CHANNEL MODELING AND ESTIMATION FOR ROBUST MC-SS SYSTEMS

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ABSTRACT

As a spread spectrum technique, multi-carrier spread spectrum (MC-SS) systems are able to mitigate the effects of fading, interferences and Doppler frequency shifts as well as to support multiple access schemes. It is possible to get optimum performance from MC-SS systems by carefully choosing the spreading sequences. However, due to inter-user interferences performance degrades as the number of users increases unless the transmission channels are modeled and estimated. In this paper, we present a new spreading sequence obtained from a complex quadratic sequence multiplied by a pseudo random noise sequence, thus exploiting the properties of constant envelope and statistical independence. The properties of the new spreading sequence enable us to estimate the multi-user channels and design a receiver that is robust to interference and intentional jammers. The performance of the proposed system is illustrated by simulations.

1. INTRODUCTION

Multi-carrier modulation techniques are known to have better performance than single carrier systems in multipath fast fading environments. On the other hand, spread spectrum communication systems are well known for their immunity to channel noise, mitigation of intentional jamming or non-intentional inter-user interference. Combining these two has led to multi-carrier spread spectrum (MC-SS) systems [1, 2]. In MC-SS, the data is spread by complex coefficients and then modulated by carriers of different frequencies. To achieve desirable flat spectrum, while providing a constant envelope, complex quadratic sequences are used as the spreading functions [2].

In multi-carrier modulation systems, spreading code design is an important issue since it influences the system performance. There is usually a tradeoff between multi-path rejection properties and inter-user interference properties. Ideally, the cross correlation between the codes must be zero to eliminate multiple access interference. Pseudo noise sequences have low correlation between shifted versions of the same sequence and a low cross correlation between different sequences. Here we present a new spreading sequence obtained from a complex quadratic sequence presented in [2] multiplied by a pseudo random noise sequence, thus taking advantages of the properties of constant envelope, and statistical independence. In the proposed MC-SS system, the data symbol $d(i)$ is spread by a new frequency domain spreading coefficients $G'(k)$ which then modulate N carriers. $G'(k)$ is defined as $G'(k)$=$G(k)P(k)$, where $P(k)$ is a pseudo random sequence. The complex quadratic chirp sequences in time and in frequency domain are

$$\begin{aligned} g(n) &= e^{-j\frac{\pi}{8}} e^{j\frac{2\pi}{N}\frac{1}{2}n^2}, \ n = 0, \cdots, N-1 \\ G(k) &= e^{j\frac{\pi}{8}} e^{-j\frac{2\pi}{N}\frac{1}{2}k^2}, \ k = 0, \cdots, N-1 \end{aligned}$$

which are shift-orthogonal, Fourier transform pair, and $G(k) = g^*(k)$. As such, these sequences do not provide enough transmission security, N distinct sequences are possible by circular shifting, and so we need a new sequence that provides much higher security. We will show how such a sequence can be obtained and its advantages in designing a robust system capable of dealing with inter-user interference as well as possible intentional jammers.

Given that time-varying nature of the mobile, wireless communication channel causes spreading of the transmitted signal in both time and frequency, equalization is needed to be able to recover the sent data. Although the time-varying nature of the channel is due to Doppler shifts, in many practical situations they are not significant or not considered. For instance, the RAKE receiver used in CDMA spread spectrum works well under slow fading even though the Doppler shifts are not considered. However the the slow fading assumption is not valid for fast moving environments. In such cases modeling and estimation of the rapidly time-varying communication channel parameters are required.

Transmission channels are modeled as random, time-varying systems [3, 4, 5]. In this paper, we use an MC-SS channel model that is linear, time varying (LTV) for the duration of a data bit. This provides a characterization of multipath, fast fading as well as slow fading channels. We will show how to use the properties of the new spreading code to estimate the parameters of the LTV channel model by means of the spreading function that is computed from the discrete evolutionary transform (DET) of the received signal. This permits an estimation of the number of paths, delays, Doppler frequency shifts and the gains characterizing the channel for one or more data bits. This information is then used to estimate the data bit sent [6].

