Orthogonal Space-Time Discrete Multitone and Space-Time Filtered Multitone Coded Architectures

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Abstract— **In this paper we describe several space-time multitone architectures for transmission with multiple antennas over flat and frequency selective fading channels. The idea behind these schemes is to perform data multiplexing over both the spatial, and the frequency domain. Two of these architectures are obtained by extending the filtered multitone (FMT) modulation concept to the multiple antenna scenario. Another novel architecture is based on the concept of deploying some form of cyclically prefixed discrete multitone (DMT) modulation. The architectures aim at orthogonalizing the time dispersive channel, and possibly the overlapping spatial channels. The efficient implementation can be performed via fast Fourier transform (FFT), and low rate polyphase filtering. These architectures can be concatenated with outer channel coding or data spreading for space-frequency diversity exploitation.**

Keywords - Space-time coding, diversity, fading channels, filtered multitone modulation, discrete multitone modulation, OFDM.

I. Introduction

It is well known that multiple-transmit multiple-receive antenna architectures can increase the capacity of wireless communication systems [3]. To approach the capacity limits we need to deploy powerful space-time coding schemes that exploit the spatial-temporal diversity of rich scattering environments. Several space-time coding schemes have been proposed initially for transmission over flat fading channels, for instance, the well known space-time trellis codes (STTC) in [8], or the space-time bit-interleaved codes (STBIC) in [9]. Although, for low transmission rates, and small number of transmit antennas good STTC and STBIC have been found, the space-time coding problem becomes more complicated if very high data rates have to be achieved, i.e., we deploy a high number of transmit antennas with high order modulation. On one hand, this is due to the difficulty of designing coding schemes that are capable of achieving full spatial diversity and delivering high coding gains. On the other hand, the optimum decoding algorithm that is based on the maximum-likelihood principle is characterized by a complexity that limits the practical implementation. Aiming at simplify the decoding complexity several space-time block codes with simple decoding have been proposed, e.g., the codes in [7], and the simple transmit diversity scheme by Alamouti.

When transmission is over frequency selective fading channels, the same space-time codes proposed for flat fading channels can be deployed. However, equalization is required to counteract the intersymbol interference, which translates into increased decoding complexity [1], [12]. In order to simplify the equalization task, it has been proposed to use cyclically prefixed orthogonal frequency division multiplexing (OFDM) over each transmit antenna, referred to as space-time cyclically prefixed discrete multitone (ST-CP-DMT) modulation in this paper. This allows for obtaining a flat frequency response for each transmit antenna link. Then, we can obtain diversity and coding gains via trellis coding [6], or bit interleaved coding [5] across the transmit antennas. In the latter case, decoding is performed through the iterative concatenation of a soft-in soft-out bit demapper with a soft-in soft-out channel decoder. Demapping can be performed independently over the OFDM sub-channels. However, optimal ML/MAP demapping still has a complexity that increases exponentially with the number of transmit antennas [9] because each sub-channel sees the superposition of the data symbols simultaneously transmitted by the antennas.

TABLE I
ACRONYMS AND NOTATION

ST-CP-DMT	conventional space-time cyclically prefixed discrete multitone modulation (space-time OFDM)
ST-FMT	space-time filtered multitone modulation.
O-ST-CP-DMT	orthogonal space-time cyclically prefixed discrete multitone modulation
O-ST-FMT	orthogonal space-time filtered multitone modulation
N_T	Number of transmit antennas.
M	Number of tones.
$N=M+\mu$	$\mu \geq 0$
T	Transmission period.
$W=1/T$	Nominal overall bandwidth.
f_k	Tone (sub-carrier) k.
$\Delta f=1/MT$	Tone spacing.
$T_0=NT$	Sub-channel data period.
$g(nT)$	Prototype sub-channel filter.
N_b	Number of bits per complex data symbol $a^k(lT_0)$.
$a^k(lT_0)$	Data symbol transmitted at time lT_0 over sub-channel k.
$a^{t,k}(lT_0)$	Data symbol transmitted over antenna t and sub-channel k

In this paper we describe several space-time multitone architectures for transmission over multiple antennas. They aim at orthogonalizing the time dispersive channel, and possibly the overlapping spatial channels. In other words, the goal is to transform the multiple antenna, ISI channel in a number of non-overlapping sub-channels. The idea behind these schemes is to perform data multiplexing over both the spatial and the frequency domain. For clarity, we list in Table I the acronyms that will be used. First, we review conventional space-time cyclically prefixed discrete multitone (ST-CP-

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DMT) modulation. Second, we devise a scheme that is obtained by extending the filtered multitone (FMT) modulation concept [2] to the multiple transmit antenna context. It is referred to as space-time filtered multitone (ST-FMT) modulation. Then, we devise two other space-time architectures whose objective is to orthogonalize not only the ISI channel but also the overlapping multiple antenna channels. They work both for flat fading channels and for frequency selective fading channels. They are respectively referred to as orthogonal space-time filtered multitone (O-ST-FMT) modulation, and orthogonal space-time cyclically prefixed discrete multitone (O-ST-CP-DMT) modulation.

