Infrared Wireless Communications using Complementary Sequence

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Abstract: The performance of an infrared wireless system using direct sequence spread spectrum techniques in multipath channels depends very much on the partial correlation properties of the spreading sequences used. Ideally, a spreading sequence should have zero sidelobes in its periodic and aperiodic auto-correlation functions in order to eliminate multipath dispersion. Unfortunately, no such ideal sequence exists in the binary field. In this paper, a new spread spectrum based binary modulation scheme is proposed in which a set of complementary sequences is transmitted simultaneously such that the sum of their aperiodic auto-correlation and cross-correlation functions are impulsive or near impulsive. The system modelling and bit error rate analysis is presented. Results show that the new scheme is able to remove multipath dispersion almost completely.

1 Introduction

One of the major problems faced by most of the modulation schemes employed in wireless IR communications is multipath dispersion. Various methods such as adaptive equalisation techniques [1], angular and imaging diversity [2] and parallel transmission using multiple sub-carriers [3] have been tested to combat multipath interference. Each of the solutions has its advantages and disadvantages and their effectiveness depends on the modulation scheme used. Direct sequence spread spectrum (DSSS) techniques have been investigated in [4-7] to combat multipath dispersion without relying on the use of complex signal processing and excessive optical components. The penalties incurred in DSSS IR systems are a consequence of non-zero sidelobes of the aperiodic auto-correlation (ACF) and cross-correlation (CCF) functions of the spreading sequences. In a binary DSSS IR system [4,5] that uses an m-sequence as the spreading sequence, the penalties can be minimised by choosing an m-sequence with small aperiodic ACF sidelobes. However, this task is difficult for M-ary orthogonal and biorthogonal DSSS systems [6,7] when a set of sequences is used as the spreading sequences. In this case, both the aperiodic ACFs and CCFs of the sequences need to be taken into consideration. Usually smaller sidelobes of the ACF leads to larger sidelobes of the CCF and vice versa.

In order to overcome the above-mentioned problems, a new DSSS based binary modulation scheme referred to as Complementary Sequence Keying (CSK), which is based on the use of complementary sequences, is proposed. By transmitting a binary complementary pair (BCP) of sequences and its mate simultaneously, the sidelobes of the aperiodic ACFs and CCFs of the transmitted sequences are summed to near zero at the correlator output, hence eliminating multipath interference almost completely. In Section 2, the correlation properties and synthesis procedures of a BCP and its mate are explained. Section 3 covers the system modelling and bit error ratio (BER) analysis of a CSK system. In Section 4, simulated performance of CSK transmitting a BCP and mate of length 4 is presented. Finally, the concluding remarks are given in Section 5.

2 Properties and Synthesis of BCP and Mates

In order to facilitate an understanding of the operation of CSK, it is necessary to first present some essential basic properties and synthesis procedures of a BCP and its mates.

2.1 Properties of BCP and Mates

A pair of binary complementary sequences of the same length N, $S_1 = \{s_{1,n}\}$ and $S_2 = \{s_{2,n}\}$, where n = 0, 1, 2, …, N–1 and the elements of the sequences, $s_{1,n}$, $s_{2n} \in \{+1, -1\}$, is characterised by the property that their aperiodic ACFs [8] sum to zero at every shift except the zero shift where the sum takes the value $2N$ [9] as defined in equation (1) where l is the discrete time shift between the sequences.

$$C_{S_1}(l) + C_{S_2}(l) = 0, \quad l \neq 0 \tag{1}$$

A complementary pair $\boldsymbol{R}_{2,N} = (R_1, R_2)$ is called a mate of another complementary pair $\boldsymbol{S}_{2,N} = (S_1, S_2)$ if the aperiodic CCFs [9] for the corresponding sequences in each pair sum to zero at all time shifts as defined in equation (2). The same result is obtained if the order of the sequences is reversed in the correlation functions. The two pairs are said to be uncorrelated in a complementary sense.

$$C_{S_1R_1}(l) + C_{S_2R_2}(l) = C_{R_1S_1}(l) + C_{R_2S_2}(l) = 0, \quad \text{for all } l \tag{2}$$

2.2 Synthesis of BCP and Mates

The method of synthesising a BCP of length $N = 2^n$ (integer $n \geq 1$) is based on the use of block structures [10]. Two of the block structures is given in equation (3) where A and B are half-length sequence blocks of length $N/2 = 2^{n-1}$. The signs + or – indicate the relative polarity of all the digits in a half-length block, and the arrows → or ← indicate the direction in which all the digits in a half-length block should be read. Block structure 3(a) or 3(b) can be recursively applied in order to generate longer BCPs.