2. MC-SS SYSTEM MODEL

In multi-carrier spread spectrum (MC-SS) communications systems the information bit is spread over K frequency domain coefficients and then used to modulate the K subcarriers of corresponding sub-channels [7, 8, 9]. In contrast to orthogonal frequency division multiplexing (OFDM),

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which is also a multi-carrier scheme, the same data bit is transmitted over all sub-carriers, so that the data rate is much slower than that of OFDM systems. However, MC-SS is very robust to intentional jamming and preferred in applications where secure communication is required.

Information symbol, d, is multiplied with a set of frequency domain spreading coefficients $C_k,\ k = 0, 1, \cdots N-1,\ |C_k| = 1$ and $dC_k,\ k = 0, 1, \cdots N-1$ is obtained. Then, just like in the OFDM systems, these coefficients are used to modulate N orthogonal sub-carriers:

$$s(n) = \frac{1}{N}\sum_{k=0}^{N-1} dC_k e^{j\frac{j2\pi k}{N}\ n} \qquad n = 0, 1, \cdots, N-1 \tag{1}$$

The modulation can be efficiently performed using the inverse discrete Fourier transform (DFT). Before sending $s(n)$ to the channel, last L_{CP} samples are inserted in front and called the Cyclic Prefix (CP). This is done to eliminate the effects of intersymbol interference (ISI) caused by the channel time spread. The length of the CP is taken at least equal to the length of the channel impulse response $h(m,\ell)$. The transmitted signal is assumed to be corrupted in the channel by additive white Gaussian noise $\eta(n)$. The received signal can then be written as;

$$r(n) = \sum_{\ell=0}^{L-1} h(n,\ell)s(n-\ell) + \eta(n) \tag{2}$$

The receiver discards the Cyclic Prefix and demodulates the signal using an N-point DFT as

$$R_k = \sum_{n=0}^{N-1} r(n)e^{-j\frac{j2\pi k}{N}\ n} \tag{3}$$

Assuming the channel is time-invariant during one transmit symbol, i.e., $0 \le n \le N-1$, then $R_k = d\, C_k\, H_k + N_k$ where H_k are the LTI channel frequency response coefficients, and N_k are the DFT coefficients of the noise, $\eta(n)$. The data bit can be estimated from above provided that the channel information is given.Most of the channel estimation methods assume a linear time–invariant model for the channel, which is not valid for fast-varying environments [10]. A complete time-varying characterization of the channel is presented here by using a time-frequency approach.

2.1 Channel Model

The time-varying frequency response of a communication channel, also known as Zadeh's function [3, 6], characterizes the channel in terms of time delays, Doppler frequency shifts and gains, all of which vary randomly in the modeling. The existing connection between the Zadeh's function and the evolutionary spectral theory can thus be exploited to estimate the channel parameters and provide a way in the receiver to detect the transmitted data. An L-path fading channel with Doppler frequency shifts is generally modeled by a separable impulse response:

$$h(n,\ell) = \sum_{\ell=0}^{L-1} \alpha_\ell \delta(n-N_\ell)e^{j\psi_\ell n} \tag{4}$$

where $\{N_\ell\}$ represent the delays, $\{\alpha_\ell\}$ are the attenuations of transmission paths, and $\{psi_\ell\}$ are the Doppler frequencies. The Doppler frequency shift ψ_i, on the carrier frequency ω_c, is caused by an object with radial velocity υ and can be approximated by $\psi_i \cong \frac{\upsilon}{c}\ \omega_c$, where c is the speed of light in the transmission medium [11]. In wireless mobile communication systems, with high carrier frequencies, Doppler shifts become significant and have to be taken into consideration. We will now show how to estimate these parameters using the evolutionary spectral theory.