The concept behind FMT modulation over single input channels (single transmit antenna) is to transmit a number of low rate data sequences over sub-channels that are shaped with an appropriate filter centered on a given sub-carrier [2], [13]. Discrete multitone modulation (DMT) is a particular implementation that deploys rectangular time domain filters. DMT is also referred to as OFDM. The design of the sub-channel filters, and the choice of the sub-carrier spacing in an FMT system aims at subdividing the spectrum in a number of sub-channels that do not overlap in the frequency domain. In a DMT system, the orthogonalization of the ISI channel is obtained with the insertion of a cyclic prefix longer than the channel time dispersion.

All the architectures here described can be efficiently implemented via FFT and low-rate polyphase filtering. In ST-FMT data detection may require sub-channel equalization in the presence of frequency selective fading. However, its complexity is low since the equivalent sub-channel impulse response spans a small number of data symbols. In O-ST-CP-DMT full space-time orthogonalization is obtained, such that the detector simplifies into a one-tap equalizer per sub-channel as in conventional OFDM over single input-single output channels. To the author's knowledge O-ST-CP-DMT is novel.

The multitone architectures herein described can be concatenated with outer coding. A good option is to use bit-interleaved codes. In this case decoding can be performed via iterative bit demapping and channel decoding. Another idea to exploit diversity is to use outer direct sequence spreading [4].

II. Channel Model

We assume to deploy N_T transmit antennas, and a single receive antenna. The multiple receive antenna scenario is a simple extension. The space-time architectures that we describe have an efficient discrete-time implementation. The filters in the digital-to-analog converter at the transmitter, and the analog-to-digital converter at the receiver are included in the equivalent discrete-time channel impulse response. The channel is assumed to be frequency selective such that the equivalent impulse response for the *t*-th antenna link is

$$h^t(nT) = \sum\nolimits_{p=0}^{N_P} \alpha_p^t \delta(nT - pT) \,. \quad (1)$$

T is the transmission period. The tap gains are Rayleigh faded, and are assumed to be time-invariant over one or more transmission frames of duration $T_0 = NT$ each. Further, we assume $N_P < N$.

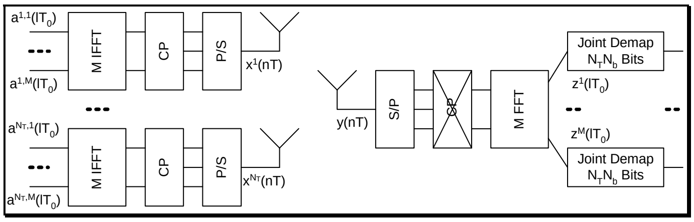

Fig. 1. Conventional Space-Time CP DMT system.

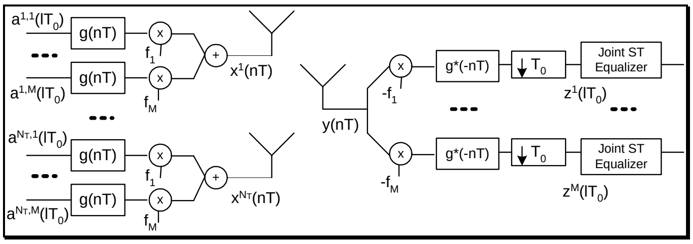

Fig. 2. Space-Time FMT system.

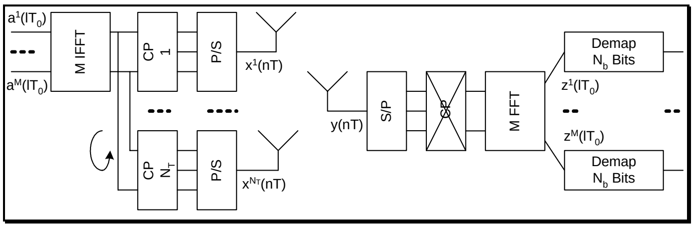

Fig. 3. Orthogonal Space-Time CP DMT system.

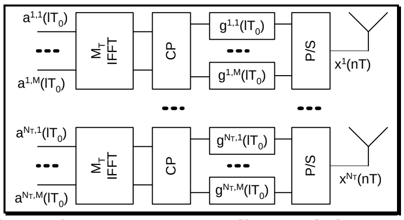

Fig. 4. Orthogonal Space-Time Critically Sampled FMT transmitter.

