ADAPTIVE CODE JAMMER EXCISION FOR MC-SS COMMUNICATION SYSTEMS WITH CONSTANT ENVELOPE

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ABSTRACT
In this paper we consider the frequency processing of jammer-affected multi-carrier spread spectrum (MC-SS) signals in the special case of complex linear chirp spreading sequences. Such sequences not only provide a constant envelope, but also allow the estimation of the channel parameters using a linear time-invariant model–time and Doppler frequency shifts are represented by effective time shifts. In the presence of jammers, adapting the frequency code at each of the receiver sub-channels allows us to estimate the channel. We then develop a notch-filter approach consisting in using the adapted frequency code in the sub-channels affected by jammers, and keeping the original code in the sub-channels affected only by noise. The original spreading function is thus adapted to deal with sub-channels affected by jamming and channel noise. To illustrate the performance of our procedure, we perform simulations with different types of jammers, with various jammer to signal ratios, and with channel noise with various signal to noise ratios. The results indicate our approach is capable of determining the presence of jammers, and of excising them from the received signal by adapting the spreading sequence and using the estimated channel parameters.

1. INTRODUCTION

Multi-carrier spread spectrum (MC-SS), as a combination of spread spectrum and orthogonal frequency division multiplexing (OFDM) [1], is suitable for communications under extraneous situations. It spreads the transmitting signal in frequency so that one copy of the transmitting signal is sent in each of several sub-bands. MC-SS can outperform direct-sequence spread spectrum systems for some jammers [2], and by means of a cyclic guard interval it is able to remove intersymbol interference (ISI) much like OFDM.

To make the envelope of the MC-SS constant, thus avoiding distortion from non-linear amplifiers, Tan and Stuber [3] propose as spreading sequence a complex linear chirp of unit magnitude with a similar Fourier transform. As we show in [4], under time- and Doppler frequency-shifts in the transmission channel, these spreading sequences display only equivalent effective time delays at the channel output permitting the channel to be considered a linear time-invariant system. Time-frequency Discrete Evolutionary Transform (DET) [6] makes possible the estimation of the effective delays from the received signal via a spreading function. These estimates are used to equalize the effects of the multi-paths, and of the time- and the Doppler frequency-shifts. The estimation of the channel parameters is however significantly affected by jammers. In this paper, we consider a frequency approach to channel estimation and jammer excision in the MC-SS systems. First, we determine the sub-channels where jammers are present, and then determine how to adapt the original spreading function to estimate the channel. Once the channel parameters are estimated, the characteristics of the adapted spreading sequence is exploited to recover the sent bit. This is done by appropriately changing at the receiver the spreading sequence, so that it counteracts the effects of the jammer frequency components in those sub-channels affected by them.

We consider three different jamming techniques [7]. One creates a partial-band jammer composed of random sinusoids appearing together or separately in a frequency band. The second type generates a pulse-jammer that intermittently jams the whole transmission bandwidth by producing a random noise that appears as pulses. Finally, the third method creates a chirp-jammer capable of jamming a band of frequencies or most of the band, while displaying changing amplitudes and phases at different frequencies. The presence of these jammers can be determined by the DET of the received signal and its marginals. Given that the transmitting signal is a chirp of unit slope, a time-frequency spectrum easily detects the presence of one or several sinusoidal jammers, of chirps with different slope and of pulse jammers. The time and frequency marginals can be used to determine the frequencies or times where the jammer is present. Adapting the frequency code in the sub-channels where jammers are present allows the estimation of the channel. The effective shifts of the transmission channel and the adapted spreading code are used to detect the sent bit in all sub-channels. The rationale of the procedure is to use the redundancy of the system –the same information is sent in each of the sub-channels– to detect the information sent.

Typically [8, 9, 10] the channel is modeled as a random linear time-varying system. In our approach, using the effective time shifts for the special case of the quadratic spreading sequences we model the MC-SS system channel as linear and time invariant for the duration of a data bit and allow it to change at random from bit to bit or for a set of bits. This can be used to characterize slow and fast fading channels.