	(a)		(b)	
Sequence 1:	$\rightarrow$(+A)	$\rightarrow$(+B)	$\rightarrow$(+A)	$\rightarrow$ (–B)
Sequence 2:	$\leftarrow$ (+B)	$\leftarrow$ (–A)	$\leftarrow$ (+B)	$\leftarrow$ (+A)

(3)

For example, take as arbitrary "seeds", A = +1, B = +1 and using 3(a):

1st recursion (n = 1)	+1	+1	(A)		2nd recursion (n = 2)	+1	+1	+1	−1	(A)
	+1	−1	(B)			−1	+1	−1	−1	(B)

The inverse of the block structures in equation (3) can also be used to synthesise a BCP. By using the block structure method described above, for $n \geq 2$, the first half of the sequences obtained from the n-th recursion are themselves a pair of complementary sequences, and the second half of the sequences also form a complementary pair, which itself is the mate of the first-half pair. A given BCP has two mates defined by $\boldsymbol{R}_{2,N} = (\Re(S_2), -\Re(S_1))$ and $-\boldsymbol{R}_{2,N} = (-\Re(S_2), \Re(S_1))$ where $\Re(S_j)$ denotes reversing the order of the elements of S_j and $-S_j$ denotes negating the sequence S_j.

3 Complementary Sequence Keying

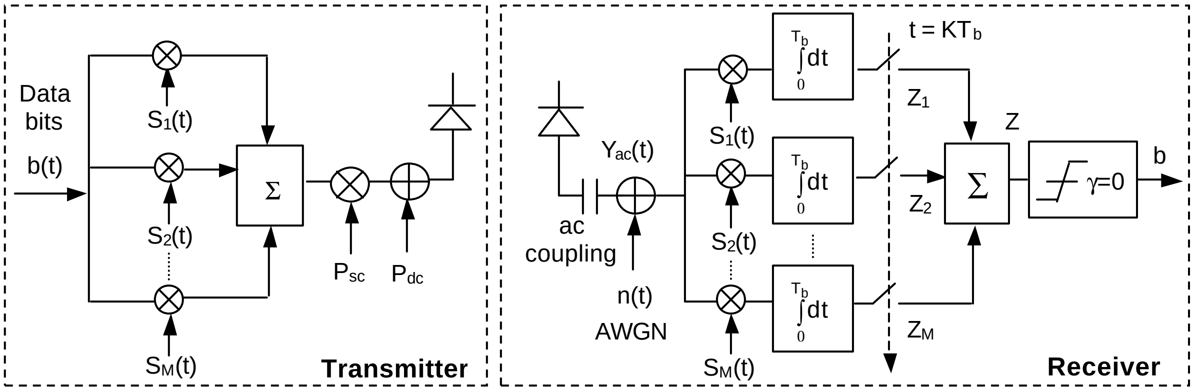

Figure 1 : Schematic diagram of a CSK system.

The schematic diagram of a CSK system is shown in Figure 1. At the transmitter, a sequence of bipolar binary rectangular data bits each of duration T_b, denoted as $b(t)$, is used to modulate a set of 4 periodic sequences of N rectangular chips constructed from a BCP and its mate. The duration of each chip is T_c such that $T_b = NT_c$. The notation for the set of sequences is $S_{4,N} = \{S_1, S_2, S_3, S_4\}$ where $S_m = (s_{m,0}, s_{m,1}, \ldots, s_{m,N\text{-}1})$ is the m-th sequence and $s_{m,n} \in \{+1, -1\}$ is the n-th chip in the m-th sequence. The modulated sequences are summed, scaled by P_{sc} and a dc offset is added to ensure that the transmitted signal is positive at all times.

$$X(t) = P_{sc}\left[\sum_{m=1}^{4} b(t)S_m(t) + P_{dc}q(t)\right] \tag{4}$$

The transmitted signal is expressed in equation (4) where $q(t)$ is a constant unit-amplitude signal. In this scheme, the dc offset is not fixed, but varies on a bit-by-bit basis to maximise the power in the signal component since the IR channel is power limited and the dc term carries no information. If the sum of the modulated BCP and mates, denoted as $\sum S_m$, contains any negative elements when the modulating data is '+1', then the sum of the same set will contain all positive elements for data '-1' and vice versa. DC offset is only added when $\sum S_m$ has any negative elements. This results in for a signal mean optical power of P_{av}, $P_{dc} = 2P_{av}$ and $P_{sc} = P_{av}/2$.

$$Y_{ac}(t) = RP_{sc}b_0 \sum_{m=1}^{4} b(t)S_m(t) + RP_{sc}\sum_{l=0}^{L-1} b_l \sum_{m=1}^{4} b(t-t_l)S_m(t-t_l) + n(t) \tag{5}$$

