JAMMING MITIGATION USING SPACE-TIME CODED COLLISION-FREE FREQUENCY HOPPING

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ABSTRACT

Frequency hopping (FH) system, which is robust under jamming interference, was originally developed for secure military communication applications. However, the efficiency of the conventional FH scheme is very low due to inappropriate use of the total available bandwidth and transmission collisions. To improve the system capacity, we develop a space-time coded collision-free frequency hopping (STC-CFFH) system based on the OFDM framework. The capacity and performance analysis of the proposed scheme is presented under frequency selective fading and partial-band jamming through both theoretical analysis and simulation examples. Our analysis indicates that the STC-CFFH scheme improves the spectral efficiency and inherent anti-jamming features of conventional FH systems.

***Index Terms*—** Frequency hop communication, Jamming, MIMO systems

1. INTRODUCTION

The combination of space-time coding [1, 2] and orthogonal frequency division multiplexing (STC-OFDM) has the potential to exploit multipath diversity and achieve high speed high quality transmissions. However, the STC-OFDM system must co-exist with various forms of jamming to provide reliable communication. This is especially true for military communication systems, which must be robust under hostile jamming. Frequency hopping (FH) system is widely used to mitigate the effects of hostile jamming [3]. Mainly limited by the collision effect, the spectral efficiency of the FH system is very low.

As an effect to develop a spectrally efficient FH system, in this paper, we present a space-time coded collision-free frequency hopping (STC-CFFH) scheme based on the OFDM framework and a secure subcarrier assignment algorithm. STC-CFFH's secure subcarrier assignment is designed to ensure that: (i) Each user hops to a different set of subcarriers in a pseudo-random manner at the beginning of each new symbol period; (ii) At each symbol period, different users always transmit on non-overlapping sets of subcarriers, hence are collision-free [4].

In [5], the effect of partial band interference in OFDM framework is studied and shows partial band interference can severely degrade the system performance. In this paper, we analyze the performance of STC-CFFH under partial band interference environment. The study is carried out for the conventional OFDMA system, an OFDMA system based on CFFH, and the proposed STC-CFFH system. Analysis and simulation for various jamming scenarios demonstrate that STC-CFFH outperforms the traditional OFDMA system and CFFH system.

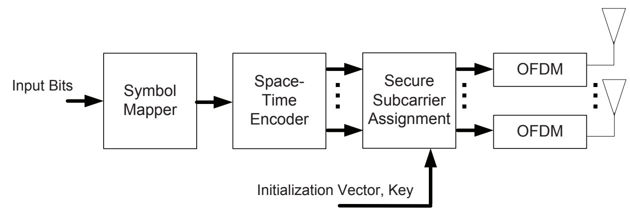

Fig. 1. Block diagram of STC-CFFH transmitter

2. SYSTEM DESIGN

2.1. Collision-Free Frequency Hopping

Assume there are U users in the OFDMA system, which has a total of K subcarriers $\{f_0, \cdots, f_{K-1}\}$. The idea is that: at each OFDM symbol period, a specific subset of the total OFDM subcarriers are assigned to each user, such that each user transmit on non-overlapping subcarriers. Assuming that at the t-th symbol, the ith user is assigned a set of subcarriers $C_t^i = \{f_{t,i_1}, \cdots, f_{t,i_{N_i}}\}$, where N_i is the total number of subcarriers assigned to the ith user. For a given OFDM symbol period, the system is designed in a way such that

$$C_t^i \bigcap C_t^j = \emptyset, \quad \text{if} \quad i \neq j, \tag{1}$$

to ensure there are no collision between the users. Ideally, for full capacity of the OFDM system, all subcarriers are assigned to a user such that,

$$\bigcup_{i=1}^{U} C_t^i = \{f_0, \cdots, f_{K-1}\}. \tag{2}$$

Each user transmits zeros on subcarriers which are not assigned to him/her, and hence ensures collision-free transmission among the users. In the following, we will first discuss the transmitter design, and then explain the receiver design.

