# A Reduced-Complexity Detector for OFDMA/SC-FDMA-Aided Space-Time Shift Keying

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*Abstract*— **We propose a novel reduced-complexity detector for the orthogonal frequency division multiple access (OFDMA)/single-carrier frequency division multiple access (SC-FDMA)-aided space-time shift keying (STSK) architecture. STSK employing OFDMA/SC-FDMA has recently been shown to be beneficial in dispersive multiuser downlink/uplink scenarios. These schemes exhibit excellent performance at a considerably reduced decoding complexity. In this paper, we propose a new detector, which is capable of further reducing the decoding complexity. The proposed detector is particularly suitable for STSK-based transmission over frequency-selective multiple-input multiple-output (MIMO) channels employing frequency-domain equalization (FDE). The complexity of the proposed scheme is quantified and it is observed that the scheme maintains its superior performance at a significantly reduced complexity.**

## I. Introduction

Space-time shift keying (STSK) [1], [2] has recently been proposed for striking a flexible diversity versus multiplexing gain tradeoff for multiple-input multiple-output (MIMO) systems, while benefitting from its low-complexity single-stream detector. The key idea behind designing STSK is that it spreads the source information in both the spatial- and time-domain, like the family of linear dispersion codes (LDCs) [3], [4]. Motivated by the low-complexity design of spatial modulation (SM) [5] as well as space-shift keying (SSK) [6], STSK was conceived for activating only one from a set of $Q$ LDC-type dispersion matrices (DMs), thereby providing the same diversity as well as multiplexing gain as LDCs, whilst imposing a substantially reduced decoding complexity.

Since the SM and the SSK schemes activate only one antenna element (AE) during each symbol interval, the matched-filter (MF) [5], the maximal-ratio combining (MRC) [7] and the maximum-likelihood (ML) [7] detectors using the signal stream of a single AE can be employed, since no inter-element-interference (IEI) is experienced at the receiver. Hence, the STSK scheme may also employ a single-stream ML [1] detector. In order to mitigate the impairments due to the channel-induced dispersion imposed by wideband channels, OFDMA-aided and SC-FDMA-aided STSK [8] have been proposed for the multiuser downlink (DL) and uplink (UL), respectively, which benefit from the employment of the single-stream ML detector proposed in [1]. To further reduce the complexity of the STSK scheme employing bandwidth-efficient quadrature amplitude modulation (QAM), two further detectors modifying the MF detectors of [5] were proposed in [9].

Against this background, we propose a new detector which further reduces the decoding complexity especially in OFDMA/SC-FDMA-aided STSK arrangements. The proposed detector employs MIMO minimum mean square error (MMSE) equalization, followed by the estimation of the index of the DM activated and of the constellation symbol utilized. The main contributions of this paper are as follows.

1) We propose a novel detector for the STSK scheme, which is particularly suitable for the OFDMA/SC-FDMA-aided STSK DL/UL proposed in [8] without sacrificing the performance achieved.
2) The complexity of the scheme is quantified in terms of the number of real-valued multiplications and the scheme is found to have a low complexity.

The rest of the paper is organized as follows. Section II gives an overview of the STSK-based system and of the conventional detectors. The proposed detector is illustrated in Section III. In Section IV, the complexity associated with the proposed detector is evaluated. The complexity as well as performance of the scheme advocated is compared to those of the existing schemes in Section V. Finally, we conclude in Section VI.

*Notations:* In general, we use capital boldface letter, for example, $\boldsymbol{A}$ to denote a matrix, whereas $\boldsymbol{A}^T$, $\boldsymbol{A}^H$, $\text{tr}(\boldsymbol{A})$ and $\| \boldsymbol{A} \|$ denote the matrix transpose, the hermitian transpose, the trace and the Euclidean norm of $\boldsymbol{A}$ respectively. The operator $| \ a \ |$ is used for the complex norm of the complex number $a$, $\otimes$ for the Kronecker product, $\boldsymbol{I}_T$ for the $(T \times T)$-identity matrix and $\Re(\cdot)$ and $\Im(\cdot)$ for the real and the imaginary parts of a complex number, respectively. Furthermore, $\mathcal{E}\{\bullet\}$ and $\text{comp}[\bullet]$ represent the expectation of '$\bullet$' and the complexity associated with the computation of the expression '$\bullet$' respectively, whereas $\mathcal{CN}(\mu, \sigma^2)$ refers to the circularly symmetric complex Gaussian distribution with mean $\mu$ and variance $\sigma^2$.

