A Hopping Code for MMFSK in a Power-line Channel

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Abstract— A uniformly distributed hopping code (UDHC) suitable for M-levelled M-ary Frequency Shift Keying (MMFSK) and Multi-tone MMFSK (M^3FSK) modulation schemes is introduced. The proposed code is designed with the requirements that it utilises all the available frequencies within the symbol period and that it is uniformly distributed, thereby making it efficient in terms of spectral usage and also easier to detect at the receiver. We have included simulation results which show that the UDHC shows better bit error rate (BER) performance in a frequency selective channel characterised by impulsive noise when compared to a pseudo-random hopping code (PRHC) and some purposely designed codes.

Index Terms— PLC, MMFSK, M^3FSK, Impulsive Noise, AWGN, Class A noise, AWCN, power-line

I. INTRODUCTION

M^3FSK has recently received some attention in literature particularly because it has been perceived as an alternative to orthogonal frequency-division multiplexing (OFDM) in such applications as broadband over power-line communication. To cope with impulsive noise, OFDM has to be equipped with a limiter at the receiver. But since the dynamic range of the signal amplitude in OFDM systems is large, the limiting operation produces non-linear distortion that affects the BER performance. Due to the constant envelope of the M^3FSK signal, the use of a limiter before the demodulator has less negative effect on the M^3FSK system than on the OFDM system. Furthermore, the parallel connection of a number of M^3FSK blocks divides the total transmission frequency band into narrower sub bands. Consequently, the duration of each tone can be made proportionally larger than that of a single system reducing the equalisation requirements.

An important feature of MMFSK/M^3FSK is that frequency hopping patterns have a dual responsibility of data scrambling and information carriage. The biggest challenge to a system designer, however, is the difficulty in obtaining hopping patterns with low hopping pattern collisions. Randomly generated hopping patterns have been extensively used in the past, but better performance can be achieved with an appropriately designed hopping pattern. Nojiri Y, et al [1] studies the use of the so called Even Odd Discrimination (EOD) system where a hopping pattern is synthesized from two hopping patterns each belonging to different hopping pattern groups A and B. In [2], Kim Y, et al also looked at masking sequences based on Quasi-orthogonal sequences (QOS) used in quasi-orthogonal modulation (QOM). In this paper, we investigate the use of UDHC as a better alternative to random frequency hopping pattern for MMFSK system in PLC applications. UDHC was introduced by the authors in [3] but the studies were restricted to AWGN noise. The new results of simulations over power-line channels disturbed by impulsive noise show that, the designed hopping pattern outperforms a randomly hopping pattern over the entire range of signal to noise ratio (SNR) values.

The rest of the paper is organised as follows: Section II gives an overview of MMFSK/ M^3FSK system, while section III presents analysis of the power-line channel, impulsive noise and the system model used in the paper. In section IV, we introduce UDHC. Families of UDHC and method of generating them are discussed in section V. The performance of the designed hopping codes is evaluated through simulations in section VI and section VII concludes the paper.

Notation: Bold face letters are used to represent matrices. Superscripts ^{T,} *, and ^{H} stand for transpose, conjugate, and conjugate transpose, respectively

II. OVERVIEW OF MMFSK SYSTEM

M^3FSK is a modulation technique that achieves higher transmission rates than M-ary multilevel FSK (MMFSK) [4], which is an extension of frequency-hopping multilevel FSK (FH-MFSK) modulation [5]. FH-MFSK is a spread-spectrum scheme that uses a single frequency-hopping pattern in combination with MFSK digital modulation. In FH-MFSK scheme, the jumps of the carrier frequency are controlled by a pseudo-random noise sequence (PN sequence), which is known at the receiver. In order to obtain an M-ary scheme, M-ary multilevel FSK (MMFSK) uses multiple numbers of frequency-hopping patterns instead of a single pattern. In an MMFSK transmitter, a block of K data bits is first divided into two sub-blocks K_1 and K_2. The sub block of K_1 bits determines a codeword out of $n = 2^{K_1}$ codewords, and the sub-block of K_2 bits selects a hopping pattern out of $n = 2^{K_2}$ hopping patterns. A hopping pattern is composed of L 'chips' in time and n levels. Next, a codeword is translated to a level and then added to a hopping pattern using a modulo-n adder.