2.2. Transmitter Design

We consider a wireless communication system employed with n_T transmit antennas and n_R receive antennas. A block diagram of the STC-CFFH transmitter is depicted in Figure 1. Initially, a block of information bits are transformed into a stream of baseband constellation complex symbols through a mapper. Then, the space-time encoder maps the complex symbols to a code matrix. We now concatenate the STC block with the OFDM modulator. Note that we are using an OFDMA system, at each OFDM symbol period, each user is assigned a specific subset of the total available subcarriers via the advance encryption standard (AES) based secure subcarrier index assignment algorithm. A detailed description of the secure subcarrier is provided in [4]. To ensure collision-free transmission among different users, each user transmits information symbols only on assigned subcarriers, and transmits zeros on subcarriers which are not assigned to him/her. For $i = 1, 2, \cdots, n_T$, and $k = 1, 2, \cdots, K$ we denote the signal transmitted from the ith antenna, the kth OFDM subcarrier at the t-th symbol period as

$$X_t^i = [x_{t,1}^i, x_{t,2}^i, \cdots, x_{t,K}^i]^T, \tag{3}$$

where T is the transpose operator. We define $X_t \triangleq [X_t^1, \cdots, X_t^{n_T}]^T$ to denote the overall signal vector transmitted through all the antennas in t-th symbol period. After the OFDM symbols are generated, cyclic prefixes of length P are inserted in the guard interval and transmitted through a frequency selective channel of order L. Inter-symbol interference (ISI), is eliminated by ensuring the guard interval P satisfies $P > L$.

2.3. Receiver Design

At the receiver, following the cyclic prefix removal, the received OFDM signal is demodulated using fast Fourier transform (FFT). For $j = 1, 2, \cdots, n_R$, $k = 1, 2, \cdots, K$, the received signal for the kth subcarrier at jth receive antenna is given by

$$R_{t,k}^j = \sum_{i=1}^{n_T} H_{t,k}^{i,j} x_{t,k}^i + N_{t,k}^j, \tag{4}$$

where $H_{t,k}^{i,j}$ is the channel frequency response at the t-th symbol for the path from the ith transmit antenna to the jth receive antenna corresponding to the kth OFDM subcarrier. It is assumed that the channel frequency response remains constant during each OFDM frame (quasi-static) and the channels between the different antennas are uncorrelated. $N_{t,k}^j$ is the OFDM demodulation output for the additive white Gaussian noise (AWGN) with zero-mean and variance σ_N^2 at the jth receive antenna and the kth subcarrier. Following OFDM demodulation, the secure subcarrier de-assignment algorithm is applied to separate and extract the signals of each user. Finally, the signal is space-time decoded with maximum likelihood decoding and mapped back into bits by the symbol de-mapper.

3. PERFORMANCE ANALYSIS OF STC-CFFH

3.1. Under Partial Band Interference

In partial band interference, the enemy uniformly distributes its jamming power I_0 over W_J contiguous subcarriers [6]. We denote the jammer occupancy (ρ) as the fraction of subcarriers that experience interference as

$$\rho = \frac{W_J}{W_{SS}} < 1, \tag{5}$$

where W_{SS} is the total spread spectrum bandwidth. The interference signal $J(t)$ can be modeled as

$$J(t) = \sum_{m \in \mathcal{A}} d_m(t) e^{j(\omega_m t + \phi_m)}, \tag{6}$$

where d_m is the baseband jamming signal with power I_0, the carrier frequency is ω_m, the initial phase is ϕ_m and $\mathcal{A}$ is the set of channels that suffer interference.

The received signal for the subcarriers that experience interference is

$$R_{t,k}^j = \sum_{i=1}^{n_T} H_{t,k}^{i,j} x_{t,k}^i + N_{t,k}^j + J_{t,k}^j, \tag{7}$$

where $J_{t,k}^j$ is the interference signal at symbol period t for the jth receive antenna on the kth OFDM subcarrier. The signal-to-noise ratio (SNR) is represented by SNR = $\frac{E_s}{N_0}$,where E_s is the average signal power and N_0 is the noise power.

The signal to interference plus noise ratio (SINR) at the receiver is represented by SINR = $\frac{E_s}{N_0+I_0}$, where I_0 is the interference power. When the signal is dominated by interference, the SINR can be represented as the signal-to-interference ratio (SIR) where SIR $= \frac{E_s}{I_0}$.