## II. System Overview

Here, we provide a brief overview of the STSK system, the OFDMA/SC-FDMA-aided STSK and of the existing detectors. The motivation for conceiving a new detector is also outlined.

### A. STSK System Architecture

The STSK transmitter maps some of the source bits to the conventional modulation symbols and the rest of the bits to the index of the DM activated from the set of $Q$ DMs. To be specific, the transmitter spreads the input bits across the $M$ transmit antenna elements (AEs) and $T$ time slots to form the space-time (ST) codeword $\boldsymbol{X}(i) \in \mathbb{C}^{M \times T}$ according to

$$\boldsymbol{X}[i] = s[i] \boldsymbol{A}[i], \tag{1}$$

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where $s[i]$ is an $\mathcal{L}$- phase-shift keying (PSK)/QAM symbol, while $\boldsymbol{A}[i]$ is one of the pre-assigned DMs, $\boldsymbol{A}_q\,(q=1,...,Q)$, which are generated by the optimization method [1], [10] under the power constraint of

$$\mathrm{tr}(\boldsymbol{A}_q^H \boldsymbol{A}_q) = T \qquad \forall q. \tag{2}$$

The corresponding system is unambiguously referred to as the STSK$(M, N, T, Q)$ scheme operating in conjunction with $\mathcal{L}$-PSK/QAM, where $N$ is the number of the receive AEs. The block-based model of a STSK system may be expressed as

$$\boldsymbol{Y}[i] = \boldsymbol{H}[i]\,\boldsymbol{X}[i] + \boldsymbol{V}[i]\,, \tag{3}$$

where $\boldsymbol{Y}[i] \in \mathbb{C}^{N\times T}$ and $\boldsymbol{X}[i] \in \mathbb{C}^{M\times T}$ represent the ST received signal and the transmit block with the block index $i$, respectively. Moreover, $\boldsymbol{H}[i] \in \mathbb{C}^{N\times M}$ and $\boldsymbol{V}[i] \in \mathbb{C}^{N\times T}$ denote the channel transfer matrix and the additive white Gaussian noise (AWGN) matrix obeying $\mathcal{CN}(0,1)$ and $\mathcal{CN}(0,N_0)$ respectively, where $N_0$ indicates the noise variance.

Rearranging (3) by the linearized system model of [4] employing the vectorial stacking operation $\mathrm{vec}(\cdot)$, we have

$$\bar{\boldsymbol{Y}}[i] = \bar{\boldsymbol{H}}[i]\,\boldsymbol{\chi}\boldsymbol{K}[i] + \bar{\boldsymbol{V}}[i]\,, \tag{4}$$

where

$$\bar{\boldsymbol{Y}}[i] = \mathrm{vec}(\boldsymbol{Y}[i]) \in \mathbb{C}^{NT\times 1}, \tag{5}$$

$$\bar{\boldsymbol{H}}[i] \triangleq \boldsymbol{I}\otimes\boldsymbol{H}[i] \in \mathbb{C}^{NT\times MT}, \tag{6}$$

$$\boldsymbol{\chi} \triangleq [\mathrm{vec}(\boldsymbol{A}_1), \cdots, \mathrm{vec}(\boldsymbol{A}_Q)] \in \mathbb{C}^{MT\times Q}, \tag{7}$$

$$\boldsymbol{K}[i] \triangleq [\underbrace{0,\cdots,0}_{q-1}, s[i], \underbrace{0,\cdots,0}_{Q-q}]^T \in \mathbb{C}^{Q\times 1}, \tag{8}$$

$$\bar{\boldsymbol{V}}[i] = \mathrm{vec}(\boldsymbol{V}[i]) \in \mathbb{C}^{NT\times 1}. \tag{9}$$

