Complementary Sequence Inverse Keying for Dispersive Indoor Wireless Infrared Channels

K K Wong† and T O'Farrellr‡

† Intel Corporation, Malaysia, ‡ University of Leeds, UK

Abstract: Complementary Sequence Inverse Keying is proposed to ameliorate multipath ISI effects in an indoor wireless infrared communication system. The method involves the transmission of a pair of complementary binary sequences. The system BER performance is presented in comparison with OOK and the results demonstrate that CSIK, unlike OOK, does not incur a power penalty due to ISI.

1 Introduction.

Direct sequence spread spectrum (DSSS) techniques have been shown to be effective against multipath dispersion in an infrared (IR) channel without the need for complex signal processing or expensive optical configurations [1]. Analysis of these DSSS IR systems revealed that the penalties attributable to multipath ISI are the consequence of non-zero sidelobes of the aperiodic auto- and cross-correlation functions (ACFs and CCFs) of the spreading sequences used. When an m-sequence is used in a binary DSSS IR system, the power penalty may be minimised by selecting an initial phase of the sequence that gives small aperiodic ACF sidelobes. To obtain good system performance in severe multipath conditions, the technique requires the use of long spreading sequences which in turn limits the achievable data rates.

To overcome the afore-mentioned problems, an alternative binary DSSS technique for indoor IR channels is proposed in this paper called Complementary Sequence Inverse Keying (CSIK). By simultaneously transmitting a binary complementary pair (BCP) of sequences, the sidelobes of the aperiodic ACFs and CCFs of the complementary sequences sum to near zero at the correlator outputs, which almost completely removes ISI due to multipath dispersion. The result is achieved using short spreading sequences. By removing ISI using a short BCP, higher data rates can be achieved on the indoor wireless IR channel.

2. Binary Complementary Sequences.

A binary complementary pair of sequences of length N is denoted by $\boldsymbol{S}_{2,N} = \{S_1, S_2\}$, where the m-th sequence, $S_m = (s_{m,1}, s_{m,2}, \ldots, s_{m,N\text{-}1})$ is bipolar with elements $s_{m,n} \in \{+1, -1\}$. A BCP is characterised by the property that the aperiodic ACFs of the component sequences sum to zero for all time shifts except zero shift as defined in (1), where $C_{S_m}(l)$ is the discrete time aperiodic AFC of S_m and l is the discrete time shift [2].

$$C_{S_1}(l) + C_{S_2}(l) = \begin{cases} 2N & l = 0 \\ 0 & l \neq 0 \end{cases} \tag{1}$$

Though the sequences of a BCP are orthogonal, the aperiodic CCFs do not necessarily sum to zero for all shifts as indicated in (2), where $\Re$ denotes the set of all real numbers. $C_{S_mS_j}(l)$ is the discrete aperiodic CCF of S_m with S_j and though $C_{S_mS_j}(l) \neq C_{S_jS_m}(l)$, their sum is a symmetric function.

$$C_{S_mS_j}(l) + C_{S_jS_m}(l) \begin{cases} = 0 & \text{if } l = 0 \\ \in \Re & otherwise \end{cases} \tag{2}$$

The summed CCFs may possess two useful properties in respect of signalling on an indoor wireless IR channel. Firstly, it may exhibit a zone of zero sidelobes on either side of the l = 0 shift referred to as a zero-correlation-zone (ZCZ). Unlike the summed ACFs, the ZCZ does not extend for all shifts l, but like the summed ACFs it removes ISI due to dispersion. As the multipaths within this zone tend to be large, then a substantial amount of ISI is removed. Secondly, the summed CCFs may exhibit a region of all positive sidelobes on either side of the l = 0 shift referred to as a positive-correlation-zone

(PCZ). Again, the zone does not extend for all shifts l. The positive sidelobes lead to constructive ISI which enhances the signal energy detected. This second property is exploited in this paper, resulting in a slightly enhanced BER performance compared with AWGN for the multipath channels studied.