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A specific tone (frequency carrier) is transmitted for each possible level. An example of this process is shown in Figure1.

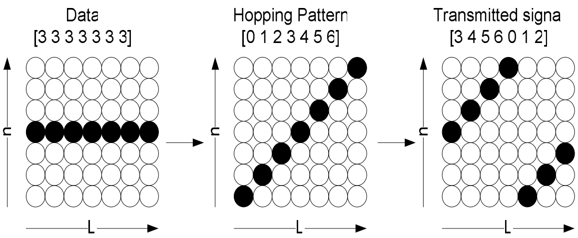

Figure 1 **:** Basic modulation process for MMFSK systems.

In order to increase the transmission rate of an MMFSK system, we may express each level as a combination of tones. This technique is known as multi-tone M-ary multilevel FSK (M^3FSK or triple MFSK) [6]. Similar to OFDM modulation, M^3FSK uses the inverse fast Fourier transform (IFFT) operation at the transmitter, the fast Fourier transform (FFT) operation at the receiver, and a cyclic prefix (CP) for avoiding inter-symbol interference (ISI). A simplified block diagram of the system is depicted in Figure 2.

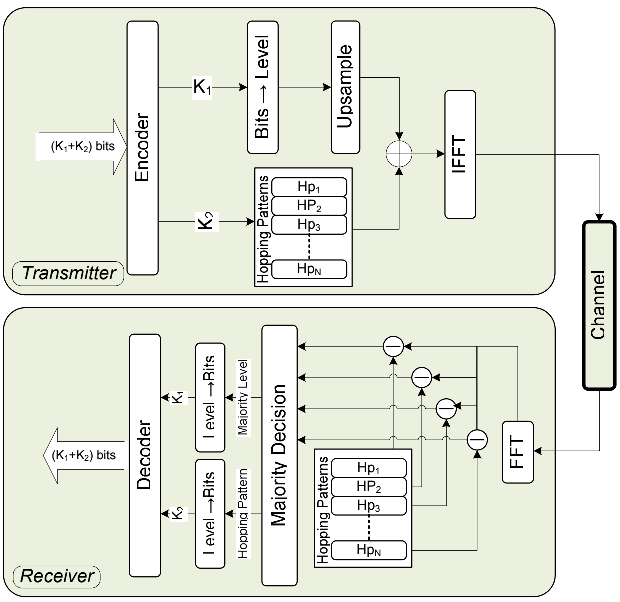

Figure 2: Block diagram of an MMFSK system showing the encoder and decoder

M^3FSK performs better than OFDM modulation when the power-line communication system uses a limiter at the receiver input to cope with the problem of impulsive noise [7], though both systems employ almost the same signal bandwidth. Furthermore, radiation power of M^3FSK is known to be 20-50 times lower than that of OFDM [1], this is a great advantage in power-line applications where Electromagnetic Interference (EMI) is a major problem [8-9].

III. CHANNEL AND SYSTEM MODEL

This section presents the analysis of the transfer function of the power-line channel and the associated impulsive noise used in the paper. We also give a generalised system model of the MMFSK system.

A. Power-line Channel

So far, there is no widely accepted power-line channel model similar to e.g. COST [10], derived for mobile radio. Considerable effort has recently been devoted to determine accurate channel models for the power-line environment employing either the field theory or the transmission-line model [11-14]. Often the frequency selective power-line channel is modeled according to [13], i.e synthesizing the band pass frequency response with N paths as

$$H(f) = \sum_{i=0}^{N} g_i e^{-\frac{2\pi f d_i}{V}} e^{-(\alpha_0+\alpha_1)(f^K)d_i} \qquad (1)$$

where each path has a weighting factor $|g_i| \leq 1$ representing the product of the reflection and transmission factors along the path, d_i is the length of path, $v = c/\sqrt{\varepsilon_r}$ with c speed of light and ε_r the dielectric constant. The parameters α_0, α_1, K are chosen to adapt the model to a specific network. More so, propagation signals are affected by attenuation increasing with length and frequency. In general, equation (1) can be used to represent a parametric model of the cable, describing the complex frequency response of the transfer function. The 6-path impulse response provided by [11] is used to evaluate the performance of our proposed system in section VI. The parameters are as shown in Table I. The impulse response is assumed to be constant over a symbol period.