III. Conventional ST-CP-DMT: Space-Time Cyclically Prefixed Discrete Multitone Modulation

In conventional ST-CP-DMT transmission, cyclically prefixed DMT modulation is deployed over each antenna [5] (see Fig. 1). For each antenna of index $t=0,\ldots,N_T-1$ we take a block of M data symbols $a^{t,k}(lT_0)$, $k=0,\ldots,M-1$, we apply an M point inverse discrete Fourier transform (IDFT), we add a cyclic prefix of length μ, and finally we transmit the output $N = M + \mu$ symbols. Each data symbol $a^{t,k}(lT_0)$ is assumed to belong to a complex constellation, e.g., M-QAM, and is obtained by mapping N_b bits. The block of symbols $x^{t,n}(lT_0)$, $n = 0,...,N-1$, transmitted by antenna t with period $T_0 = NT$, is generated as follows

$$x^{t,n}(lT_0) = x^t(lT_0 + nT) = \sum_{k=0}^{M-1} a^{t,k}(lT_0) e^{j\frac{2\pi}{M}k(n-\mu)} \,. \quad (2)$$

The resulting transmission bit rate is $R_{ST-CP-DMT} = MN_T N_b / T_0$ bits/s.

With the channel model (1), and with the assumption of using a cyclic prefix longer than the channel time support, the received signal reads for $l=-\infty,...,\infty$, and $n=\mu,...,N-1$

$$y(lT_0+nT)=\sum_{t=0}^{N_T-1}\sum_{p=0}^{N_P}\alpha_p^t x^{t,n-p}(lT_0)+\eta(lT_0+nT) \quad (3)$$

where $\eta(nT)$ are assumed to be i.i.d. Gaussian random variables with zero mean.

Now, demodulation is accomplished by dropping the received samples that correspond to the cyclic prefix of each received block, and applying an M-point discrete Fourier transform (DFT) to obtain for the $\hat{k}$ -th sub-channel output

$$z^{\hat{k}}(lT_0)=\sum_{t=0}^{N_T-1}H^{t,\hat{k}}a^{t,\hat{k}}(lT_0)+w^{\hat{k}}(lT_0)\,,\quad H^{t,\hat{k}}=\sum_{p=0}^{N_P}\alpha_p^t e^{-j\frac{2\pi}{M}p\hat{k}} \quad (4)$$

with $w^{\hat{k}}(lT_0)$ being i.i.d. zero mean Gaussian random variables. That is, each DFT output sees a flat faded channel. However, although no intersymbol interference (ISI) is introduced, the N_T spatial channels do overlap. Therefore, to recover the transmitted bits, the optimal maximum likelihood demapper has to perform, for each of the M frequency sub-channels, bit demapping jointly over the N_T spatial channels. Its complexity grows exponentially with the number of transmit antennas. Several demapping algorithms are described in [9], [10], [11]. Finally, note that if the channel is flat there is no point to deploy ST-CP-DMT.

IV. ST-FMT: Space-Time Filtered Multitone Modulation

A different approach is to use FMT modulation [2] instead of CP-DMT modulation over each transmit antenna. The difference relies on the presence of sub-channel shaping pulses. A general architecture is shown in Fig. 2. The discrete-time signal that is transmitted by antenna t is obtained as follows

$$x^t(nT)=\sum_{k=0}^{M-1}\sum_{l=-\infty}^{\infty}a^{t,k}(lT_0)g(nT-lT_0)e^{j2\pi f_k nT} \quad (5)$$

where $g(nT)$ is the prototype pulse that is used to shape the sub-channels, while $f_k=k/MT$ is the *k-th* sub-channel tone. An efficient FFT based implementation is possible resulting in a space-time extension of the one described in [2]. If $M=N$ the scheme is referred to as critically sampled, otherwise if $N>M$ the scheme is referred to as non-critically sampled. The prototype pulse is designed to be frequency concentrated, so that sub-channels do not overlap in frequency. As an example, we can use square-root-raised cosine pulses, or Gaussian pulses [13]. The choice $N>M$ allows for a better sub-channel separation.

The resulting transmission bit rate is $R_{ST-FMT}=MN_TN_b/T_0$ bits/s, and can be higher than that in ST-CP-DMT depending on the choice of $N\geq M$, and consequently of T_0.