Note, orthogonal space-time codes are capable of perfectly decoding the transmitted symbols under partial band interference and noise-free environments when at least one frequency band is not jammed. For example we consider a 4×4 space-frequency orthogonal code design, which is depicted in Table 1. Each column represents the symbols transmitted on each frequency band, whereas each row represents the symbols transmitted on each transmit antenna. The 4×4 orthogonal code design is represented by the inner block matrix with transmit symbols x_1, x_2, x_3, and x_4. The OFDM modulation converts the time diversity into frequency diversity. Due to the orthogonality of the code design, during a given symbol period, each frequency band contains full information about the transmitted symbols. As a result, the transmitted symbols are recovered perfectly when there is at least one un-jammed frequency band.

Table 1. A 4x4 Space-Frequency block with Orthogonal Code Design.

Tx \ *freq.*	f_0	f_1	f_2	f_3
1	x_1	x_2	x_3	x_4
2	$-x_2$	x_1	$-x_4$	x_3
3	$-x_3$	x_4	x_1	$-x_2$
4	$-x_4$	$-x_3$	x_2	x_1

In this case, the average probability of error P_e, due to partial band jamming, is the sum of the probabilities that i out of 4 frequency bands are jammed for $i = 0, 1, \cdots, 4$. The average probability of error can be expressed as

$$P_e = \sum_{i=0}^{4} P_{e,i} \; Pr\{i \; out \; of \; 4 \; bands \; are \; jammed\}, \tag{8}$$

where $P_{e,i}$ is the probability of error when i out of 4 bands are jammed.

3.2. Under Rayleigh Fading

In this section, we analyze the pairwise error probability of the STC-CFFH system under Rayleigh fading. Assuming ideal channel state information (CSI) and perfect synchronization between transmitter and receiver, the maximum likelihood decoding rule of the transmitted signal is given by

$$\hat{X}_t = \arg\min_{X_t} \sum_{j=1}^{n_R} \sum_{k=1}^{K} \left| R_{t,k}^j - \sum_{i=1}^{n_T} H_{t,k}^{i,j} x_{t,k}^i \right|^2, \tag{9}$$

where $\hat{X}_t$ denotes the recovered codeword. Note that the minimization is performed over all possible space-time codewords.

The pairwise error probability of transmitting X_t and deciding in favor of another codeword $\hat{X}_t$, given the realizations of the fading channel H_t is given by

$$P(X_t, \hat{X}_t|H_t) \leq \exp\left(-d^2(X_t, \hat{X}_t)\frac{E_s}{4N_0}\right), \qquad (10)$$

where $H_t \triangleq \{H_{t,k}^{i,j}\}$ for $i = 1, 2, \cdots, n_T$, $j = 1, 2, \cdots, n_R$, and $k = 1, 2, \cdots, K$. In other words, H_t is a three-dimensional matrix of size $n_T \times n_R \times K$ that contains the channel frequency response corresponding to each transmit-receive antenna pair. $d^2(X_t, \hat{X}_t)$ is a modified Euclidean distance between the two space-time codewords X_t and $\hat{X}_t$, and is given by

$$d^2(X_t, \hat{X}_t) = \sum_{k=1}^{K}\sum_{j=1}^{n_R}\left|\sum_{i=1}^{n_T} H_{t,k}^{i,j}(\hat{x}_{t,k}^i - x_{t,k}^i)\right|^2, \qquad (11)$$

where $\hat{x}_{t,k}^i$ is the estimated version of $x_{t,k}^i$.

Let us define a codeword difference matrix $C(X_t, \hat{X}_t) = X_t - \hat{X}_t$ and define a codeword distance matrix $B(X_t, \hat{X}_t)$ with rank r_B as $B(X_t, \hat{X}_t) = C(X_t, \hat{X}_t) \cdot C(X_t, \hat{X}_t)^\dagger$, where † denotes the Hermitian of a matrix. Since the matrix $B(X_t, \hat{X}_t)$ is nonnegative definite Hermitian matrix, the eigenvalues of $B(X_t, \hat{X}_t)$ are nonnegative real numbers.