2. SYSTEM MODEL

An MC-SS system, just like direct-sequence spread spectrum, spreads the input data symbol in the time domain using
a typically ortho-normal code \( g(n) \). Likewise, the MC-SS system can be considered an orthogonal frequency division multiplexing system where the input data symbol modulates frequency code signals \( \{ G(k)e^{j\omega_k n} \ 0 \leq k \leq N-1 \} \) (See Fig. 1) where \( \{ G(k) \} \) are Fourier coefficients of \( g(n) \). In [3], the authors suggest a linear chirp for \( g(n) \) with a Fourier pair \( G(k) \) that is also a linear chirp,
\[
g(n) = e^{-j\pi \frac{N}{n} n^2}, \quad G(k) = e^{j\pi \frac{N}{n} k^2 (k+1)}
\]
(1)
The pair \( g(n) \) and \( G(k) \) are linear chrips in \( n \) and \( k \), both having unit constant envelope to avoid distortion from non-linear amplifiers, and \( G(k) = g^*(k) \). It can be also shown these sequences are orthogonal to their cyclic-shift versions. With the use of the proposed \( g(n) \) and \( G(k) \), detection of the sent data symbol is possible in either time or frequency domains, or in a joint time-frequency domain in the presence of intentional or non-intentional channel interference.

We have shown before that the above \( g(n) \) permits us to obtain a linear time-invariant model for the transmission channel by converting the time- and Doppler frequency-shifts into equivalent effective time-shifts [4]. We will show in this paper that it is also possible to counteract the effects of different jammers in the modeling estimation by adapting the spreading code \( g(n) \) in the receiver. This can be done in the frequency domain by taking advantage of the redundancy present in the MC-SS.

2.1 Channel Model.

In the time-domain the baseband transmitted signal of an MC-SS system is given by \( s(n) = dg(n) \), where \( d \) is the data symbol. The channel output, affected by multi-path, time- and Doppler frequency-shifts, is
\[
y(n) = d \sum_{\ell=0}^{L-1} \alpha_\ell g(n - N_\ell) e^{j\phi_\ell n} \quad (2)
\]
where \( L \) is the random number of paths, and \{ \( \alpha_\ell, N_\ell, \phi_\ell \) \} are the attenuation, and the time- and Doppler frequency-shifts for each path. Thus the channel is modeled as a random time-varying system. In [4], we observed that when using \( g(n) \) shifts in time and frequency can be jointly represented by an effective time shift. In fact, when the channel shifts in time by \( N_0 \) and in frequency by \( \phi_1 = 2\pi N_1/N \) the spreading signal is
\[
g(n-N_0)e^{j\phi_1 n} = g(n-N_0+N_1)e^{-j\frac{\pi(N_1^2-2N_0N_1)}{n}} \quad (3)
\]
or as a result of the chirp nature of \( g(n) \), it is effectively shifted in time by \( N_c = -N_0 + N_1 \), and multiplied by a complex factor. Consequently, the estimation of the channel is simplified so that it now consists in finding the effective time shifts for an LTI system.

Just as in [5], we consider Equation (2) the output corresponding to each data symbol, and let the channel parameters remain constant for the length of \( g(n) \) or of the transmitted signal \( s(n) \). Depending on whether we are simulating slow or fast fading, the channel parameters are allowed to change slowly or fast from one set of parameters to another. The channel parameter estimation is blind as we only have the received data and the information about \( g(n) \) and \( G(k) \), and we implement it using the discrete evolutionary transform (DET), [6]. Connecting the time-frequency kernel \( Y(n, \omega_k) \) of the output \( y(n) \) with the time-varying frequency response of the system \( H(n, e^{j\omega_k}) \), we found that its related spreading function \( S(\Omega, k) \) [5] provides the channel parameters. In fact, for a channel with parameters \{ \( L, \alpha_\ell, N_\ell, \phi_\ell \) \}, the spreading function is
\[
S(\Omega, k) = 2\pi \sum_{\ell=0}^{L-1} \alpha_\ell \delta(\Omega - \phi_k) \delta(k - N_\ell)
\]
For the case when the spreading function is \( g(n) \), according to our results in [4] the time-invariance makes it so that
\[
S(0, k) = 2\pi \sum_{\ell=0}^{L-1} \alpha_\ell \delta(k - N_c)^\ell
\]
is only needed, simplifying the estimation. These computations are affected by interferences, channel noise and especially jamming signals, present in the received signal. It is necessary first to determine the type of jammers present and the time intervals or frequencies occupied by them.