The frequency response of the LTV channel is given by;

$$H(n,\omega_k) = \sum_{\ell=0}^{L-1} \alpha_\ell e^{j\psi_\ell n}e^{-j\omega N_\ell}, \tag{5}$$

which is the Fourier Transform of the impulse response $h(n,\ell)$ in (4). Now, the bi-frequency function $B(\Omega,\omega_k)$ is found by computing the Fourier transform of $H(n,\omega_k)$ with respect to the n variable:

$$B(\Omega,\omega) = 2\pi \sum_{\ell=0}^{L-1} \alpha_\ell e^{-j\omega N_\ell}\delta(\Omega-\psi_\ell) \tag{6}$$

Finally, from the inverse Fourier transform of $B(\Omega,\omega)$, with respect to ω, the spreading function is given by;

$$S(\Omega,k) = 2\pi \sum_{\ell=0}^{L-1} \alpha_\ell \delta(\Omega-\psi_\ell)\delta(k-N_\ell) \tag{7}$$

which displays peaks located at the delays and the corresponding Doppler frequencies, and with $2\pi\alpha_\ell$ as their amplitudes, which are used to estimate the bit sent.

3. A ROBUST MC-SS SYSTEM

The proposed multi-user, MC-SS communication system for uplink transmission [1, 7] is shown in Figure 1:

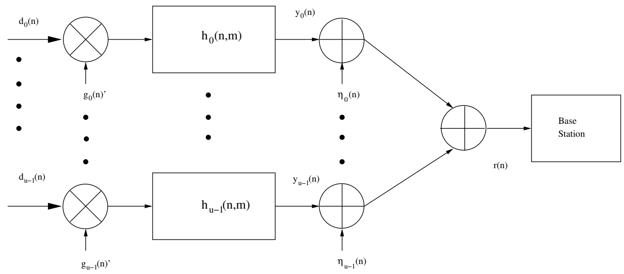

Figure 1: Multi-user MCSS transmission (uplink)

The proposed spreading sequence $g'(n)$ is complex and can be obtained from the product of $G(k)$ and a pseudo-noise sequence $P(k)$. Clearly the spectrum of $g'(n)$ is unity given that both $|G(k)| = |P(k)| = 1$, thus the $g'(n)$ is a white-noise like sequence. To obtain an expression for $g'(n)$, let us assume $G(k)$ and $P(k)$ are of length N each, then

$$\begin{aligned} G(k)P(k) &= G(k)\sum_{i=0}^{N-1} p_i \delta(k-2\pi i/N) \\ &= \sum_{i=0}^{N-1} G(2\pi i/N)p_i\delta(k-2\pi i/N) \end{aligned}$$

where $p_i = \pm 1$ randomly chosen. Its inverse Fourier transform is of the form:

$$g'(n) = \frac{1}{N}\sum_{s=0}^{N-1} p_s G(2\pi s/N)e^{-j\frac{2\pi sn}{N}} \tag{8}$$

a sequence with complex coefficients that has all possible frequencies. The time characterization of the proposed MC-SS system is obtained by assuming $g'_u(n)$ is a complex pseudo-noise sequence obtained by different circular shifts of the above $g'(n)$, and so the spread sequence is $s_u(n) = d_u g'_u(n)$.

To recover the sent data for one of the users, we need to estimate the parameters of its corresponding channel. This is possible using a time-frequency spreading function that can be obtained from the discrete evolutionary transform of the received signal [6]. It can be shown then even in the multi-user case this is possible.

3.1 Channel Estimation

In the above wireless MC-SS system, the received signal at the base station is

$$\begin{aligned} r(n) &= \sum_{u=0}^{U-1}\sum_{\ell=0}^{L_u-1} \alpha_{u,\ell}\, e^{j\psi_{u,\ell}n}\, s_u(n-N_{u,\ell}) + \mu_u(n) \\ &= \frac{1}{N}\sum_{u,k} d_u\, G'_u(k) \sum_{\ell=0}^{L_u-1} \alpha_{u,\ell}\;\; e^{j\omega_k(n-N_{u,\ell})}\; e^{j\psi_{u,\ell}n} + \mu_u(n) \end{aligned}$$

where $\mu_u(n)$ corresponds to channel noise plus the intentional jammer, $\eta_u(n) + j_u(n)$. After replacing for the generalized frequency response in the above equation, we get,

$$\begin{aligned} r(n) &= \frac{1}{N}\sum_{u,k} d_u\, G'_u(k)\, H_u(n,\omega_k)\, e^{j\omega_k n} + \mu_u(n) \quad (9) \\ &= \sum_{u=0}^{U-1}\sum_{k=0}^{N-1} Y_u(n,\omega_k) e^{j\omega_k n} + \mu_u(n) \quad (10) \end{aligned}$$

where (10) is the discrete evolutionary transform of the received signal $r_u(n)$. Time-frequency kernel of this transform, $Y_u(n,\omega_k)$, can be directly calculated from the signal [12]:

$$Y_u(n,\omega_k) = \sum_{\ell=0}^{N-1} y_u(\ell) \mathrm{w}_k(n,\ell) e^{-j\omega_k \ell} \quad (11)$$