After undergoing multipath dispersion, the detected photocurrent is ac coupled to remove the dc component to produce $Y_{ac}(t)$ expressed in equation (5) where R is the responsivity of the photodiode and b_l and t_l are the relative power and delay of the resolved multipaths of the equivalent discrete IR channel [4], respectively. The channel noise process $n(t)$ is modelled as zero-mean additive white Gaussian noise (AWGN) with two-sided power spectral density $N_o/2$. The receiver is assumed to be synchronised to the strongest resolved multipath. Without lost of generality, the delay of the strongest resolved multipath, t_0, is set to zero. $Y_{ac}(t)$ is then despread by multiplying with a bank of 4 correlators whose coefficients are the 4 sequences of the set, integrated over T_b duration and sampled at intervals of T_b to produce Z_1, Z_2, Z_3, Z_4 at the outputs of the correlators, which are summed to produce Z as expressed in equation (6).

$$Z = T_b^{-1}\sum_{j=1}^{4}\int_0^{T_b} b_0 RP_{sc}\sum_{m=1}^{4} b(t)S_m(t)S_j(t)dt + T_b^{-1}\sum_{j=1}^{4}\int_0^{T_b} RP_{sc}\sum_{l=1}^{L-1} b_l b(t-t_l)S_j(t-t_l)S_j(t)dt \qquad (6)$$

$$+ T_b^{-1}\sum_{j=1}^{4}\int_0^{T_b} RP_{sc}\sum_{l=1}^{L-1} b_l \sum_{m=1, m\neq j}^{4} b(t-t_l)S_m(t-t_l)S_j(t)dt + T_b^{-1}\sum_{j=1}^{4}\int_0^{T_b} n(t)S_j(t)dt$$

$$= 4b_0 b_0 RP_{sc} + \frac{RP_{sc}}{N}\left(\sum_{l=1}^{L-1} b_l \sum_{j=1}^{4}\left[b_{-1}C_{S_j}(l-N) + b_0 C_{S_j}(l)\right] + \sum_{l=1}^{L-1} b_l \sum_{j=1}^{4}\sum_{m=1, m\neq j}^{4}\left[b_{-1}C_{S_m,S_j}(l-N) + b_0 C_{S_m,S_j}(l)\right]\right) + n_o$$

Z consists of four components. The first term, D_{sig}, is the signal component; the second term, I_{md}, is the interference caused by the delayed sequence correspond to the despreading sequence at each correlator; the third term, I_{mai}, is the interference from other delayed sequences except that equal to the despreading sequence and the last term is the Gaussian noise. Since the sequences in a BCP and its mate are orthogonal to each other, D_{sig} is reduced to $4b_0b_0RP_{sc}$ where b_0 denotes the present modulating data bit. For I_{md} and I_{mai}, the integral over $0 \le t \le T_b$ are split into two ranges, $0 \le t \le t_l$ and $t_l \le t \le T_b$, in which the delayed sequences are modulated by the previous data bit b_{-1} during the first range and by the present data bit b_0 during the second range. I_{md} and I_{mai} can be further simplified in terms of the discrete aperiodic ACFs and CCFs of the complementary sequences as shown in equation (6).

Without multipath dispersion and Gaussian noise, Z is given by D_{sig}. A positive Z means a '+1' data is received while a negative Z means a '-1' is received. With multipath dispersion, interference on Z depends on I_{md} and I_{mai}. However, due to the aperiodic autocorrelation property defined in equations (1), I_{md} is zero for resolved paths $1 \le l \le N-1$ regardless of the values of b_{-1} and b_0. Depending on the particular BCP and mate, the normalised sum of the aperiodic CCFs of the complementary sequences in I_{mai}, denoted as $\sum\sum C_{Sm,Sj}(l)/N$, is equal to zero for $l = 0$, but not necessarily zero for all $l \neq 0$. However, there are zero windows (a run of consecutive shifts where the values of the aperiodic correlation are zero) for $1 < |l| < N$, which helps to reduce the amount of interference. Hence, the objective is to find BCPs and mates that result in I_{mai} with large zero windows.

3.1 Bit Error Ratio Analysis

The lower bound for the BER is obtained by considering the performance in an AWGN channel. Assuming $b_0 = +1$ is transmitted and ignoring the multipath interference term, $Z = 4b_0b_0RP_{sc} + n_o$. The signal component is determisnistic. Since the complementary sequences are orthogonal to each other, the noise components at each correlator output are zero-mean uncorrelated Gaussian random variables with a common variance $N_o/2T_b$. Therefore, the mean and variance of Z is $4b_0RP_{sc}$ and $2N_o/T_b$, respectively. Substituting $P_{sc} = P_{av}/2$, the signal-to-noise ratio of Z, $SNR_{out} = 2(RP_{av})^2T_b/N_o$. The BER is given by $Q([SNR_{out}]^{1/2})$ where $Q(\cdot)$ is the Marcum-function.