TABLE I: POWER-LINE MULTIPATH CHANNEL PARAMETERS

	Frequency Domain		**Time Domain**	
Path No. i	$\lvert g_i \rvert$	d_i	β_i	τ_i
1	0.760	200	0.18	1.33
2	0.369	224	0.08	1.5
3	-0.190	248	-0.02	1.65
4	0.098	272	0.01	1.81
5	-0.050	296	-0.0025	1.973
6	0.026	320	0.000625	2.13

In addition to signal distortion due to cable losses and multipath propagation, interference and impulsive noises are the key factors influencing digital communications over power-line networks, particularly, in the frequency range up to 30 MHz. In this work, we will concentrate on the asynchronous impulsive noise caused by switching transients in the network.

One suitable model for this type of noise is the complex memoryless additive white Class A noise (AWCN) channel model [15]. The probability density function (PDF) of the complex class A noise is given by

$$P_Z(Z) = \sum_{m=0}^{\infty} \frac{\alpha_m}{2\pi\sigma_m^2} \exp\left(-\frac{|Z|^2}{2\sigma_m^2}\right) \quad (2)$$

with

$$\alpha_m = e^{-A} \frac{A^m}{m!} \quad (3)$$

and

$$\delta_m^2 = \sigma^2 \frac{(m/A) + T}{1+T} \quad (4)$$

where δ^2 is the total variance of the class A noise, m denotes the channel state, σ_m^2 represents the noise variance for channel state m, the parameter A is the impulsive index, and the parameter T is the Gaussian-to-impulse noise power ratio.

B. System Model

Figure 3 shows a simplified schematic diagram of MMFSK transmission over a single-input single-output power-line channel. Let c[k] (k = 0, 1, .., M – 1) be a sequence of M tone data symbols to be transmitted, each with unit average energy, represented by a $Mx1$ vector $c = [c[0]\ c[1] \cdots c[M-1]]^T$ .In MMFSK, an inverse fast Fourier transform (IFFT) operation is first performed on the sequence of symbols to be transmitted over each pair of wires. This yields the (time domain) vector $\vec{c} = [\vec{c}[0]\ \vec{c}[1] \cdots \vec{c}[M-1]]^T$.

$$\vec{c} = \mathbf{D}^H c \quad (5)$$

where **D** is an MxM unitary matrix whose pz^{th} element is given by

$$[\mathbf{D}]_{p,z} = \frac{1}{\sqrt{P}} \exp[-j2\pi(p-1)(z-1)/M]. \quad (6)$$

In order to combat the Inter Symbol Interference (ISI) caused by the multipath delay of the power-line channels, new sequence $\hat{\vec{c}}$ is constructed by appending a cyclic prefix (CP) of length L – 1 (L the length of the channel) to the vector $\vec{c}$.

At each receiver point, the CP is striped off and a fast Fourier transform (FFT) operation is performed on the signal. The signal received after performing the FFT operation at the k[th] frequency tone is given by

$$r[k] = \sqrt{\frac{E_s}{2}} w[k] c[k] + \tilde{n}[k] \quad (7)$$

where E_s is the average energy available at the transmitter per frequency, c is the $MMFSK$ symbol transmitted over the k[th] frequency tone, $w(k)$ represents the channel gain given by

$$w[k] = \sum_{l=0}^{L-1} h[l] e^{-\frac{j2\pi k l}{P}},\ k = 0, 1, 2, ..., M-1 \quad (8)$$

and $h[l]$ $(l = 0, 1, 2, ..., L-1)$, denotes the baseband channel impulse response. In this paper, the channel impulse response is obtained from channel frequency response (1). The noise term $\tilde{n}[k]$ is considered to be an independent identically distributed (i.i.d.) complex random variable according to Class A noise model (2).

After the FFT operation, maximum-likelihood (ML) detector decides in favor of c', among all the symbols of c of the MMFSK constellation S if

$$c' = \arg\min_{c \in C} |y - c|^2 + (-1 + |\omega|^2) c^2 \quad (9)$$

Where

$$y = r\omega^*$$

The output of the ML detector is subsequently passed into MMFSK decoder where decisions on the original data and corresponding hopping pattern are made based on majority rows and modulo-n subtraction.