The window $\mathrm{w}_k(n,\ell)$, in general, depends on time and frequency [12]. Hence comparing the representation of $y_u(n)$ in (9) and (10), we have that $H_u(n,\omega_k) = N\, Y_u(n,\omega_k)/(d_u G'_u(k))$. In [6], windows that are adapted to the Doppler frequencies ψ_p of the received signal are used to estimate the kernel: $\mathrm{w}_p(m,\ell) = e^{j\psi_p(m-\ell)}$. The estimation procedure of α_ℓ, ψ_ℓ, and N_ℓ via the spreading function $S(\Omega_s, m)$ is explained in detail in [6]. In 2, we show the spreading function estimate of user $u = 1$ in a 3-user MC-SS system using $G'_u(k)$ as the spreading code. From the spreading function, all the channel parameters of this user can be observed and used for the detection.

After estimating the channel parameters, it is possible to estimate the data sent from the received signal at the base station. Assume now that the parameters of the shortest transmission path $\hat{\alpha}_{u,0}$, $\hat{\psi}_{u,0}$ and $\hat{N}_{u,0}$ are obtained. A decision variable can be calculated from the noisy received signal at

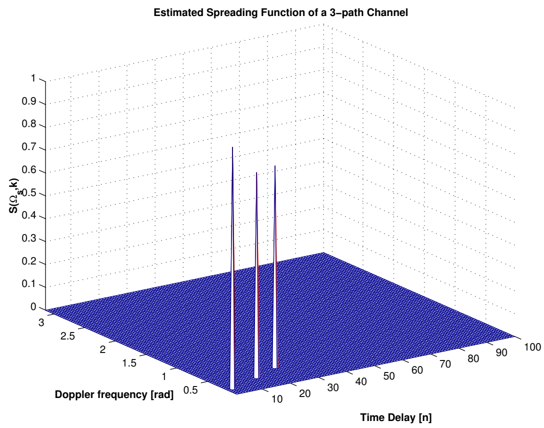

Figure 2: Estimated spreading function for one user.

the base station for user u such that,

$$\begin{aligned} r_{u,0}(n) &= r(n)\; g'^{*}_u(n-\hat{N}_{u,0}) \frac{e^{-j\hat{\psi}_{u,0}(n)}}{\hat{\alpha}_{u,0}} \\ &= \left[\sum_{u=0}^{U-1}\sum_{\ell=0}^{L_u-1} d_u\; \alpha_{\ell,u} g_u(n-N_{u,\ell}) e^{j\psi_{u,\ell}(n)} + \mu_u(n)\right] \\ &\times \frac{g'^{*}_u(n-\hat{N}_{u,0}) e^{-j\hat{\psi}_{u,0}(n)}}{\hat{\alpha}_{u,0}} \end{aligned}$$

Using the orthogonality of $g'_u(n)$ with its shifted versions (i.e., for different u), and the fact that $g'_u(n)$ are uncorrelated with the noise and the jammer, we are able to minimize the effects of other users and the additive noise. In fact, the average value of $r_{u,0}(n)$ gives an estimate of d_u. We show in the experiments that $g'_u(n)$ is very efficient in mitigating the effects of white noise and wide-band intentional jammers.