4 Results

The line-of-sight IR channel configuration used in the study is an empty 10×10×3 m (W×L×H) rectangular room with the left hand bottom corner of the front wall as the Cartesian origin (0, 0, 0). The x-axis points to the right, the y-axis points into the page and the z-axis point up. The room surfaces have a reflection coefficient of 0.8. The transmitter is located at (5m, 5m, 3m) pointing downwards and the receiver is at (1.25m, 1.25m, 0m) pointing upwards. The IR source is assumed to have a Lambertian radiation pattern with 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 multipath impulse response up to 3 reflections is obtained using the simulation model in [1]. The equivalent discrete channels obtained from the simulated channel impulse response at 10, 20 and 40 Mb/ are listed in Table 1.

Bit rate (Mb/s)	Equivalent Channel									
	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
10	1	0.2593	0.0258	0.0016						
20	1	0.6181	0.2944	0.1322	0.0354	0.0085	0.0026			
40	1	0.3542	0.3797	0.4574	0.2556	0.1430	0.1116	0.0674	0.0333	0.0146

Table 1 : The equivalent channels at 10, 20 and 40 Mb/s.

There are 32 BCP of length 4 [9]. The mate of each pair can be generated from equation (4). A search over all the 32 pairs found that each pair and its mate produce $\sum\sum C_{Sm,Sj}(l)/N = 0$ for all l, i.e. $I_{mai} = 0$. Hence multipath interference can be removed completely in this case. The elements of $\sum S_m$ for all the 32 pairs and their mates consists of one element of value –4 or +4 and three elements of value 0, denoted as {1(–4), 3(0)} or {1(+4), 3(0)}. The transmitted sequence is either $2P_{av}(1, 0, 0, 0)$ or $2P_{av}(0, 1, 1, 1)$.

The BER versus SNR_{out} performance of CSK transmitting any one of the pairs and its mate at 10, 20 and 40 Mb/s is presented in Figure 2. The solid line represents the analytical result in an AWGN channel and the dash-dot lines with symbols are the Monte Carlo simulation results. In an AWGN channel, CSK has the same performance as SIK [4]. In a multipath channel, there is no degradation up to 20 Mb/s, which means that the multipath interference is completely eliminated. At 40 Mb/s, the number of delayed paths are more than the spreading factor, N = 4. The delayed sequences with delays at integer multiples of the bit duration will not be decorrelated at the receiver. In Figure 3, when b_4 and b_8 are set to zero, the BER curve for 40 Mb/s is brought back to the AWGN case. This clearly shows that the penalty is due to the inter-symbol interference from the delayed sequences, which are in phase with the despreading sequences. Using sequences with larger spreading factors or long masking sequences could alleviate this problem.

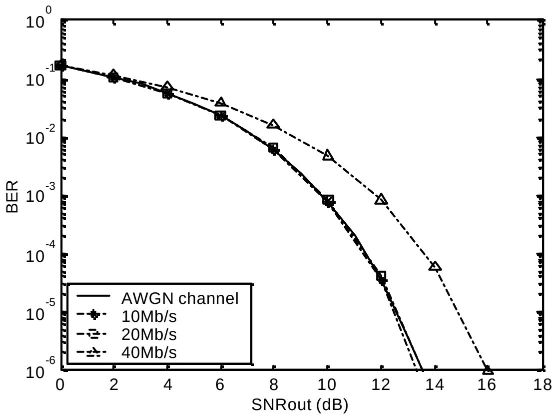

Figure 2 : BER vs SNR_{out} for CSK transmitting a BCP and mate of length 4 at 10, 20 and 40Mb/s.

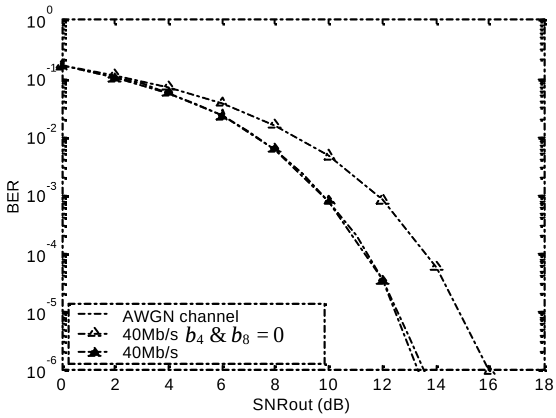

Figure 3 : BER vs SNR_{out} for CSK transmitting a BCP and mate of length 4 at 40 Mb/s. The penalty is due to the delayed sequences in phase with the despreading sequences.

5 Conclusions

The performance of an IR wireless system substantially depends on the transmitted signal waveform. This study demonstrates the simplicity and effectiveness of the use of complementary sequences with special aperiodic correlation properties to reduce the impact of multipath dispersion. The benefit of this approach is less receiver complexity compared to other mitigation techniques such as equalisations and coding. The application of longer sequences and other BCP combinations are the subject of further research by the authors.

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