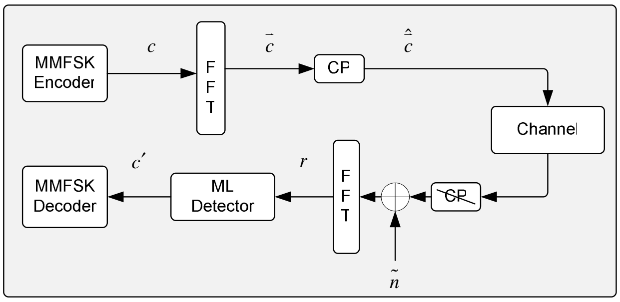

Figure 3 MMFSK system model

IV. UDHC

Special rules for designing efficient hopping patterns are required for a high performance MMFSK system. Although there are some purposely designed codes in literature, there are no defined rules on how to generate such codes and some of the simulations and papers available still generally utilise random codes. Our proposed hopping codes ensure that all available frequencies are occupied at all time. This enhances efficient use of the available spectrum.

Figure 4 presents examples of time-frequency matrices which represent the state of the frequency tones during each period. For simplicity, consider a case of L = 7 and n = 7. At the transmitter, if a codeword n = [3 3 3 3 3 3 3] and hopping pattern h = [0 1 2 3 4 5 6] are summed using modulo-7 addition, matrix Tx = [3 4 5 6 0 1 2] is the resultant transmitted matrix (see figure 4.A). A tone signal selected from a set of n frequencies corresponding to the value of each entry of n is transmitted as MMFSK signal.

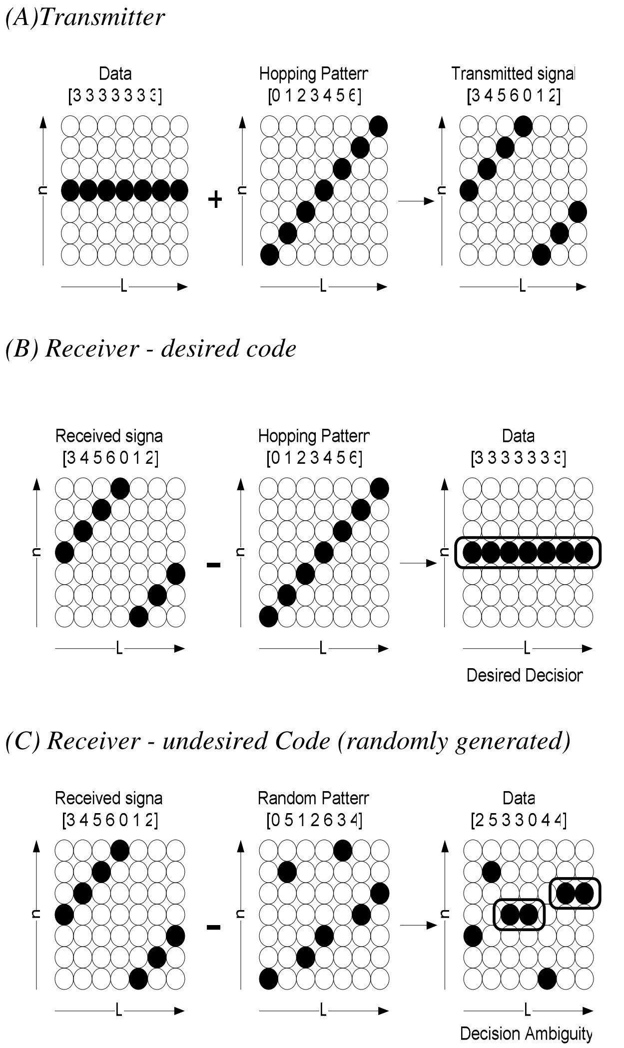

Figure 4: Behaviour of subtraction of desired and undesired code from the transmitted signal