3. ADAPTIVE CODE FOR MODELING AND JAMMER EXCISION

3.1 Jammers Detection.

We assume as interference Gaussian channel noise as well as jammers of three different types: partial- or almost full-band jammers of the sinusoidal and chirp forms, and partial-time jammers consisting of pulses of random noise [7]. The detection of these jammers can be efficiently done by using the joint time-frequency DET of the received signal \( r(n) \), as well as its time and frequency marginals. The frequency marginal provides the frequencies where they occur, and determine the relation between the energies of the jammed received signal and the transmitted signals at each sub-channel. For a non-stationary received signal \( r(n) \), the DET [6], has a kernel
\[
R(n, \omega_k) = \sum_\ell r(\ell) W_\ell(n, \ell) e^{-j\omega_k \ell}
\]
where \( W_\ell(n, \ell) \) is a time- and frequency-dependent window obtained from the Gabor or Malvar signal representation, [6]. The evolutionary spectrum corresponding to \( r(n) \) is given by \( |R(n, \omega_k)|^2 \). The inverse transform is given by
\[
r(n) = \sum_k R(n, \omega_k) e^{j\omega_k n}
\]
It is important to indicate that the DET is one of the few time-frequency methods where besides the non-stationary spectrum the signal has a representation based in the evolutionary kernel. The time- and frequency-marginals corresponding to the signal are defined as

\[ TM(n) = \sum_k |R(n, \omega_k)|^2, \quad FM(k) = \sum_n |R(n, \omega_k)|^2 \]

The evolutionary spectrum combined with the time- and frequency-marginals provide the information about localization of the jammers in joint time-frequency, and separately in time or frequency.

In order to detect the jammers, we compute the DET of \( r(n) \), and compare its frequency marginals to the frequency marginals of the transmitting signal \( s(n) = dg(n) \). After setting a threshold we are able to determine in which sub-channels there is a jammer frequency component.

### 3.2 Adaptation for Channel Estimation.

Assuming that jammers significantly affect the signal in some of the sub-channels, to estimate the parameters of the channel it is necessary to adapt the received signal so as to minimize the effects of the jammers. Our approach is based on the frequency characterization of the received signal. If the channel noise is assumed white and if jammers are present the received signal \( r_k(n) \) in each sub-channel displays a constant component \( \eta \) from the channel noise, and a jammer component, \( J_k \), for those sub-channels where there is a jamming signal, so that

\[
r_k(n) = [dG(k)H(e^{j\omega_k}) + \eta + p_k J_k]e^{j\omega_k n} \tag{4}
\]

where

\[
H(e^{j\omega_k}) = \sum_i \alpha_i e^{-j\omega_k N_i i}
\]

is the frequency response of the equivalent channel, and \( p_k = 1 \) for frequencies where a jammer component exists, and zero otherwise.

![MCSS frequency sub-channel](image)

Figure 2: MCSS frequency sub-channel.

Given the possible concentration of the jammer at certain frequencies, the \( J_k \) component could be quite large and capable of overpowering the useful data at those frequencies. Thus the estimation is improved by changing the output \( r_k(n) \) at those sub-channels. To effect this we replace these \( r_k(n) \) by

\[
r_k(n) = r(n)e^{jLkG(k)} / |r(n)| = G(k) / |J_k|.
\]

Adding the rest of the frequency components, we have a modified received signal \( \bar{r}(n) \) that can be used for the channel estimation which is done as indicated in [4]. The results of this estimation, for each data symbol, are the number of paths \( \{L\} \), attenuations \( \{\alpha_k\} \) and the effective time delays \( \{N_{e,i}\} \) for each path.

### 3.3 Adaptation for Data Detection.

In order to recover at the receiver the sent data symbol \( d_k \), we need to get rid of the effect of the jammers. This is done by adapting the original spreading function \( g(n) \) so that the jammer is excised and that the obtained channel parameters can be used. We consider two types of sub-channels: \( N \) affected by channel noise only, and \( N \not\in\mathcal{J} \) affected by both channel noise and jammers and the jammer detection procedure presented above is used for differentiating these sub-channels. Suppose that the channel estimation gives that the closest signal (i.e., least attenuated) has an effective delay estimate \( \hat{N}_{e,0} \), then we create an adapted spreading function

\[
\hat{g}(n - \hat{N}_{e,0}) = \sum_{k \in N} G(k)e^{j\omega_k(n - \hat{N}_{e,0})} + \sum_{k \not\in N \not\in J} \hat{G}(k)e^{j\omega_k(n - \hat{N}_{e,0})}
\]