*B. OFDMA/SC-FDMA-aided STSK*

Recently OFDMA-aided STSK DL and SC-FDMA-aided STSK UL have been proposed in [8], which are capable of mitigating the impairments of realistic dispersive channels while facilitating multi-user transmissions. As shown in Fig. 1, the original frequency-domain (FD) symbols of the OFDMA-aided scheme or the discrete Fourier transformed (DFT) symbols of the SC-FDMA-aided scheme are mapped to a number of subcarriers. The resulting signal is then transmitted after the inverse DFT (IDFT) operation from each of the transmit antenna elements (AEs). The signals received by the receive AEs are first equalized in the FD using MMSE or zero-forcing (ZF)-based single-tap MIMO FDE. The source information is then estimated by a single-stream based detector in the FD for OFDMA or in the time-domain (TD) for SC-FDMA.

*C. Existing Detectors*

Here, we briefly describe the optimal ML detector [1], [7] and the two detectors proposed in [9]. In the following, we omit the block index $i$ for the sake of notational simplicity. The detectors estimate both the index of the activated DM $q$ and the index of the transmitted constellation symbol $l$ and thereby estimates the source information.

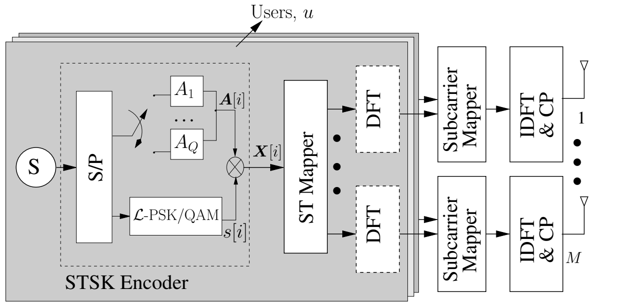


Fig. 1. Simplified architecture of the SC-FDMA-aided STSK transmitter. The dotted 'DFT' block does not exist in the OFDMA-aided scheme.

*1) The Optimal ML Detector:* The single-stream based ML detector finds the estimates $(\hat{q}, \hat{l})$ from:

$$\left(\hat{q}, \hat{l}\right) = \arg\min_{q,l} \left\{ \left\| \bar{\boldsymbol{Y}} - \bar{\boldsymbol{H}}\boldsymbol{\chi}\boldsymbol{K}_{l,q} \right\|^2 \right\}, \tag{10}$$

where $\boldsymbol{K}_{l,q}$ represents the vector $\boldsymbol{K}$ defined in (8) when the $\mathcal{L}$-PSK/QAM symbol $s_l$ is placed in the $q$-th position.

*2) The Detectors of [9]:* Two detectors were proposed in [9] for reduced-complexity detection of STSK, which we refer to as Detector I and Detector II in this paper.

*a) Detector I:* Detector I normalizes each column $\bar{\boldsymbol{h}}_q$ of $\bar{\boldsymbol{H}}$ to generate $\boldsymbol{H}' = \left[\frac{\bar{\boldsymbol{h}}_1}{\|\bar{\boldsymbol{h}}_1\|}, \ldots, \frac{\bar{\boldsymbol{h}}_Q}{\|\bar{\boldsymbol{h}}_Q\|}\right]$ and exhaustively searches through $\boldsymbol{Z} = [z_1, \ldots z_Q]^T = \boldsymbol{H}'\bar{\boldsymbol{Y}}$ to yield:

$$\begin{aligned}\hat{q} \;=\; \arg\max_{q,\forall l'} \Bigg[ 2\,\|\bar{\boldsymbol{h}}_q\| \Big\{ &|\Re(z_q)||\Re(s_{l'})| \\ &+ |\Im(z_q)||\Im(s_{l'})| \Big\} - \|\bar{\boldsymbol{h}}_q\|^2 |s_{l'}|^2 \Bigg], \end{aligned} \tag{11}$$

where $s_{l'}$ $(l' = 1, 2, \ldots, \mathcal{L}')$ represents the constellation points in the first quadrant only. Having estimated the DM index $\hat{q}$ using (11), the constellation symbol index is estimated from:

$$\hat{l} \;=\; \arg\min_{l} |\, z_{\hat{q}} - \|\bar{\boldsymbol{h}}_{\hat{q}}\|\, s_l \,|\,. \tag{12}$$

Thus the search space for (11) is $Q\mathcal{L}'$, which is one-fourth of $Q\mathcal{L}$ for optimal ML detector. This detector, however, has an additional search space of $\mathcal{L}$ to calculate $\hat{l}$ from (12).