3. Complementary Sequence Inverse Keying Modulation.

CSIK is based on the concept that the sequences in a BCP modulated by the same data bit are transmitted simultaneously. The received signal is correlated with the same BCP. The correlator outputs are summed, resulting in the total cancellation of the aperiodic ACF sidelobes and the partial cancellation of the aperiodic CCFs sidelobes. In a multipath channel, the degree by which the ISI is reduced depends on how much of the CCF sidelobes cancel, which depends on the type and length of the BCP used.

A schematic of the CSIK scheme is illustrated in Figure 1 [3]. At the transmitter, a sequence of bipolar binary rectangular data bits each of duration T_b, denoted as $b(t)$, sequence inverse key a BCP denoted generally as $\boldsymbol{S}_{2,N} = \{S_1, S_2\}$ where N is the length of each sequence. The m-th sequence in the pair is denoted by $S_m = (s_{m,0}, s_{m,1}, \ldots s_{m,n}, \ldots s_{m,N-1})$ where $s_{m,n} \in \{+1, -1\}$ constitutes a chip of the sequence.

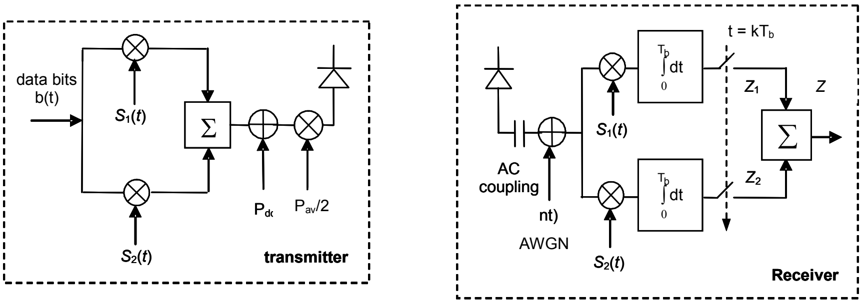

Fig. 1: Schematic of CSIK Transmitter and Receiver.

Assuming unit amplitude rectangular pulse shaping Γ(t) for the chips, the m-th sequence is represented by a sequence waveform $S_m(t)$ as expressed in (3). The duration of N chips in one period of the complementary sequence is equal to the bit duration such that $T_b = NT_c$. The modulated sequences are summed and a DC offset $P_{dc} = 2$ is added to ensure that the transmitted signal is positive at all times. The unipolar signal is then scaled by a factor of $P_{av}/2$ where P_{av} is the signal mean optical power. This offset and scaling process realises the bipolar-to-unipolar mapping described in [1]. The transmitted signal $X(t)$ is expressed in (4) where $q(t)$ is a constant unit amplitude signal.

$$S_m(t) = \sum_{n=0}^{N-1} s_{m,n}\Gamma(t - nT_c) \tag{3}$$

$$\begin{aligned} X(t) &= \frac{P_{av}}{2}\left[\sum_{m=1}^{2} b(t)S_m(t) + 2q(t)\right] \\ &= \frac{P_{av}}{2}\sum_{m=1}^{2} b(t)\sum_{n=0}^{N-1} s_{m,n}\Gamma(t - nT_c) + P_{av}q(t) \end{aligned} \tag{4}$$

In DSSS, the duration of a chip pulse may be comparable to the *rms* delay spread of a LOS or diffuse multipath channel and hence the delayed multipaths are resolved. The continuous time IR channel impulse response (CIR) can be meaningfully represented by an equivalent discrete-time channel [3] which simplifies the system study. The equivalent multipath channel with a total number of L resolved multipaths can be represented by (5) where β_l and $\tau_l = lT_c$ are the relative optical power and time delay of the l-th resolved multipath, respectively.

$$h(t) = \sum_{l=0}^{L-1} \beta_l \delta(t - \tau_l) \tag{5}$$

At the receiver, the detected photocurrent $Y_{ac}(t)$ after AC coupling, consists of the LOS signal $X(t)$, the delayed components $X(t - \tau_l)$, and the channel noise process $n(t)$, which is modelled as zero-mean

AWGN with two-sided power spectral density $N_o/2$. An expression for $Y_{ac}(t)$ is given in (6) where R is the responsivity of the photodiode.

$$Y_{ac}(t) = \frac{RP_{av}}{2}\sum_{l=0}^{L-1}\beta_l \sum_{m=1}^{2} b(t-\tau_l)S_m(t-\tau_l) + n(t) \tag{6}$$