4. EXPERIMENTAL RESULTS

We tested the bit error rate (BER) performance of the proposed multi-user MC-SS system with different levels of channel noise, Doppler frequency shifts, and intentional jammer using 5 methods: (1) no channel estimation, (2) TF channel estimation in MC-SS system with quadratic chirp $g(n)$, (3) with the proposed sequence $g'(n)$, (4) LTI channel model, ignoring Doppler effects, (5) known channel. Available bandwidth is assumed 500 kHz, and $N = 100$ subcarriers are used to modulate the data symbols. Fig. 3 shows the BER versus SNR of the additive noise when the maximum Doppler on each path is 500 Hz in a 4 user system. In the second simulation, we tested the BER versus Doppler ($500 - 5000$ Hz), when the SNR is 15 dB and the results are given in Fig. 4. Finally, we show in Fig. 5 the BER versus jammer to signal ratio (JSR) for SNR = 10 dB, $\psi_{max} = 500$.

5. CONCLUSIONS

We present a robust MC-SS system with a random and complex spreading code that combines the advantages of quadratic chirps in [2] and DS-SS systems. LTV channel parameters are estimated via the spreading function that is calculated by the discrete evolutionary transform of the received noisy signal. We illustrate the performance of our method for different channel noise, Doppler frequency shift, and jammer levels and find that the results are much better than LTI channel assumption, and LTV channel estimation for the system with quadratic chirps.

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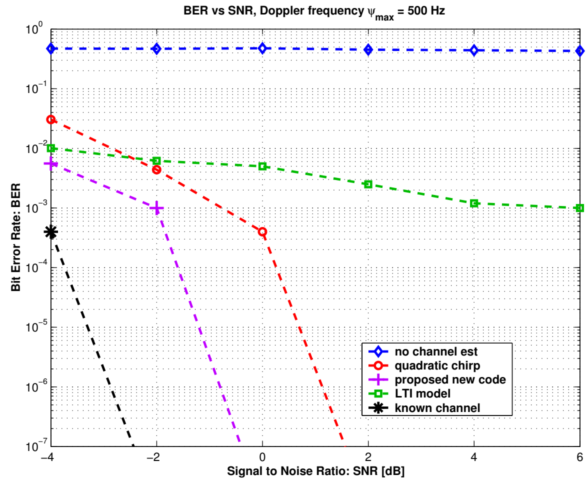

Figure 3: BER versus SNR for $\psi_{\max} = 500Hz$.

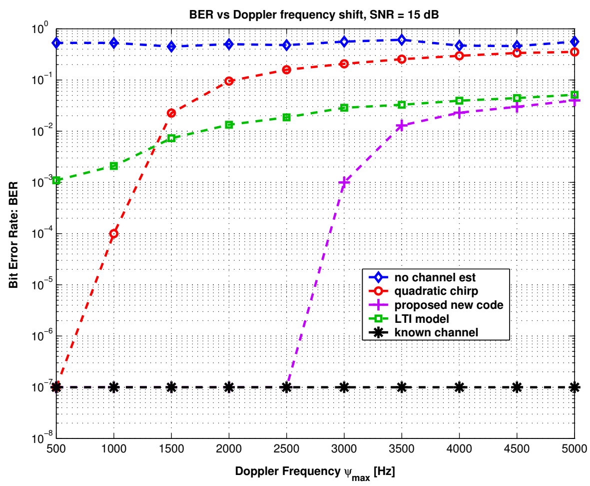

Figure 4: BER versus $\psi_{\max}$ for SNR=15 dB.

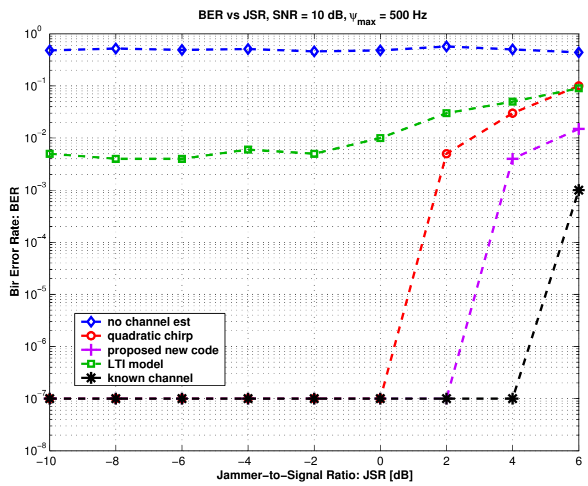

Figure 5: BER versus JSR with $\psi_{\max} = 500Hz$ and SNR=10 dB.