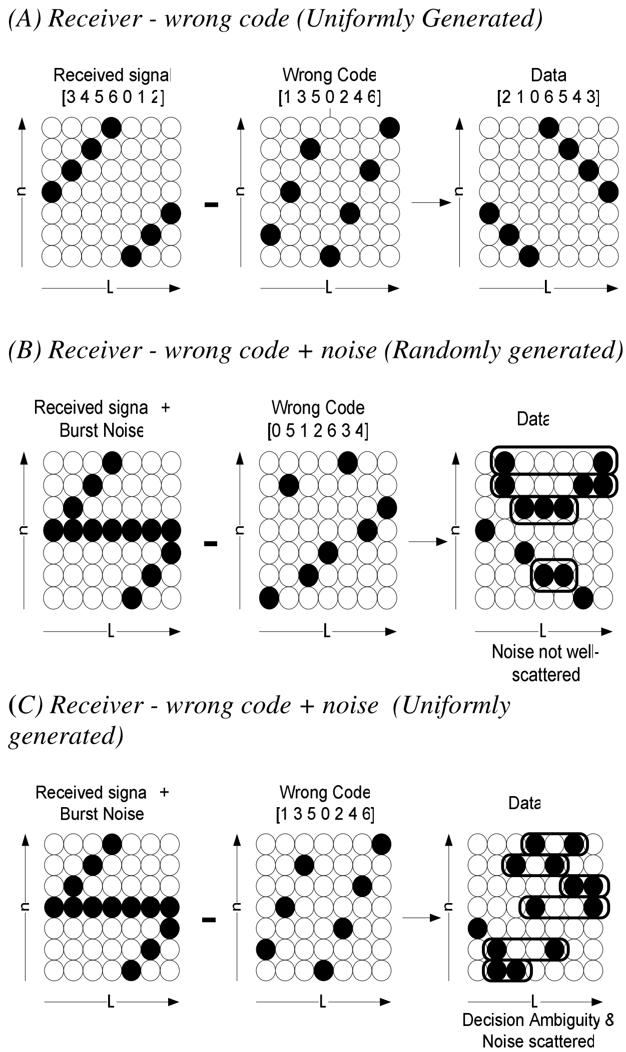

Figure 5: Example of MMFSK systems using Random codes and UDHC.

Matrix Rx (see figure 4.B) is the received matrix in the absence of noise. To recover the original data (n+h), the same hopping patterns available to both the transmitter and receiver are subtracted from Rx. This subtraction is carried out using modulo-7 subtraction. Usually, there is a high probability, under sufficiently high SNR, that the correct row corresponding to the desired symbol has the largest entries; for this reason, decisions on the original data and corresponding hopping pattern are made based on majority rows. Data signal similar to the one in figure 4.C is obtained when a wrong hopping pattern is subtracted from the received signal. Since correct data and hopping pattern is detected using "majority row" rule, it is difficult to detect data where there are two or more rows with the same number of entries. In a randomly generated hopping pattern, it is common to obtain convergence of signals at some frequencies when the wrong hopping pattern is subtracted from the received signal. This situation is undesirable as it might lead to a wrong decision even in the absence of noise. (see figure 4.C). The proposed codes, however, distribute the energy of the signal uniformly across the frequencies thus making signal detection much easier (see figure 5.A)

The advantage of a UDHC over random code becomes even clearer in the presence of noise. Figures 5. B and C represent these scenarios. It was easier to decide that the wrong code had been used in the case of Figure 5.C than in 5.B. Table II, presents a comparison of UDHC and code in [19] in terms of frequency usage

TABLE II: COMPARISION OF REFRENCE CODE and UDHC

Ref code[19]	
Available frequencies	8
Chips/sec	4
bit /chip	1
Bits/sec	4/1
Spectral Usage Hz/bit/sec	8/1/4 =2
UDHC	
Available frequencies	8
Chips/sec	8
bit /chip	1
Bits/sec	8/1
Spectral Usage Hz/bit/sec	8/8/1 =1

V. FAMILIES OF UDHC

Considering the advantages of a uniformly distributed hopping code described above, the question is, how do we generate such codes? In this section, we will define the rules and methodology for generating a uniformly distributed code.

Rules:

i. The hopping sequence should utilise all the available frequencies during the L chips.
ii. In addition to (i), the hopping sequences must have a uniform distribution, and the mutual modulo addition and subtraction of two hopping codes must also result in a uniform distribution.

