MC-CDMA Aided Multi-User Space-Time Shift Keying in Wideband Channels

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Abstract—In this paper, we propose multi-carrier code division multiple access (MC-CDMA)-aided space-time shift keying (STSK) for mitigating the performance erosion of the classic STSK scheme in dispersive channels, while supporting multiple users. The codewords generated by the STSK scheme are appropriately spread in frequency-domain (FD) and transmitted over a number of parallel frequency-flat subchannels. We propose a new receiver architecture amalgamating the single-stream maximum-likelihood (ML) detector of the STSK system and the multiuser detector (MUD) of the MC-CDMA system. The performance of the proposed scheme is evaluated for transmission over frequency-selective channels in both uncoded and channel-coded scenarios. The results of our simulations demonstrate that the proposed scheme overcomes the channel impairments imposed by wideband channels and exhibits near-capacity performance in a channel-coded scenario.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) wireless systems have attracted substantial research interests over the past two decades owing to their potential of attaining beneficial diversity and/or multiplexing gains. The pioneering study of Foschini [1] reveals that MIMO systems have the capability to achieve a high transmission rate without requiring additional bandwidth. On the other hand, space-time block codes (STBCs) [2] were designed for improving the link reliability by the maximum attainable spatial diversity.

It is, however, not desirable that antenna elements (AEs) will be used either entirely for multiplexing or solely for diversity. Specifically, a particular MIMO configuration may be utilized for attaining both the diversity and the multiplexing gains. To this end, linear dispersion codes were proposed [3], [4], which outperformed the previous systems, but the decoding complexity was substantially increased. As a low-complexity design alternative, spatial modulation (SM) [5] as well as space shift keying (SSK) [6] adopted the principle of shrewd transmit-antenna activation to provide additional bandwidth efficiency. Motivated by these ideas, STSK [7], [8] was proposed, which extends the concept of pure spatial-domain antenna activation of SM/SSK schemes to both the spatial and temporal dimensions. To be more specific, the idea is to rely on beneficial dispersion matrix (DM) activation, rather than on the simple antenna activation process of SM/SSK in addition to the conventional modulation based signalling. The STSK system can thus provide substantial diversity as well as multiplexing gain. However, the majority of STSK studies were focused on narrowband scenarios, rather than on realistic wideband scenarios. Although the mitigation of the impairments due to channel dispersion was studied in [9], [10], the spreading of user information across the FD remained an open problem. Against this background, our main contributions are:

1) We propose MC-CDMA aided STSK systems, which can attain a beneficial diversity versus multiplexing gain tradeoff even in multi-path environments, while supporting multi-user transmissions. The space-time codewords generated by STSK are appropriately mapped to the MC-CDMA subcarriers. As a result, the STSK signal generated for each subcarrier of the parallel modem experiences frequency-flat fading. FD spreading provides additional diversity benefits.

2) We propose a novel MUD amalgamated with the low-complexity single-stream ML detector of [7], [8] in order to estimate the user information which is spread over different subcarriers. We consider both the multi-user downlink (DL) and uplink (UL) scenarios and evaluate their performances against both the single-user and narrowband benchmarkers.

3) Furthermore, we design a near-capacity coding assisted MC-CDMA STSK arrangement and evaluate its performance.

The rest of the paper is organized as follows. Section II details the transceiver model of our MC-CDMA aided STSK system. The channel-coded MC-CDMA aided STSK philosophy is discussed in Section III. In Section IV, the system performance is characterized for both the uncoded and channel-coded scenarios. Finally, we conclude in Section V.

II. SYSTEM MODEL

Consider an MC-CDMA aided STSK system having \( N_T \) transmit and \( N_R \) receive AEs and communicating over frequency-selective Rayleigh fading channels. Furthermore, \( N_p \) subcarriers are employed by our MC-CDMA modem for transmitting \( N_p \) STSK codewords.

A. The Transmitter and the Channel

Fig. 1 depicts the transmitter model of our MC-CDMA aided STSK scheme. The STSK transmitter generates space-time codewords from the users’ source information. These codewords are further spread across the FD and are then mapped to a number of subcarriers, before being transmitted
using $N_T$ transmit AEs over $T$ time slots. More specifically, each STSK signalling block $X^u[n_p]$, $n_p = 0, 1, \ldots, (N_p - 1)$ is created from $\log_2(L \cdot Q)$ source bits of user $u$, $u = 0, 1, \ldots, (U - 1)$, in accordance with [7], [8], [11]. The STSK scheme may be unambiguously optimized employing a certain objective function.