With the channel model (1), the received signal reads

$$y(nT)=\sum_{t=0}^{N_T-1}\sum_{p=0}^{N_P}\alpha_p^t x^t(nT-pT)+\eta(nT)\,. \quad (6)$$

Demodulation is accomplished by first deploying a bank of filters matched to the sub-channel transmit pulses. Then, we sample the outputs at rate $1/T_0$ to obtain for the $\hat{k}$ -th matched filter (MF) output

$$\begin{aligned}z^{\hat{k}}(mT_0)&=\sum_{n=-\infty}^{\infty}y(nT)e^{-j2\pi f_{\hat{k}}nT}g^*(nT-mT_0)\\&=\sum_{t=0}^{N_T-1}\sum_{k=0}^{M-1}\sum_{l=-\infty}^{\infty}a^{t,k}(lT_0)\sum_{p=0}^{N_P}\alpha_p^t e^{-j2\pi f_k pT}\sum_{n=-\infty}^{\infty}e^{j2\pi(f_k-f_{\hat{k}})nT} \quad (7)\\&\quad\times g(nT-pT-lT_0)g^*(nT-mT_0)+w^{\hat{k}}(mT_0)\end{aligned}$$

Using Parseval theorem it can be shown that if the sub-channels do not frequency overlap, relation (7) differs from zero only for $k=\hat{k}$. This holds true if $|G(f)|=0$ for $|f|>1/(2MT)$. Under such hypothesis that can be met with the appropriate system design we obtain that

$$\begin{aligned}z^{\hat{k}}(mT_0)&=\sum_{t=0}^{N_T-1}\sum_{l=-\infty}^{\infty}a^{t,\hat{k}}(lT_0)\beta^{t,\hat{k}}(mT_0-lT_0)+w^{\hat{k}}(mT_0)\\\beta^{t,\hat{k}}(mT_0)&=\sum_{p=0}^{N_P}\alpha_p^t e^{-j\frac{2\pi}{M}p\hat{k}}\sum_{n=-\infty}^{\infty}g(mT_0-pT+nT)g^*(nT)\end{aligned} \quad (8)$$

According to (8), the $\hat{k}$ *-th* sub-channel output sees some ISI contribution. Further, the N_T spatial channels overlap. Therefore, to accomplish bit demapping we need to run a bank of M equalizers each performing joint spatial, and temporal equalization. The optimal ST-MAP equalizer is described in [12]. More in general, optimal multicarrier MAP equalization is described in [13].

The interesting feature in this architecture is that the number of intersymbol interferers is small (note that each sub-channel has taps spaced by multiples of T_0). Thus, each equalizer can have moderate complexity depending on the transmission bandwidth, channel time dispersion, and number of tones. The fact that no cyclic prefix is deployed can translate in higher spectral efficiency than with ST-CP-DMT.

V. O-ST-CP-DMT: Orthogonal Space-Time Cyclically Prefixed Discrete Multitone Modulation

In this section we propose a novel (to the author's knowledge) scheme that is still based on the concept of deploying some form of cyclically prefixed DMT modulation. We start from the observation that in both conventional ST-CP-DMT, and ST-FMT the spatial channels do overlap. Indeed this allows for increasing the peak transmission rate. However, the optimal detector/equalizer has a complexity that grows exponentially with the number of transmit antennas. Further, note that there is no point to deploy ST-CP-DMT over a flat faded channel. The scheme that we describe in this section aims at orthogonalizing the spatial channels, and can be used in both flat, and frequency selective channels. We refer to this scheme as O-ST-CP-DMT (see Fig. 3).

We start by taking a block of $M\geq N_T+N_P-1$ data symbols $a^k(lT_0)$, k=0,…,M-1. Then, we generate N_T blocks of $N=M+\mu$ symbols each, as follows

$$x^{t,n}(lT_0)=x(lT_0+nT-tT)=\sum_{k=0}^{M-1}a^k(lT_0)e^{j\frac{2\pi}{M}k(n-\mu-t)} \quad (9)$$

for t=0,…,N_T-1, and n=0,…,N-1. Each block is transmitted over a distinct antenna. The above operation corresponds to apply a cyclic prefix over both time and space. This can be better understood if we explicitly write (9) in a $N_T \times N$ matrix

$$N_T \updownarrow \begin{bmatrix} x_{M-\mu} & x_{M-\mu+1} & \cdots & x_{M-1} & x_0 & x_1 & \cdots & x_{M-1} \\ x_{M-\mu-1} & x_{M-\mu} & \cdots & x_{M-2} & x_{M-1} & x_0 & \cdots & x_{M-2} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{M-\mu-N_T+1} & \cdots & \cdots & x_{M-N_T} & x_{M-N_T+1} & \cdots & \cdots & x_{M-N_T} \end{bmatrix}$$

$$\overset{\longleftrightarrow}{N}$$

whose rows are transmitted over distinct antennas, and where $x_n = \sum_{k=0}^{M-1} a^k(lT_0)e^{j2\pi nk/M}$. The resulting transmission bit rate is $R_{O-ST-CP-DMT} = N_b M / T_0$ bits/s. Note that in flat fading channels we can set $\mu = 0$, and $M = N_T$.