$Y_{ac}(t)$ is despread by multiplying with the same bipolar BCP, integrating over one data bit duration T_b and sampling at intervals of T_b to produce Z_1 and Z_2 at the outputs of the two correlators. Z_1 and Z_2 are then summed to produce the detection metric Z (see Fig. 1). An expression for the j-th correlator output Z_j is given in (7) and consists of four terms. The first term is due to the LOS signal, the second term is the interference caused by the delayed sequence $S_j(t)$ at the j-th correlator, the third term is the interference from the other delayed sequence and the last term n_j is the Gaussian noise component at the correlator output.

$$\begin{aligned} Z_j = {} & \frac{\beta_0 RP_{av}}{2T_b}\int_0^{T_b}\sum_{m=1}^{2} b(t)S_m(t)S_j(t)dt + \\ & \frac{RP_{av}}{2T_b}\int_0^{T_b}\sum_{l=1}^{L-1}\beta_l b(t-\tau_l)S_j(t-\tau_l)S_j(t)dt + \\ & \frac{RP_{av}}{2T_b}\int_0^{T_b}\sum_{l=1}^{L-1}\beta_l \sum_{m=1, m\neq j}^{2} b(t-\tau_l)S_m(t-\tau_l)S_j(t)dt + n_j \end{aligned} \tag{7}$$

Data bits '+1' and '-1' are declared for positive and negative Z, respectively. Due to the aperiodic ACF property defined in (1), the second term in (7) equals zero for all resolved multipaths. Due to the aperiodic CCF property defined in (2), the third term in (7) equals zero for $l = 0$, while for $l \neq 0$ advantage is taken of the PCZ and partial cancellation properties of the summed CCFs to ameliorate ISI effects. In the absence of multipath, the BER performance is given by (8) [3]. Compared with OOK, in AWGN CSIK incurs an E_b/N_o penalty of 1.76 dB due to the BCP signalling format.

$$BER = Q\left(\sqrt{\frac{2E_b}{3N_o}}\right) \tag{8}$$

4. Results

In this section, the BER performance of CSIK is evaluated in comparison with OOK for indoor non-directed LOS IR dispersive channels. The non-directed LOS IR channel configuration consists of an empty 10×10×3 m (W×L×H) rectangular room. The locations and directionalities of a transmitter and receiver pair are specified in terms of Cartesian co-ordinates (x, y, z) with the origin (0, 0, 0) located at the (left, front, bottom) corner of the room. The x, y, z axes point to the right, into the page and up the page, respectively. The transmitter is located at (5m, 5m, 3m) pointing downwards while the receiver is located at (1.25m, 1.25m, 0m) pointing upwards. The room surfaces were assigned a reflection coefficient of 0.8. The IR source is assumed to have a Lambertian radiation pattern of mode 1 and the field-of-view, area and the responsivity of the photodiode are 180°, 1 cm^2 and 1 A/W, respectively. The CIR for up to 3 reflections was obtained using the simulation model of [4]. Based on a chip resolution T_c and a BCP of length 8, the equivalent discrete CIRs for data rates of 10 and 20 Mbit/s are listed in Table 1 [3]. The relative power in the first resolved multipath β_0 is normalised to unity so as to correspond to the LOS path.

Bit rate (Mbit/s)	Chip resolution T_c (ns)	Multipath Amplitudes for chip resolution T_c								
		β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8
10	12.50	1	0.62	0.30	0.13	0.04	0.01	0.01		
20	6.25	1	0.35	0.38	0.46	0.26	0.14	0.11	0.07	0.03

Table 1: Discrete IR Channel impulse responses for data rates 10 and 20 Mb/s.