where \( G(k) \) correspond to the original code \( g(n) \) and for the \( N \not\in\mathcal{J} \) sub-channels we let \( \hat{G}(k) = G(k)/|J_k| \) which tends to zero for large values of the jammer component \( J_k \). It can be shown experimentally that the adapted sequences \( \hat{g}(n) \) are approximately orthogonal with respect to cyclic shifts. Using this characteristic we have that the received signal \( r(n) \) multiplied by \( \hat{g}^*(n - \hat{N}_{e,0}) \) gives

\[
\sum_k r_k(n) = \sum_{k \in N} r_k(n) \hat{g}^*(n - \hat{N}_{e,0}) / \alpha_0 + \sum_{k \not\in N} r_k(n) \hat{g}^*(n - \hat{N}_{e,0}) / \alpha_0
\]

where \( r_k(n) \) is the output of the sub-channels \( \alpha_0 \) is the attenuation channel parameter corresponding to \( \hat{N}_{e,0} \). Replacing \( H(e^{j\omega_k}) \), given above, letting

\[
\hat{g}(n - \hat{N}_{e,0}) = \sum_{k \in N} G(k)e^{j\omega_k(n - \hat{N}_{e,0})}
\]

by assuming that \( |J_k| \) is significantly large, and using the approximate orthogonality of the adapted sequences \( \{\hat{g}(n)\} \) with respect to cyclical shifts we obtain

\[
\sum_k r_k(n) = d|\hat{g}(n - \hat{N}_{e,0})|^2 + \sum_{k \in N} \eta \hat{g}^*(n - \hat{N}_{e,0}) e^{j\omega_k n} / \alpha_0 + \sum_{k \not\in N \not\in J} \hat{g}^*(n - \hat{N}_{e,0}) e^{j\omega_k n} / \alpha_0
\]

Averaging over time the above equation we find a decision variable

\[
y = dS + \sum_{n \in N} \eta \hat{g}^*(n - \hat{N}_{e,0}) e^{j\omega_k n} / \alpha_0 + \sum_{n \not\in N} \hat{g}^*(n - \hat{N}_{e,0}) e^{j\omega_k n} / \alpha_0 \tag{5}
\]
where $S = \sum_{n} |\hat{g}^*(n - N_n, 0)|^2$. If the average of the modulated adapted sequences is close to zero the above will give a good estimate for $d$, the sent bit.

Since only the frequencies where the jammer frequency component are affected and changed as indicated, leaving other frequency components unchanged, the effect is like that of a notch filter. Clearly the above derivation indicates that it is necessary to have a significant number of sub-channels where only noise is present, and that the jammer components have a larger energy than the noise and the clean received signal. If these conditions are not satisfied the above derivation will not be valid.

4. SIMULATIONS

The simulations are done using the base-band signal, and assuming that the channel changes at random bit by bit–simulating fast fading. Under these conditions, we simulate the proposed process for channel noise with different signal to noise ratios (SNRs) and different jammer to signal ratios (JSRs). The bit error rate are found by implementing 5000 Monte Carlo iterations with different noises and jammers. As mentioned above we considered three different types of jammers: partial and wide band jammers implemented by sinusoids and chirps and pulse jamming that affects the whole bandwidth. For each simulation the magnitude, phase and frequency of the sinusoidal and chirp jammers vary at random, the bandwidth of the chirps also changes at random. Likewise we let the width of the pulses vary for the pulse jammers. Using the evolutionary spectrum and its frequency marginals (See an example in Fig. 3 where the jamming signal is made up by three sinusoids, a chirp and pulse noise, the red line indicates the used threshold to detect the jammers) we can find a threshold to determine the sub-channels where jammers exist. The used jammer detection does not work when only channel noise. The results of our simulations are shown in Figs. 4 and 5. As expected, the BER decreases as the SNR increases for different JSRs, and it increases as we increase the JSR for different SNRs.

5. CONCLUSIONS

In this paper we have shown a procedure capable of excising jammers of different types in a MCSS communications system by adapting the input spreading sequence. The linear chirp spreading sequence displays special characteristics that simplify the estimation of the channel, and provides an efficient way to detect the sent data symbol. Our algorithm considers the frequency interpretation of the MCSS system, and changes the spreading sequence at the receiver to permit a better channel estimation and to excise possible jammer components at the different sub-channels. The procedure takes advantage of the redundancy in the MCSS transmission where the same data symbol is modulated by sub-carriers of different frequencies. The results are encouraging given the strong conditions under which we are simulating the process. Presently we are extending this work by considering adaptive filtering to accomplish an optimal choosing of the spreading sequence at the receiver.
REFERENCES


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