If we consider two i.i.d random variables each of which is uniformly distributed , it has been shown in [16] that summation of these variables gives rise to distribution similar to that obtained when their individual PDF are convoluted. From [17] we also know that convolution of two i.i.d results in a triangular distribution. But if we pass the resultant sum of these variables through a modulo operator, then we end up with a uniform distribution as shown in figure 6.

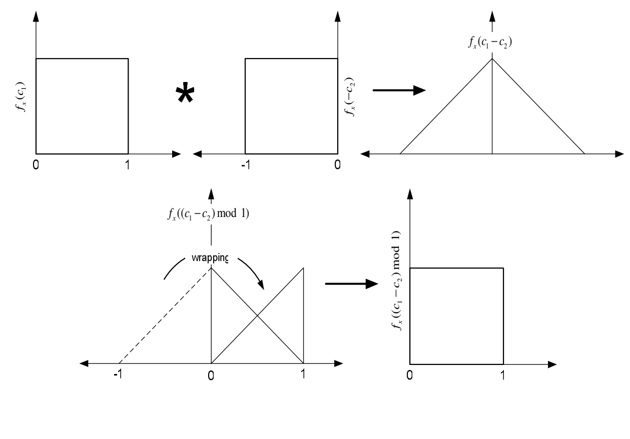

Figure 6 Uniform distribution – convolution- uniform distribution

With the postulate above, we can realise our uniformly distributed hopping code using the following generator matrix:

$$\begin{bmatrix} 0 & 1 & 2 & \cdots & q-1 \\ \eta_{11}+1 & \eta_{12}+2 & \eta_{13}+3 & \cdots & \eta_{1q}+q \\ \eta_{21}+1 & \eta_{22}+2 & \eta_{23}+3 & \cdots & \eta_{2q}+q \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \eta_{(q-2)1}+1 & \eta_{(q-2)2}+2 & \eta_{(q-2)3}+3 & \cdots & \eta_{(q-2)q}+q \end{bmatrix} (\bmod q) \qquad (10)$$

where "q" is the length of the code and η_{11}, η_{12} .. are elements of the matrix in equation (10)

Since it is required that modulo subtraction of the two codes must also be uniform, the following conditions may apply in generating the codes:

a. The length of the chips is equal to the level L=M
b. Length q of the code is a prime number.

Table III shows examples of uniformly distributed codes when the lengths of the codes are 5, 7, 11 and 13. More codes can be generated by increasing the length of the code.

TABLE III: EXAMPLES OF UDHP OF LENGTH q

Length	**Codes**												
q=5	0	1	2	3	4								
	1	3	0	2	4								
	2	0	3	1	4								
	3	2	1	0	4								
q=7	0	1	2	3	4	5	6						
	1	3	5	0	2	4	6						
	2	5	1	4	0	3	6						
	3	0	4	1	5	2	6						
	4	2	0	5	3	1	6						
q=11	0	1	2	3	4	5	6	7	8	9	10		
	1	3	5	7	9	0	2	4	6	8	10		
	2	5	8	0	3	6	9	1	4	7	10		
	3	7	0	4	8	1	5	9	2	6	10		
	4	9	3	8	2	7	1	6	0	5	10		
	5	0	6	1	7	2	8	3	9	4	10		
	6	2	9	5	1	8	4	0	7	3	10		
	7	4	1	9	6	3	0	8	5	2	10		
	8	6	4	2	0	9	7	5	3	1	10		
	9	8	7	6	5	4	3	2	1	0	10		
q=13	0	1	2	3	4	5	6	7	8	9	10	11	12
	1	3	5	7	9	11	0	2	4	6	8	10	12
	2	5	8	11	1	4	7	10	0	3	6	9	12
	3	7	11	2	6	10	1	5	9	0	4	8	12
	4	9	1	6	11	3	8	0	5	10	2	7	12
	5	11	4	10	3	9	2	8	1	7	0	6	12
	6	0	7	1	8	2	9	3	10	4	11	5	12
	7	2	10	5	0	8	3	11	6	1	9	4	12
	8	4	0	9	5	1	10	6	2	11	7	3	12
	9	6	3	0	10	7	4	1	11	8	5	2	12
	10	8	6	4	2	0	11	9	7	5	3	1	12

It can easily be shown that these codes have properties of uniform distribution over the finite field of characteristic q. The total numbers of codes which satisfy these properties are (q-1). For instance, in Table III, for q = 5, only 4 uniformly distributed codes are available, and for q = 11, there are 10 codes. To engineer these codes for practical use, we first select q (a prime number) to generate the codes using the generator matrix (1), and then remove the last column (truncate), so that for a code with length 5, you end up with the hopping patterns in Table IV.