*b) Detector II:* Detector I was further modified in [9] for simplifying (11) as:

$$\hat{q} \;=\; \arg\max_{q,\forall v} [|\Re(z_q)|\, x_{v,I} + |\Im(z_q)|\, x_{v,Q}]\,, \tag{13}$$

while (12) invoked for estimating $\hat{l}$ remains unchanged. Note that $x_{v,I}$ and $x_{v,Q}$ indicate the real and imaginary parts of the unit vectors having the same phase angles as those of the first-quadrant constellation points respectively.

Detector I and Detector II impose a considerably reduced complexity, especially in case of a high channel coherence interval and higher order QAM. However, in an OFDMA/SC-FDMA-aided STSK, MIMO FDE is employed and the resulting data estimation does not explicitly involve the channel transfer matrix. Against this background, we conceived a modified reduced-complexity detector, which estimates the DM index and contellation index after MIMO FDE and is particularly useful for OFDMA/SC-FDMA-aided multiuser STSK transmissions in dispersive channels.

## III. The Proposed Detector

The schematic diagram of the OFDMA/SC-FDMA-aided STSK receiver employing the proposed detector is shown in Fig. 2. After the discrete Fourier transform (DFT) operation and subcarrier demapping at the receive AEs, the detector employs MIMO MMSE FDE and then separately estimates the indices of the activated DM $q^v$ and of the PSK/QAM symbol $l^v$ corresponding to a particular user[1] $v$.

To be specific, the detector first invokes the MIMO MMSE FDE in an attempt to minimize the average squared error. The MIMO ZF equalizer suffers from a performance degradation due to the noise enhancement when a subcarrier is in deep fade and hence is not used in the proposed scheme.

Let the ST codewords corresponding to user $u \quad [u = 0, 1, \ldots, (U-1)]$ of the SC-FDMA-aided STSK in Fig. 1 be denoted by $\boldsymbol{X}^u$, and the transmit blocks obtained by DFT operation of the codeword symbols be represented by $\tilde{\boldsymbol{X}}^u$. For the OFDMA-aided STSK, the DFT-precoding block in Fig. 1 does not exist and we have, $\tilde{\boldsymbol{X}}^u = \boldsymbol{X}^u$.

The block-based FD output $\tilde{\boldsymbol{Y}}$ in Fig. 2 obtained after DFT operation at the receive antennas may be expressed as [8]

$$\tilde{\boldsymbol{Y}} = \sum_{u=0}^{(U-1)} \tilde{\boldsymbol{H}}^u \tilde{\boldsymbol{X}}^u + \tilde{\boldsymbol{V}} \tag{14}$$

where $\tilde{\boldsymbol{H}}^u$ represents the FD channel transfer matrix corresponding to user $u$ and $\tilde{\boldsymbol{V}}$ denotes the AWGN matrix.

For estimating the transmit blocks $\tilde{\boldsymbol{X}}^v$ of user $v$, the subcarriers are first demapped and the demapped signal $\tilde{\boldsymbol{Y}}^v$ is then multiplied by the MMSE weight matrix $\boldsymbol{W}^v$, which minimizes $\mathcal{E}\left\{\left[\boldsymbol{W}^v\tilde{\boldsymbol{Y}}^v - \tilde{\boldsymbol{X}}^v\right]\left[\boldsymbol{W}^v\boldsymbol{Y}^v - \tilde{\boldsymbol{X}}^v\right]^H\right\}$, yielding [11]

$$\boldsymbol{W}^v = \left[\left(\tilde{\boldsymbol{H}}^v\right)^H \tilde{\boldsymbol{H}}^v + \sigma_N^2 \boldsymbol{I}_M\right]^{-1} \left(\tilde{\boldsymbol{H}}^v\right)^H, \tag{15}$$

where $\sigma_N^2$ indicates the noise variance. The MMSE estimate $\boldsymbol{\mathcal{Z}}^v$ may then be expressed as [12, Ch. 5]: $\boldsymbol{\mathcal{Z}}^v = \boldsymbol{W}^v\tilde{\boldsymbol{Y}}^v$. After MIMO FDE, the signal is passed through the 'IDFT' block, which results in the ST blocks $\mathbb{Z}^v$. In case of the OFDMA-aided STSK, however, we have, $\mathbb{Z}^v = \boldsymbol{\mathcal{Z}}^v$.