After averaging with respect to the Rayleigh fading coefficients, the pairwise error probability is upper bounded by [7]

$$P(X_t, \hat{X}_t|H_t) \leq \left(\prod_{j=1}^{r_B}\lambda_j\right)^{-n_R}\left(\frac{E_s}{4N_0}\right)^{-r_B n_R}, \qquad (12)$$

where λ_j are the eigenvalues of the codeword distance matrix $B(X_t, \hat{X}_t)$.

In the case of low signal-to-noise ratio (SNR), the upper bound in (12) can be expressed as [8],

$$P(X_t, \hat{X}_t|H_t) \leq \left(1 + \frac{E_s}{4N_0}\sum_{j=1}^{r_B}\lambda_j\right)^{-n_R}. \qquad (13)$$

3.3. Under Rayleigh Fading and Partial Band Interference

In the presence of Rayleigh fading and partial band interference, the pairwise error probability can be expressed in terms of the interference power I_0 and average signal power E_s. In the case of high SNR, the upper bound in (12) can be expressed as

$$P(X_t, \hat{X}_t|H_t) \leq \left(\prod_{j=1}^{r_B}\lambda_j\right)^{-n_R}\left(\frac{E_s}{4I_0}\right)^{-r_B n_R}, \qquad (14)$$

where I_0 is the dominant degrade factor. In Section 4, the simulation results indicate that the limiting performance factor is the interference power I_0.

In the case of low SNR, the system is severely degraded by the interference I_0 and noise power N_0. From (13), the upper bound in the presence of Rayleigh fading and partial band interference can be expressed as

$$P(X_t, \hat{X}_t|H_t) \leq \left(1 + \frac{E_s}{4(N_0+I_0)}\sum_{j=1}^{r_B}\lambda_j\right)^{-n_R}. \qquad (15)$$

At low SINR the diversity gain is low, however at high SINR the diversity gain becomes noticeable by the STC-CFFH system.

3.4. Capacity

In this section, we compute the capacity of the STC-CFFH system in the presence of partial band interference. Assuming perfect channel state information at the receiver, the ergodic capacity of a $n_T \times n_R$ multiple-input, multiple-output (MIMO) system can be calculated as

$$C_0 = log_2(det(I_{n_R} + \frac{SNR}{n_T}HH^\dagger)), \qquad (16)$$

where I is an n_R x n_R identity matrix, H is the realizations of the fading channel, SNR is the signal to noise ratio per receive antenna, † represent the Hermitian matrix, and *det* is the determinant.

In the frequency-hopped system, the transmitted signals are frequency-hopped over a band much larger than the required communication bandwidth. Under partial band interference, the probability of any subcarrier being jammed is equal the jammer occupancy ρ. The per-subcarrier SINR is given by [9]

$$SINR = \begin{cases} \delta * SNR & \text{if jammed} \\ SNR & \text{otherwise} \end{cases}$$

where $\delta = \frac{N_0}{N_0+I_0}$.

The ergodic capacity of the STC-CFFH system under partial band interference parameterized by SNR, δ, and ρ is given by

$$C(SNR, \delta, \rho) = \rho C_0(\delta \cdot SNR) + (1-\rho)C_0(SNR). \qquad (17)$$

4. SIMULATION RESULTS

In this section, the performance of the symbol error rate (SER) of the proposed STC-CFFH system and the OFDM systems are evaluated by simulations.

The simulations are carried out over a frequency selective Rayleigh fading channel with partial band jamming. An Alamouti space-time coding system with two transmit antennas and one receive antenna is applied to the proposed STC-CFFH system. We assume perfect timing and frequency synchronization, as well as uncorrelated channels for each antenna. The total number of available subcarriers is K = 256 and the number of users is U = 16; therefore each user is assigned 16 subcarriers.

We consider the performance of three systems: (i) A conventional OFDM system, (ii) an STC-OFDM system, and (iii) the proposed STC-CFFH system. For systems (i) and (ii), each user transmits on 16 fixed subcarriers. In system (iii), each user transmits on 16 pseudo-random secure subcarriers. We assume the jammer intentionally interferes 8 contiguous fixed subcarriers per user.