Figure 2 shows simulated BER versus E_b/N_o curves for CSIK obtained using the length 8 BCP S_1 = (1,1,1,-1,1,-1,1,1) and S_2 =(1,1,-1,1,1,-1,-1,-1). The curves correspond to an AWGN channel and the 10 Mbit/s and 20 Mbit/s multipath channels of Table 1. Also plotted in Figure 2, for the same channel conditions, are simulated BER versus E_b/N_o curves for OOK. The simulated BER curves for OOK were verified by the analysis in [1]. The CSIK curve for AWGN agrees with (8) and confirms the 1.76 dB E_b/N_o penalty incurred by CSIK compared with OOK. However, in the 10 Mbit/s multipath channel, the CSIK curve marginally improves on its AWGN performance, while the OOK curve incurs a 2 dB E_b/N_o penalty compared with its AWGN performance. In the 20 Mbit/s multipath channel, the CSIK curve shows a slight further improvement while the OOK curve incurs an 8.5 dB E_b/N_o penalty compared with its AWGN performance. The latter result demonstrates the data rate limitation in OOK due to multipath ISI which is not present in the proposed CSIK scheme even though the power in delayed paths are as large as 62% of the LOS path. All E_b/N_o penalties are measured at 10^{-6} BER.

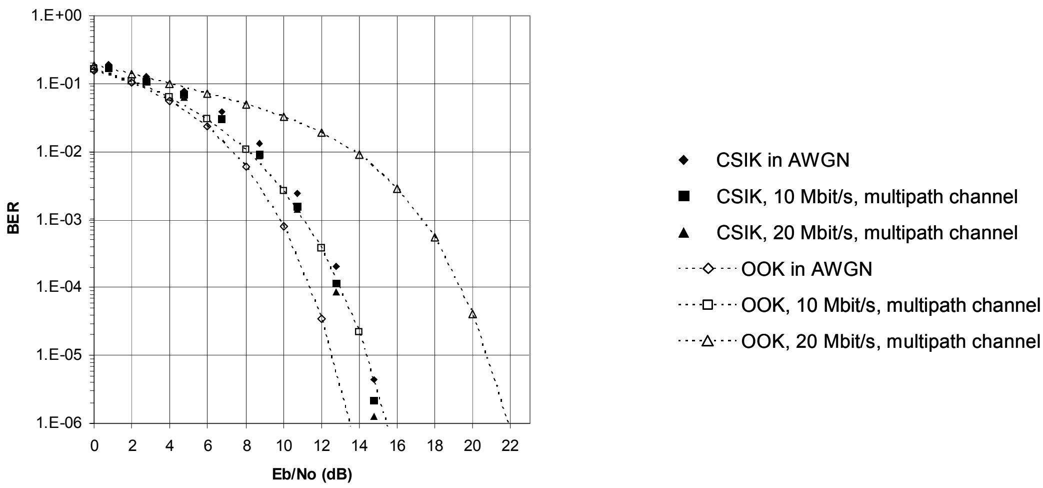

Fig. 2: BER against E_b/N_o for CSIK and OOK in AWGN and multipath channels for data rates 10 and 20 Mb/s

6. Conclusions.

The BER performance of CSIK has been evaluated in comparison with OOK for the indoor wireless IR channel. The results demonstrate that CSIK, unlike OOK, does not incur a power penalty due to multipath ISI. By using a BCP for which the sum of the aperiodic ACFs and CCFs is near impulsive, multipath ISI is almost completely removed. Further, by exploiting a BCP with a positive-correlation-zone, constructive ISI is obtained leading to a BER enhancement over the AWGN case. CSIK using short spreading sequences removes the limitation on data rate caused by multipath ISI. Improving the bandwidth efficiency of DSSS schemes based on complementary sequences is the subject of further research by the authors.

References.

[1] Wong, K.K., O'Farrell, T. and Kiatweerasakul, M.: 'Infrared wireless communication using spread spectrum techniques', IEE Proc. on Optoelectron., 2000, 147, (4), pp. 308-314

[2] Fan, P. and Darnell, M.: 'Sequence Design for Communications Applications', Research Studies Press Ltd., Somerset, U.K., 1996

[3] Wong, K.K. "Bandwidth efficient modulation techniques for spread spectrum based wireless infrared transmission", Ph.D. Thesis, University of Leeds, 2001

[4] Barry, J.R., Kahn, J.M., Krause, W.J., Lee, E.A. and Messerschmitt, D.G.: 'Simulation of multipath impulse response for indoor wireless optical channels', IEEE Journal on Sel. Areas in Comm., 1993, 11, (3), pp. 367-379