TABLE IV: EXAMPLE OF UDHP OF LENGTH 4

0	1	2	3
1	3	0	2
2	0	3	1
3	2	1	0

The length of codes is now 4, thus a power of 2. This is important for MMFSK applications. The truncated codes are still uniformly distributed over modulo-5 field.

VI. PERFORMANCE RESULTS

This section summaries the performance of the proposed hopping code in power-line environments-multiplicative power-line transfer function and the additive AWCN. In all measurements, we have assumed perfect channel state information (CSI).

To test the performance of the proposed hopping codes, we simulated MMFSK systems which use a UDHC of length q= 17, truncated to 16 required for our application. The number of chips, L= 16. The 16 symbols generated are modulated using IFFT length of 16 to produce the transmitted signal; the guard time is assumed to be greater than the maximum delay spread of channel.

Firstly, the UDHC is compared with a random code of the same length in AWCN. The same system was used in a more realistic power-line channel with frequency transfer function modeled as in (1) and AWCN modeled using (2). In our simulations, the total variance of the class A noise is normalised to $1/2SNR$ per complex dimension and $T=10^{-3}$. Because the parameter A determines the impulse degree of the class A noise [18], we have set A = 0.1. This corresponds to a power-line channel that is heavily disturbed by "impulsive" noise because the inter-arrival times between strong impulses are very short.

The pseudo-random hopping codes (PRHC) used in our simulations are comparable to our UDHC, in terms of length and the frequency spectrum they occupy. The only difference is that they are not selected to meet the strict requirement of UDHC as described in section IV.

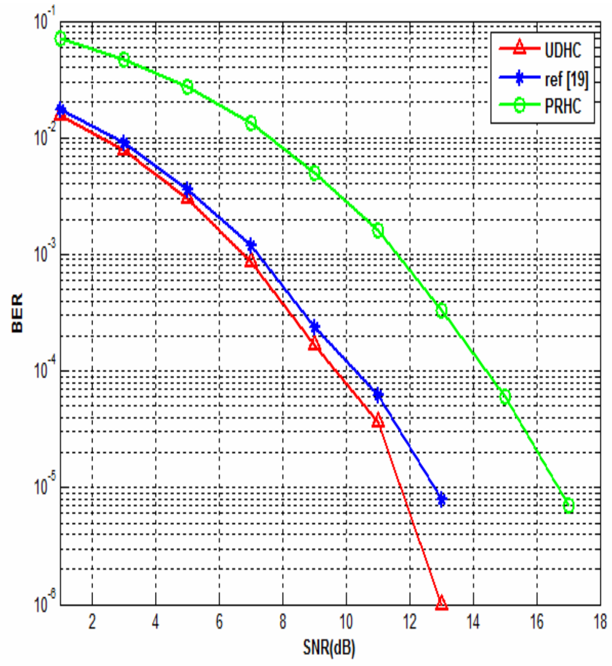

Figure 7 : BER performance comparison for UDHC, PRHC and Hopping code in ref [19] in AWNC environment