Under the idealized assumption of perfect synchronization and of perfect orthogonality of the subcarriers, the scheme is free from multiuser interference (MUI), albeit the MMSE scheme imposes self-interference (SI). Assuming the SI to be low, the decision variable for user $v$ can be expressed as

$$\mathbb{Z}^v = \boldsymbol{X}^v + \tilde{\boldsymbol{V}}^v. \tag{16}$$

Upon applying the vectorial stacking operation $\mathrm{vec}(\cdot)$ to both sides of (16), we have

$$\bar{\boldsymbol{Z}}^v = \boldsymbol{\chi}\boldsymbol{K}^v + \bar{\boldsymbol{V}}^v, \tag{17}$$

where

$$\bar{\boldsymbol{Z}}^v = \mathrm{vec}(\mathbb{Z}^v) \in \mathbb{C}^{MT\times 1}, \tag{18}$$

$$\bar{\boldsymbol{V}}^v = vec(\tilde{\boldsymbol{V}}^v) \in \mathbb{C}^{MT\times 1}, \tag{19}$$

and $\boldsymbol{\chi}$ and $\boldsymbol{K}^v$ are as defined in (7) and (8), respectively.

[1]The generalized user is denoted by $u$, whereas $v$ refers to the desired user.

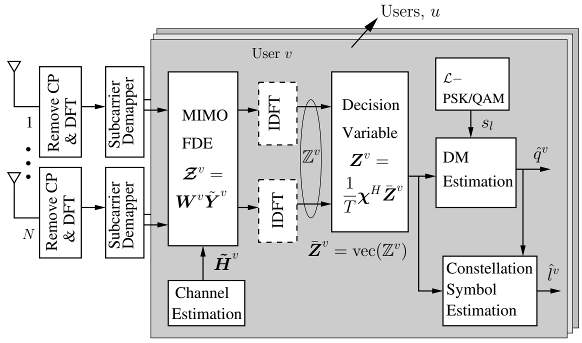


Fig. 2. The receiver architecture of the OFDMA/SC-FDMA-aided STSK employing the proposed detector. The dotted 'IDFT' block does not exist in the OFDMA-aided STSK receiver.

The decision variable $\boldsymbol{Z}^v$ may now be obtained by multiplying (17) by $\frac{1}{T}\boldsymbol{\chi}^H$ as:

$$\boldsymbol{Z}^v = \frac{1}{T}\boldsymbol{\chi}^H\bar{\boldsymbol{Z}}^v = \left[z_1^v, \ldots z_Q^v\right]^T \in \mathbb{C}^{Q\times 1}. \tag{20}$$

We now perform an exhaustive search for the estimates:

$$(\hat{q}^v, \hat{l}^v) = \arg\min_{q,l} \parallel \boldsymbol{Z}^v - \boldsymbol{K}_{l,q} \parallel^2 \tag{21}$$

$$\begin{aligned} &= \arg\min_{q,l}\left(\mid z_q^v - s_l\mid^2 + \sum_{q'\neq q}\mid z_{q'}^v\mid^2\right) \\ &= \arg\max_{q,l}\Bigg[2\Big\{\mid \Re(z_q^v)\mid\mid\Re(s_l)\mid \\ &\qquad + \mid\Im(z_q^v)\mid\mid\Im(s_l)\mid\Big\} - \mid s_l\mid^2\Bigg]. \end{aligned} \tag{22}$$

Assuming the $\mathcal{L}$-PSK/QAM constellation to be symmetric about the I- and Q-axis, we can rewrite (22) to estimate $q^v$ as

$$\begin{aligned} \hat{q}^v = \arg\max_{q\ \forall l'}\Bigg[2\Big\{\mid\Re(z_q^v)\mid\mid\Re(s_{l'})\mid \\ + \mid\Im(z_q^v)\mid\mid\Im(s_{l'})\mid\Big\} - \mid s_{l'}\mid^2\Bigg], \end{aligned} \tag{23}$$

where $l'$ denotes the index of the constellation symbol $s_{l'}$ that lies in the first quadrant only [9].

