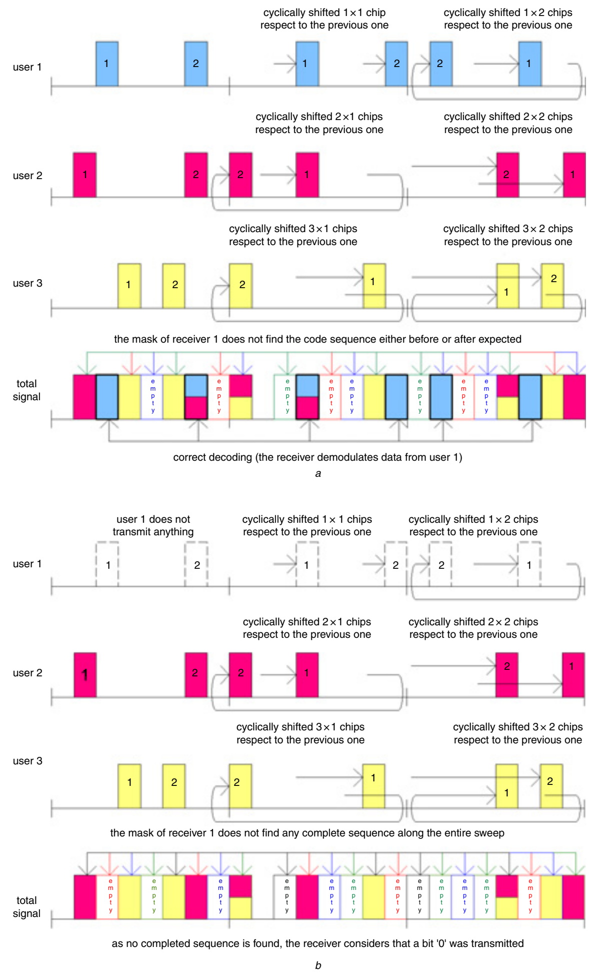

Fig. 1 *Illustration of proposed CCSE scheme and its efficiency to avoid 'false detections'*

Example for $s = 3$ users, $E = 2$ code extensions and base-code parameters $L = 8$ and $w = 2$ (time instants when synchroniser checks channel are symbolised with different colours)
a Transmission of bit '1'
b Transmission of bit '0'

From [5], we can see that the optimum weight for codes with length $L \leq 150$ is $w = 3$ for $(1/3)L \leq s \leq (1/2)L$. Moreover, from [5, 6] a tight upper bound for error bit probability P_e of the new proposed scheme can be inferred:

$$P_e \lesssim \frac{1}{2^s} \sum_{i=0}^{s} \binom{s}{i} \left[1 - \left(1 - \frac{w}{L}\right)^i\right]^{w(E+1)} \qquad (1)$$

Note that the previous P_e estimation only depends on the number s of simultaneous users, the parameters of the code L and w and the number E of code extensions. From (1), it is found that error probabilities of approximately or below 10^{-3} can be obtained for $E \geq 2$ when $s \leq (2/5)L$. Thus, for $L = 50$ we can accommodate up to $s = 20$ users with an acceptable error probability by extending the base code at least twice.

It is possible to accommodate k bits per transmitted symbol by assigning $M = 2^k$ different codes to each user, each code representing a specific word of k bits. As now every user is compelled to transmit a code sequence to symbolise a specific bitword, from (1) it is deduced that, for the same $w_v = w$, the new base-code length has to be doubled, $L_v = 2L$, so as to make scheme for $k = 1$ hold similar error performance,

$P_S^{(k=1)} \simeq P_e$. Moreover, now we require M different synchronisers (decoders), thus the symbol error rate of this 2^k-CCSE keying is given by $P_S^{(k)} = 1-(1-P_S^{(k=1)})^{M-1} \simeq (M-1)P_e$ for $P_e \ll 1$, since $(1-P_S^{(k=1)})^{M-1}$ represents the joint probability that no decoder, different from that associated to the transmitted symbol, erroneously detects its corresponding code sequence. Finally, if we apply the symbol error-to-bit error relationship for orthogonal signalling, we have for the BER $P_B^{(k)}$ for 2^k-CCSE keying

$$P_B^{(k)} = \frac{2^{k-1}}{2^k-1}P_S^{(k)} \simeq \frac{M/2}{M-1}(M-1)P_e = \frac{M}{2}P_e \qquad (2)$$