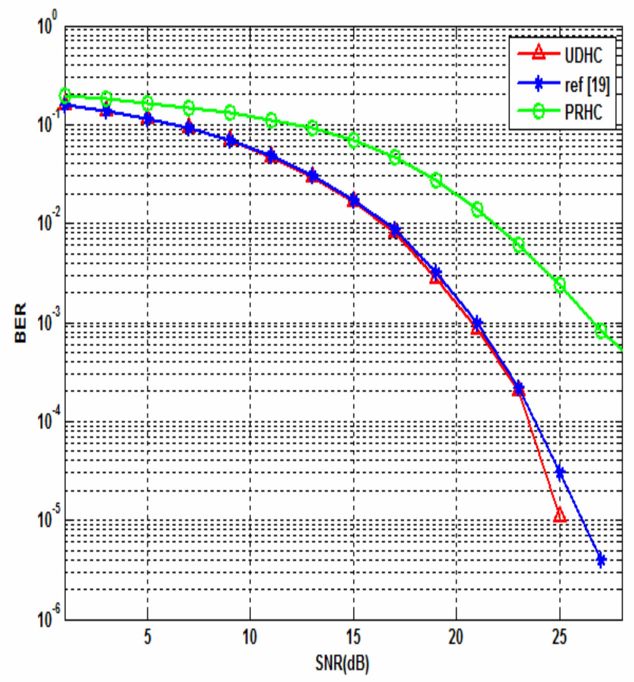

Figure 8: BER performance comparison for UDHC, PRHC and hopping code in ref [19] in power-line + AWNC environment

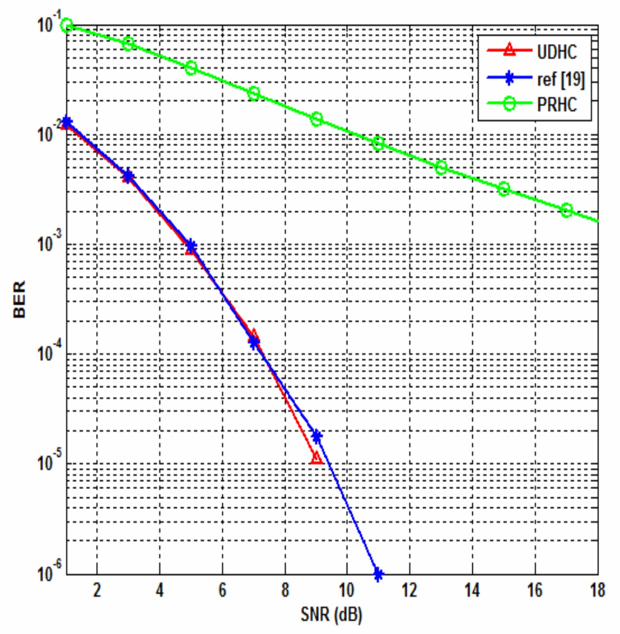

Figure 9: BER performance comparison for UDHC, PRHC and hopping code in ref [19] in a wireless environment (Raleigh fading + AWGN)

Figure 7 shows the BER performance of the proposed hopping codes, random hopping codes and hopping code used in ref [19]. For fair comparison the 8x4 hopping codes in [19] have been extended to 16x16. From figure 7, we can see that the proposed code shows some performance improvement over the codes in [19], and both our code and the referenced codes performed much better than the randomly generated codes. At BER of 10^{-5}, for example, UDHC has an improvement of about 1.5dB over [19] and 6dB over the PRHC.

Figure 8 shows a channel environment that depicts a more realistic power-line communications channel; here the codes are compared in a power-line channel impaired by impulsive noise. It was shown that UDHC also shows a slight improvement over hopping codes in [19] and also the PRHC. At BER of 10^{-5}, for example, UDHC has an improvement of about 1.4 dB over [19] and substantial improvement over the PRHC.

In figure 9, we have tested the proposed codes in a wireless environment. The wireless channel is a Rayleigh fading plus additive white Gaussian noise (AWGN). The performance results in figure 9 follows the same trend as in the two previous communication environments. UDHC also shows, little or no improvement over the codes in ref[19], it outperformed the PRHC across all SNR. The performance superiority showed by UDHC over the PRHC could be attributed to the characteristics of the UDHC as discussed in section IV. The dispersion of energy across the spectrum makes detection decision less ambiguous in UDHC than in other codes. In addition, while the hopping codes employed in [19] did not use all the available frequencies, the proposed method considered the whole available spectra in L chips, within which a level is transmitted. In other words, the proposed method utilises the spectrum in a more efficient way.

VII. CONCLUSION

In this paper, we investigated a hopping code suitable for MMFSK system in a frequency selective environment impaired by impulsive noise. The performance of some families of the proposed codes have been compared to a pseudo-random code and a purposely designed code.

The UDHC out-performed the random codes in both power-line and wireless environments. It also shows some performance improvement over a purposely designed code. Another characteristic of this code is that it utilises all available frequencies within a symbol period, thus spreading energy across the spectrum and simplifying signal detection.

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