Orthogonality, the subcarrier frequencies have to be equally spaced with

$$f_{n_e} = \frac{n_e}{N_c T}.$$  \hspace{1cm} (3)

Defining the FD-spread symbol stream of user $u$ by

$$S^u_{n_T, T_i} = c^u_{n_T, T_i}, \quad s_f = 1, 2, \ldots, (S_f - 1),$$

the TD samples may thus be expressed by

$$s^u_{n_T, T_i}[n_s] = \frac{1}{\sqrt{N_c}} \sum_{n_e=0}^{(N_c - 1)} S^u_{n_T, T_i}[n_e] e^{j 2 \pi n_e n_s / N_c},$$  \hspace{1cm} (4)

which is given by the $N_c$-point inverse discrete Fourier transform (IDFT) of $S^u_{n_T, T_i}$:

$$S^u_{n_T, T_i} = \text{IDFT}_{N_c} \left\{ S^u_{n_T, T_i} \right\}.$$  \hspace{1cm} (5)

After the IDFT operation, cyclic prefixes (CP) of appropriate length are incorporated for eliminating the effects of inter-symbol interference (ISI).

We assume that each channel component of the MIMO system corresponding to user $u$ is frequency-selective, and is described by its discrete-time channel impulse response (CIR), $h^u_{n_R, n_T}, \quad n_R = 0, 1, \ldots, (N_R - 1), \quad n_T = 0, 1, \ldots, (N_T - 1),$ whereas $H^u$ denotes the corresponding $(N_R \times N_T)$-element FD channel transfer matrix.

1) Multi-user uplink (UL) scenario: In the multi-user UL scenario, the signals from the mobile stations (MSs) of different users are received at the base station’s (BS) AEs through different channels. Hence the TD and the FD channel coefficients are independent between users.
2) Multi-user downlink (DL) scenario: During DL transmissions, the desired signal and the interfering signals are received at any MS through the same channel. The channel variables for all the users may thus be expressed as identical to those of the intended user $v$ for DL transmissions:

$$h_{nR, nT}^v = h_{nR, nT}^u \quad \hat{H}^u = \hat{H}^u \quad \forall u.$$  \hfill (6)

B. The Receiver

Fig. 3 illustrates the receiver architecture of our MC-CDMA aided STSK system. The received signal, after CP removal, is demodulated by Fourier-transforming it. Assuming perfect synchronization at the receiver, the discrete-time signal impinging on the $nR$-th receive AE during time interval $T_i$ can be expressed as [14]

$$r_{nR, T_i} = \sum_{u=0}^{(U-1)} \sum_{nT=0}^{(N_T-1)} h_{nR, nT}^u \circ s_{nT}^u + w_{nR, T_i},$$  \hfill (7)

where $\circ$ denotes $N_c$-point circular convolution and $w_{nR, T_i}$ represents the additive white Gaussian noise (AWGN). After applying $N_c$-point discrete Fourier transform (DFT) denoted by DFT$_{N_c}\{\cdot\}$, the FD MIMO output $\hat{R}[n_c]$ is given by

$$\hat{R}[n_c] = \sum_{u=0}^{(U-1)} \hat{H}^u[n_c]S^u[n_c] + W[n_c]$$  \hfill (8)

for every $n_c = 0, 1, \ldots, (N_c - 1)$, such that

$$\hat{R}_{nR, T_i} = \text{DFT}_{N_c}\{r_{nR, T_i}\}, \quad \hat{R}[n_c] \in \mathbb{C}^{N_R \times T},$$  \hfill (10)

$$\hat{H}_{nR, nT}^u = \text{DFT}_{N_c}\{h_{nR, nT}^u\}, \quad \hat{H}^u[n_c] \in \mathbb{C}^{N_R \times N_T},$$  \hfill (11)

$$S_{nT}^u = \text{DFT}_{N_c}\{s_{nT}^u\}, \quad S^u[n_c] \in \mathbb{C}^{N_T \times T},$$  \hfill (12)

$$W_{nR, T_i} = \text{DFT}_{N_c}\{w_{nR, T_i}\}, \quad W[n_c] \in \mathbb{C}^{N_T \times T}.$$  \hfill (13)