Results: Several experiments have been performed on a prototype similar to that of [4] for 2 m range wireless optical communications, where all the digital logics (OCDMA encoders and decoders, modules for communications with computers and so on) were developed on Xilinx Virtex-5 field programmable gate arrays. In the trials, a much collapsed scenario was evaluated (worst case), where all the active transmitters were sending random data continuously (with short random delays between consecutive frames, different to each user, to emulate asynchronous communication). The chip rate was $R_c = 1/T_c = 12.5$ Mcps, leading to a maximum data rate per channel of 83 kbit/s (maximum aggregate data rate of 1.67 Mbit/s for $s = 20$ users).

Fig. 2 compares analytical predictions given by (1) with the experimental results obtained for a base code with parameters $L = 50$ and $w = 3$, and different code extensions E. The good agreement between these results for all the cases confirms that (1) constitutes an effective tool to design in advance the code characteristics to accomplish the specific performance requirements. The system was also tested for the transmission of high-quality digital audio data by several simultaneous communication channels with very satisfactory results.

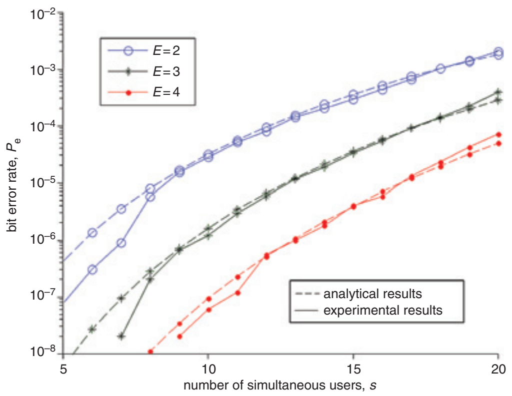

Fig. 2 *Comparison of analytical and experimental results for code-parameters L = 50 and w = 3 and different code extensions E*

Table 1: Comparison of different 2^k-CCSE schemes ($L_v = 2L = 100$, $w_v = w = 3$) with basic CCSE keying (R_0 refers to data rate of basic scheme)

E	k	1	2	3	4	5	6
2	E_v	2	3	3	3	4	4
3		3	4	4	4	5	5
4		4	4	5	5	6	6
2	R_v/R_0	0.5	0.75	1.125	1.5	1.5	1.8
3		0.5	0.8	1.2	1.6	1.67	2
4		0.5	1	1.25	1.67	1.79	2.14

Finally, the proposed 2^k-CCSE scheme was also experimentally evaluated. Table 1 shows the code extension E_v required by the multi-bit encoding strategy to obtain a similar error performance to that of the previous basic scheme. The achievable data rate gain (R_v/R_0) with this new scheme is also presented. We can see that the data rate enhancement is not especially significant considering the increase of the receiver complexity (M decoders against only one required by the basic method). In fact, 2^k-CCSE keying throughput does not always exceed that of the basic scheme when seeking a similar error performance. Thus, for example, for $E = 2$, $k \geq 3$ is required so as to improve basic CCSE keying performance. Moreover, for a complex scheme with $k = 6$ ($M = 64$ decoders per user), the achievable data rate scarcely doubles that of the significantly simpler basic scheme.

Conclusion: CCSE keying has been proposed to enable asynchronous multi-user optical wireless communications for scenarios where achieving high-data rates is not a major issue but allowing a large number of users to perform simultaneous asynchronous transmission is imperative. The proposed scheme is also characterised by its simplicity and total reconfigurability to the required error performance and number of simultaneous users. Moreover, the system is able to automatically resynchronise after receiving each new data bit '1'. An analytical expression to determine in advance the system performance of the given environmental conditions has also been presented, which allows us to easily define the system parameters to eventually accomplish design requirements. The experimental results obtained with a prototype for medium-range optical wireless communications have confirmed the validity and usefulness of the given theoretical expression. Finally, a variant of this basic CCSE keying which encodes several (k) bits per transmitted symbol, thus providing higher-data rates, has been described. However, the evaluated results show that the enhancement in achievable data rates is not clearly significant with respect to the basic method when considering the complexity increase required by this new 2^k-CCSE strategy. Therefore, we can conclude that the basic CCSE scheme constitutes a good trade-off between simplicity and achievable data rates for asynchronous multi-user optical wireless communications.

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One or more of the Figures in this Letter are available in colour online.

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