The index of the constellation symbol used in forming the STSK codeword can be estimated from

$$\hat{l}^v \quad = \quad \arg\min_l \mid z_{\hat{q}}^v - s_l\mid. \tag{24}$$

The rationale of multiplying $\bar{\boldsymbol{Z}}^v$ by the term $\frac{1}{T}\boldsymbol{\chi}^H$ in (20) is outlined as follows. Substituting the value of $\bar{\boldsymbol{Z}}$ from (17) into (20), we have

$$\boldsymbol{Z}^v \quad = \quad \frac{1}{T}\boldsymbol{\chi}^H\bar{\boldsymbol{Z}}^v \tag{25}$$

$$\begin{aligned} &= \frac{1}{T}\boldsymbol{\chi}^H\left[\boldsymbol{\chi}\boldsymbol{K}^v + \bar{\boldsymbol{V}}^v\right] \\ &= \frac{1}{T}\boldsymbol{\chi}^H(\boldsymbol{\chi})_{q^v}s_{l^v} + \bar{\boldsymbol{N}}_0, \end{aligned} \tag{26}$$

where $(\boldsymbol{\chi})_{q^v}$ denotes the $q^v$-th column of the matrix '$\boldsymbol{\chi}$' and $\bar{\boldsymbol{N}}_0 \in \mathbb{C}^{Q\times 1}$.

We have $\boldsymbol{\chi}^H = [\text{vec}(\boldsymbol{A}_1), \cdots, \text{vec}(\boldsymbol{A}_Q)]^H \in \mathbb{C}^{Q\times MT}$ and $(\boldsymbol{\chi})_{q^v} = [\text{vec}(\boldsymbol{A}_{q^v})] \in \mathbb{C}^{MT\times 1}$, and hence,

$$\boldsymbol{\chi}^H(\boldsymbol{\chi})_{q^v} = [z'_1, z'_2, \cdots, \underset{q^v-\text{th}\ \overset{\uparrow}{\text{position}}}{T}, \cdots, z'_Q]^T, \quad (27)$$

where $z'_i = \text{tr}(\boldsymbol{A}_i^H \boldsymbol{A}_{q^v})$, $i = 1, 2, \ldots, Q$ with $i \neq q^v$ and $\text{tr}(\boldsymbol{A}_{q^v}^H \boldsymbol{A}_{q^v}) = T$ according to (2). Thus we obtain,

$$\boldsymbol{Z}^v = [z'_1, z'_2, \cdots, \underset{q^v-\text{th}\ \overset{\uparrow}{\text{position}}}{s_{l^v}}, \cdots, z'_Q]^T + \bar{\boldsymbol{N}}_0. \quad (28)$$

Equation (28) demonstrates that the ML search of (21) can be simplified to obtain the detection rules of (23) and (24).

The optimal ML detector [1], Detector I and Detector II [9] were conceived mainly for non-dispersive MIMO channels. By contrast, the proposed detector is designed for realistic dispersive scenarios. Detector I and Detector II are capable of reducing the complexity of the optimal ML detector at the cost of a modest performance penalty. None of them can, however, be directly employed in the SC-FDMA-aided STSK scheme, because the TD data estimation has to be preceded by FD equalization. After MIMO equalization in FD, the search for the user information given by (23) and (24) in our proposed scheme does not explicitly involve the channel transfer function for calculating $\hat{q}^v$ and $\hat{l}^v$. Hence the number of multiplications and additions involved is significantly lower than that required by the existing detectors.

## IV. Complexity Analysis

We quantify the complexity of the proposed scheme in terms of the number of real-valued multiplications required per bit of information and summarize it in Table I in order to compare with the complexity imposed by the existing detectors.