Figure 2 depicts the SER versus SNR over frequency selective fading with SIR equal to 0dB. Due to the secure subcarrier assignment, the proposed STC-CFFH system outperforms the STC-OFDM and OFDM systems. The pseudo-random secure subcarrier assignment randomizes each users' channel occupancy at a given time, therefore allowing for multiple access over a wide range of frequencies. We also notice that at high SNR levels, the performance limiting factor for all systems is the partial-band jamming. Interference suppression methods can be included in the system design to further reduce the affect of jamming, however such methods may complicate the system design.

In Figure 3, the SER versus the jammer occupancy (ρ) is evaluated with SNR = 15dB and SIR = -5dB for the STC-CFFH and STC-OFDM systems. Recall the jammer occupancy is the fraction of subcarriers that experience interference. As the jammer occupancy ratio approaches full jammer occupancy ($\rho = 1$), STC-CFFH

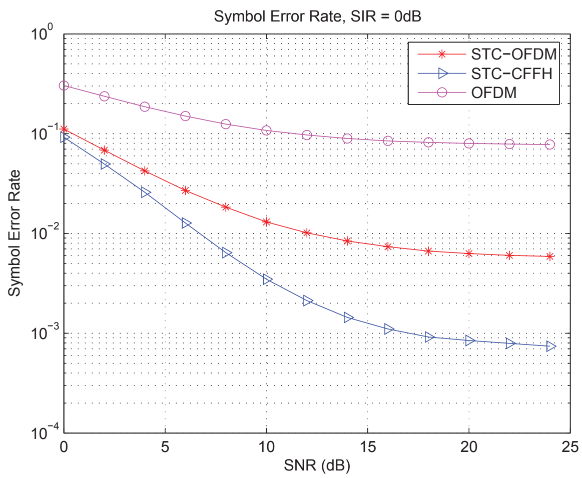

Fig. 2. Comparison of the SER over frequency selective fading channel with partial-band jamming. Number of subcarriers K = 256, number of users = 16 and SIR = 0dB.

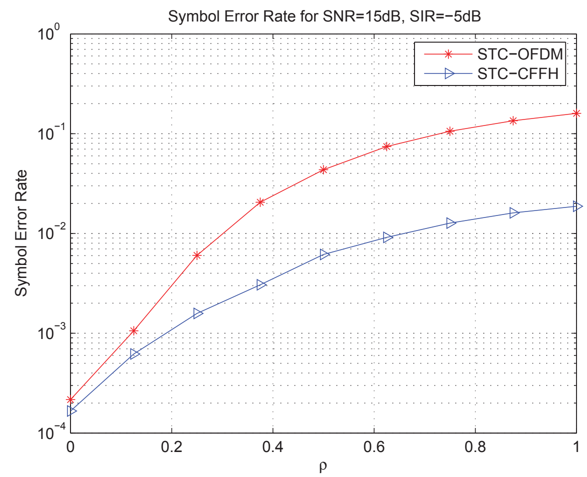

Fig. 3. SER versus Jammer Occupancy over frequency selective fading channel with partial-band to full-band jamming. Number of subcarriers K = 256, number of users = 16, SIR = -5dB and SNR = 15dB.

and STC-OFDM systems increase in SER as expected. However, the STC-CFFH outperforms the STC-OFDM system at full jammer occupancy. Note, the spectral efficiency of the proposed STC-CFFH system is the same as the corresponding OFDM system.

5. CONCLUSIONS

In this paper, a spectrally efficient anti-jamming space-time coded collision-free frequency hopping system is presented and evaluated in the presence of partial-band jamming. The STC-CFFH system is based on the OFDM framework and the secure subcarrier assignment scheme. The secure subcarrier assignment ensures at the start of each new symbol period, each user hops to a different set of subcarriers in a pseudo-random manner and each user always transmits on non-overlapping sets of subcarriers. The pairwise error probability is derived for the STC-OFDM system under frequency selective fading and partial-band jamming. Analysis and simulation examples are provided to demonstrate the effectiveness of the proposed STC-CFFH system. As an effort to meet the increasing demand for highly reliable and capacity reaching wireless communications, the proposed scheme can be applied directly to commercial and military applications.

6. REFERENCES

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