The linearized system model of [4] reduces to (8)

$$\bar{R}[n_c] = \sum_{u=0}^{(U-1)} \hat{H}^u[n_c]\chi [c_{sf}^u K^u] + W[n_c], \quad s_f = 1, 2, \ldots, (S_f - 1), \quad n_c = (n_p S_f + s_f),$$  \hfill (14)

where we have $\bar{R}[n_c] = \text{vec}(\bar{R}[n_c]) \in \mathbb{C}^{N_R T \times 1}$ by using the vectorial stacking operator $\text{vec}()$, $\hat{H}^u[n_c] = I_T \odot \hat{H}^u[n_c] \in \mathbb{C}^{N_R T \times N_T T}$ is the stacked FD channel transfer matrix of user $u$, $\odot$ denotes the Kronecker product and $I_T$ represents the $(T \times T)$ identity matrix, and the linear transformation matrix $\chi \in \mathbb{C}^{N_T \times Q}$ [4], [8] is given by $\chi = [\text{vec}(M_1), \ldots, \text{vec}(M_Q)]$. Furthermore, $\bar{W}[n_c] = vec(W[n_c]) \in \mathbb{C}^{N_R T \times 1}$ is the AWGN vector, while the equivalent transmit signal vector $K^u \in \mathbb{C}^{Q \times 1}$ is defined by [8]

$$K^u = [0, \ldots, 0, x^u, 0, \ldots, 0]^T,$$  \hfill (15)

where a constellation symbol $x^u$ exists only at position $q$, such that the $q$-th DM is activated.

Since the source information of users in a particular space-time block indexed by $n_p$ is spread over $S_f$ number of outputs from $\bar{R}[n_p S_f]$ to $\bar{R}(n_p + 1) S_f - 1$, the single-stream maximum-likelihood (ML) detector of [7], [8] in combination with the multi-user detector (MUD) of [12] is employed over these $S_f$ number of matrices to jointly detect the information of the users corresponding to the specific block. The single-stream maximum-likelihood multiuser detector (ML-MUD) [7], [12] may hence be used for estimating the set of $U$ users, $\hat{q}[n_p] = \{q_1, q_2, \ldots, q(U-1)[n_p]\}$ and the constellation symbol indices, $l_c[n_p] = \{l_{c1}[n_p], \ldots, l_{c(U-1)}[n_p]\}$. More explicitly, given the received signals of (14), the ML-MUD may thus be formulated as [7], [12]:

$$\hat{q}[n_p], l_c[n_p] = \arg \min_{q, l_c} \sum_{s_f = 0}^{(S_f - 1)} \sum_{x^u} \left| \bar{R}[n_p S_f + s_f] \right|^2$$

$$\times c_{sf}^u \hat{H}^u[n_p S_f + s_f] x^K_{q^u, l_c^u}^T,$$  \hfill (16)

where $K_{q^u, l_c^u}$ denotes the equivalent transmit signal vector defined in (15) when the transmitted indices are $q^u$ and $l_c^u$, respectively, $s_f^u$ denotes the $s_f^u$-th constellation symbol of user $u$ and $(\cdot)_{q^u}$ indicates the $q^u$-th column of the matrix ‘.’.

1We use the notation $u$ to represent the generalized user and $v$ to denote the intended user.

2Equations (7) - (14) and (16) are applicable for both the UL and DL scenarios and may be simplified further using (6) for downlink channels.
III. CHANNEL-CODED SCHEME

We propose a powerful iterative-detection aided MC-CDMA STSK transceiver as shown in Fig. 4. We employ a recursive systematic convolutional (RSC) and unity-rate coding (URC) architecture, where the information bits, after being channel-encoded by the RSC code, are passed to the random bit interleaver \( \Pi_1 \). After being randomly permuted, these bits are then UR encoded\(^3\) and after a second interleaving by \( \Pi_2 \), are transmitted through the MC-CDMA STSK scheme.

The received signals, after discarding the CP, are demodulated by the FD MC-CDMA demodulator. The symbols, after DFT processing at the demodulator, are input to the MC-CDMA STSK demapper block. Then, the three soft-decision decoders (the STSK demapper, the URC and the RSC decoder) start exchanging extrinsic information iteratively. The URC decoder generates extrinsic information employing the \( a \ priori \) information gleaned from the STSK demapper. More specifically, if the band of linearized FD signals from \( \mathbf{R}[n_p S_f + s_f] \) to \( \mathbf{R}[n_p + 1, S_f - 1] \) contains \( N \) channel coded bits \( b_0, b_1, \ldots, b_{N-1} \), then (17) written at the top of the page formulates the extrinsic logarithmic-likelihood ratio (LLR), \( L_e(b_i) \) for the bit \( b_i \), \( i = 0, 1, \ldots, (N-1) \), as detailed in [11], [15]. In (17), \( L_o(\bullet) \) refers to the \( a \ priori \) LLR for the bit \( \bullet \). \( K_1^u \) and \( K_0^u \) denote the subsets of the possible \( K^u \) vectors defined by (15) corresponding to the bit values \( b_i = 1 \) and \( b_i = 0 \), respectively, whereas other notations were defined earlier in Sec. II. Equation (17) can be further simplified using the approximate-logarithmic-maximum \( a \ posteriori \) (Approx-

\[^3\]The URC has been used to beneficially spread the extrinsic information owing to its infinite impulse response [11], thus facilitating iterative convergence to extremely low bit-error rate (BER).