The complexity associated with our multiple-antenna-based MMSE FDE is given by[2],

$$\text{comp}\left[\left[\left(\tilde{\boldsymbol{H}}^v\right)^H \tilde{\boldsymbol{H}}^v + \sigma_N^2 \boldsymbol{I}_M\right]^{-1} \left(\tilde{\boldsymbol{H}}^v\right)^H\right] = 4MN + 4M^2N. \quad (29)$$

The complexity imposed by computing $\boldsymbol{\mathcal{Z}}^v = \boldsymbol{W}^v \tilde{\boldsymbol{Y}}^v$ may be written as

$$\text{comp}\left[\boldsymbol{\mathcal{Z}}^v = \boldsymbol{W}^v \tilde{\boldsymbol{Y}}^v\right] = 4MN. \quad (30)$$

Similarly, we have:

$$\text{comp}\left[\boldsymbol{Z}^v = \frac{1}{T}\boldsymbol{\chi}^H \bar{\boldsymbol{Z}}^v\right] = 4MTQ + Q. \quad (31)$$

$$\text{comp}\left[\arg\max_{q\ \forall l'}\left\{2\left(\mid \Re(z_q^v) \mid\mid \Re(s_{l'}) \mid + \mid \Im(z_q^v) \mid\mid \Im(s_{l'}) \mid\right) - \mid s'_{l'} \mid^2\right\}\right] = 2Q\mathcal{L}', \quad (32)$$

[2]The complexity associated with the inversion of the $(M \times M)$ matrix at this stage is $O\left(M^{2.807}\right)$, if Strassen algorithm is used. This has not been included in our complexity calculation, because we quantify complexity in terms of the number of real-valued multiplications. The proposed scheme, however, has a significantly reduced complexity, even if the complexity associated with this matrix inversion is also taken into account.

TABLE I
Complexity of the detection Schemes

| Detection Scheme | Complexity per bit of information |
|---|---|
| ML | $\frac{4MNTQ+4NTQ\mathcal{L}+2NTQ\mathcal{L}}{log_2(Q\cdot\mathcal{L})}$ |
| Detector I | $\frac{4MNTQ+8NTQ+4Q\mathcal{L}'+4\mathcal{L}}{log_2(Q\cdot\mathcal{L})}$ |
| Detector II | $\frac{4MNTQ+8NTQ+2VQ+4\mathcal{L}}{log_2(Q\cdot\mathcal{L})}$ |
| Proposed detector | $\frac{4M^2N+8MN+4MTQ+2Q\mathcal{L}'+Q+2\mathcal{L}}{log_2(Q\cdot\mathcal{L})}$ |

and

$$\text{comp}\left[\arg\min_{l} \mid z_{\hat{q}}^v - s_l \mid\right] = 2\mathcal{L}. \quad (33)$$

The overall complexity of the proposed detector for estimating $\log_2(Q\cdot\mathcal{L})$ bits of source information carried by any transmit block is thus given by

$$\text{Complexity} = 4M^2N + 8MN + 4MTQ + 2Q\mathcal{L}' + Q + 2\mathcal{L}.$$

From the numerical expressions in Table I, we can see that our scheme exhibits a substantially reduced complexity.

## V. Performance Comparison

We have investigated the complexity of the proposed detector, which was compared to that of the existing detectors in Figs. 3 and 4, upon varying the number of DMs $Q$ and the number of symbol intervals $T$ in conjunction with $M = 4$, $N = 4$ and employing both the $4-$QAM and $16-$QAM. We observe that Detector-I and Detector-II impose an identical complexity, which is lower than that imposed by the optimal ML detector in OFDMA-aided STSK, albeit their complexity is not significantly reduced for lower-order constellations. On the other hand, our proposed detector exhibits a more significantly reduced complexity for all the scenarios, where we have included the complexity of the MIMO FDE stage in the overall complexity calculation of the proposed detector.

The bit-error ratio (BER) performance of our scheme was investigated in Fig. 5 for OFDMA/SC-FDMA-aided single-user STSK (2,2,2,2) employing BPSK modulation for transmission over the COST 207-TU12 dispersive channel employing 64 subcarriers. Detector I and Detector II cannot be directly employed for the SC-FDMA-aided STSK scheme, because the source information has to be detected in the TD after MIMO FDE. In case of OFDMA, however, both the ML detector and the proposed detector can be employed. We observe that our proposed scheme exhibits a performance comparable to the detector proposed in [8], but at a substantially reduced complexity. While the ML detector for the OFDMA STSK scheme provides better performance, the proposed scheme is sufficiently reduced in complexity.

The performance of Detector II for transmission over narrowband channels is also shown in Fig. 5 for a fair comparison with other schemes. Observe that the proposed detector as well as the detector advocated in [8] for SC-FDMA-aided transmission even over dispersive channel outperforms Detector II in narrowband channel. This is because a beneficial

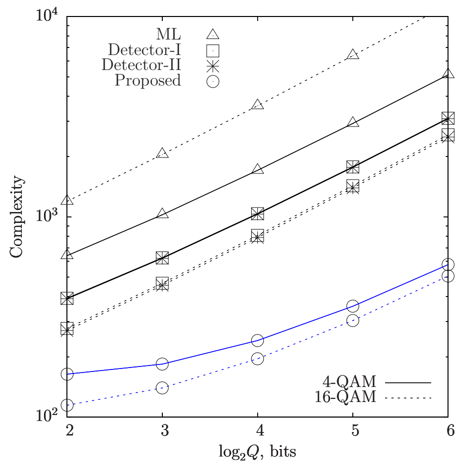


Fig. 3. Complexity of the detection algorithms considered as a function of the number of DMs. The parameters are: $M = 4$, $N = 4$, with $T = 4$.

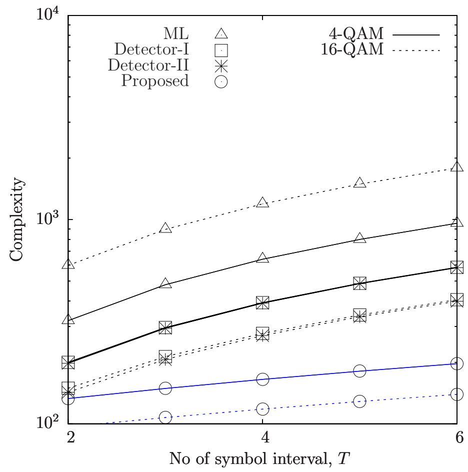


Fig. 4. Complexity of the detection algorithms considered as a function of $T$. The parameters are: $M = 4$, $N = 4$, with $Q = 4$.

frequency-domain diversity is provided by the DFT-based precoding in our SC-FDMA aided STSK scheme. Thus it can be inferred that the proposed detector reduces the complexity of the existing detector without sacrificing its performance, especially in the SC-FDMA aided STSK uplink.

## VI. Conclusion

We have proposed a new reduced-complexity detector for the OFDMA-aided STSK DL and the SC-FDMA-aided STSK UL. The proposed detector is inherently immune to IEI as a benefit of activating a single DM in the STSK and it has a reduced complexity compared to the existing detectors. It is a promising candidate for employment in OFDMA/SC-FDMA-aided STSK transmissions over frequency-selective channels even under multiuser scenarios in terms of its performance versus complexity tradeoff.

The effectiveness of the STSK system depends mainly on the specific objective function used for the optimization of the DMs [2]. We have employed an exhaustive search over $10^6$ candidate DM sets for minimizing the maximum pairwise symbol error probability under the power constraint given by

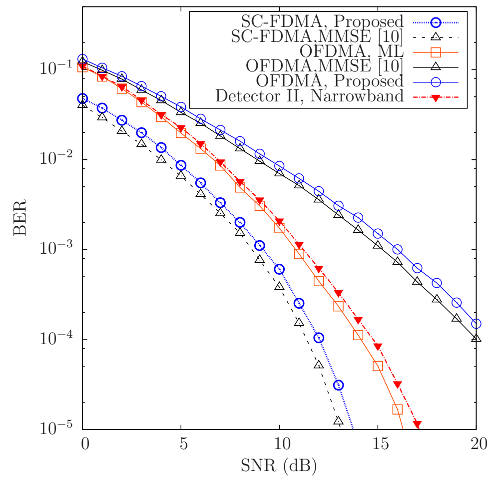


Fig. 5. BER performance of OFDMA/SC-FDMA aided single-user STSK (2,2,2,2) scheme employing BPSK modulation in COST 207-TU12 channel model and the different detectors. The performance of Detector II in narrow-band STSK (2,2,2,2), BPSK is also shown as a fair comparioson.

(2). Further detailed discussion on the design of efficient DMs may be found in [10, Ch. 7], [13].

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