\[ L_e(b_i) = \ln \left( \sum_{K_1^u, \mathbf{H}^u \in K_1^u} K_1^u \right) - \ln \left( \sum_{K_0^u, \mathbf{H}^u \in K_0^u} K_0^u \right) \]  

(18)

Table I

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<thead>
<tr>
<th>MAIN SYSTEM PARAMETERS</th>
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<tbody>
<tr>
<td>Channel model</td>
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<td>Fast fading envelope</td>
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<td>Normalized Doppler frequency</td>
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<tr>
<td>Spreading code</td>
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<td>No. of subcarriers, ( N_c )</td>
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<td>CP length</td>
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<tr>
<td>STSK ((N_T, N_R, T, Q, \mathcal{L}))</td>
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<td>Outer iterations, ( I_{outer} )</td>
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<td>Inner iterations, ( I_{inner} )</td>
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<td>Inner iterations, ( I_{inner} )</td>
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The RSC decoder, after several iterative exchange of extrinsic information, outputs the estimate of the information bits.

IV. RESULTS AND DISCUSSIONS

We characterize STSK and MC-CDMA aided STSK scheme both in narrowband and wideband environments. The basic simulation parameters are listed in Table I.

It is demonstrated in Fig. 5 that classic single-carrier STSK (2, 2, 2, 2) scheme works well in narrowband scenarios, but it exhibits a severe error floor in dispersive channels, when the COST207-RA channel model is considered. In the typical
The investigation of our channel-coded scheme was carried out in narrowband and in dispersive channels. The performance of the MC-CDMA aided STSK scheme both in narrowband and in dispersive channels is also compared to that of the MC-CDMA based STBC $(N_T, N_R) = (2, 2)$, BPSK and QPSK respectively having similar throughput, which demonstrates the strength of the proposed scheme.

Additionally, the performances of the multi-user MC-CDMA aided STSK scheme for the DL and the UL scenarios in the COST207-RA channel are characterized in Fig. 7 and Fig. 8 respectively, which were found to be more or less similar under the idealized conditions of perfect synchronization. Furthermore, the achievable performance improved upon increasing $S_f$, while both the UL and the DL BER degraded under multiuser scenarios as a result of the increased MUI imposed by multiple users.

Fig. 9 characterizes the performance of the serially concatenated RSC- and URC-coded single-user MC-CDMA STSK $(2, 2, 4, 4)$ scheme communicating over broadband channels. The investigation of our channel-coded scheme was carried out using the simulation parameters of Table I. Fig. 9 demonstrates that the channel-coded scheme provides a sharp decrease in
BER after a few iterations. The maximum achievable rates, where the scheme can still exhibit an extremely low BER, were computed using EXIT chart analysis and are shown as the ultimate benchmark of the proposed scheme. Specifically, as discussed in [8, 17], the area under the inner decoder’s EXIT characteristic gives the maximum achievable rate for the specific scheme. The signal-to-noise ratios (SNRs) which provide maximum achievable rates for the MC-CDMA STSK (2, 2, 2, 4, 4) schemes having spreading factors of $S_f = 1$ and $S_f = 4$ are computed and are shown in Fig. 9. The scheme is observed to exhibit an infinitesimally low BER, especially with higher value of $S_f$, after a few outer iterations.

V. CONCLUSIONS

In this contribution, both uncoded and channel-coded FD MC-CDMA aided STSK schemes are proposed. The proposed MC-CDMA aided STSK system is found to attain an improved performance, especially in dispersive multi-path channels, which are typical of high-rate urban scenarios. Moreover, the attainable performance improves upon increasing the spreading factor $S_f$, although as expected, it suffers from MUI under multiuser scenario.

The performance degradation of classic STSK system in broadband channels may be mitigated by orthogonal frequency division multiplexing (OFDM)-aided STSK system [9]. For further exploitation of the frequency diversity provided by FD spreading, while facilitating multi-user communications, we have employed MC-CDMA in our proposed scheme. The scheme has also the capability of benefitting from the employment of our joint single-stream ML-MUD.

The effectiveness of our system largely depends on the optimization of the DMs utilized. We have optimized the spreading matrices minimizing the pairwise symbol error probability by an exhaustive search so that the power constraint used in [7, 8] is satisfied. Furthermore, in order to reduce the computational complexity associated with the exhaustive search, genetic algorithm (GA)-aided DM optimization [18] may also be applied.

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