With the channel model (1), and with the assumption of a cyclic prefix that satisfies the relation $\mu \ge N_P$, the received signal reads for $l = -\infty,...,\infty$, and $n = \mu,...,N-1$

$$y(lT_0 + nT) = \sum_{t=0}^{N_T-1} \sum_{p=0}^{N_P} \alpha_p^t x^{t,n-p}(lT_0) + \eta(lT_0 + nT) . \quad (10)$$

Now, demodulation is accomplished by dropping the cyclic prefix (the samples of the l-th block corresponding to index $n = 0,...\mu-1$), and applying an M-point DFT to obtain

$$z^{\hat{k}}(lT_0) = H^{\hat{k}} a^{\hat{k}}(lT_0) + w^{\hat{k}}(lT_0) , \quad H^{\hat{k}} = \sum_{p=0}^{N_P} \sum_{t=0}^{N_T} \alpha_p^t e^{-j\frac{2\pi}{M}(p+t)\hat{k}} . (11)$$

Therefore, each DFT output sees a flat faded channel, and the N_T spatial channels do not overlap. In other words, we have othogonalized both the ISI channel, and the N_T spatial channels. The complexity of the optimal maximum likelihood bit demapper does not grow as the number of antennas grows.

Now the question is: what is the advantage of such a scheme ? The advantage is that transmission takes place over M non overlapping channels. Further, it can be proved that the rank of the MIMO-ISI channel remains unchanged, and therefore the achievable diversity gain. In particular if the $N_T N_P$ channel taps α_p^t are independent, then the rank of the $M \times M$ correlation matrix whose entries are $E[H^{k_1} H^{k_2^*}]$ is $N_T N_P$. Indeed, to exploit diversity we need to deploy some form of coding. We address this problem in Section VII.

VI. O-ST-FMT: Orthogonal Space-Time Filtered Multitone Modulation

A different way to achieve spatial, and temporal orthogonalization is to use a variation of the ST-FMT modulation scheme of Section IV. It is obtained by assigning distinct tones to distinct antennas. If the sub-channels do not frequency overlap, then distinct spatial channels occupy distinct portions of the available spectrum, thus they don't overlap. We refer to this scheme as O-ST-FMT. In formulae, the signal transmitted by antenna t can be written as

$$x^t(nT) = e^{j\frac{2\pi}{M}nt} \sum_{k=0}^{M_T-1} \sum_{l=-\infty}^{\infty} a^{t,k}(lT_0) g(nT - lT_0) e^{j\frac{2\pi}{M_T}nk} \quad (12)$$

if we assume to interleave the tones across the antennas, and we denote the number of tones per antenna with M_T=M/N_T. The resulting transmission bit rate is $R_{O-ST-FMT} = N_b M / T_0$. It can be higher than that in O-ST-CP-DMT depending on the choice of N, and consequently of T_0.

From (12) an efficient polyphase implementation can be derived. For example, assuming a critically sampled system, we have that $M = N$ such that the sequence of symbols transmitted by antenna t reads

$$\begin{aligned} x^{t,n}(mT_0) &= x^t(mT_0 + nT) = \sum_{l=-\infty}^{\infty} g^{t,n}(mT_0 - lT_0) A^{t,n}(lT_0) \\ g^{t,n}(lT_0) &= g(lT_0 + nT)e^{j\frac{2\pi}{M}nt} \quad A^{t,n}(lT_0) = \sum_{k=0}^{M_T-1} a^{t,k}(lT_0) e^{j\frac{2\pi}{M_T}nk} \end{aligned} \quad (13)$$

for $m = -\infty,...,\infty$, $n = 0,...,M-1$. The implementation is shown in Fig. 4. Now, we need to deploy an IDFT with M_T points per antenna. The output block of length M_T is cyclically extended to obtain the block $A^{t,n}(lT_0)$ of length M . Then, low-rate filtering with $g^{t,n}(lT_0)$ is performed. Finally, P/S conversion follows.

Similarly, to the ST-FMT modulation case, demodulation is accomplished by first deploying a bank of M filters matched to the sub-channel transmit pulses. With the channel model (1), under the assumption of non overlapping (in frequency) sub-channels, and under the assumption of deploying distinct tones over distinct antennas, the matched filter output sample reads

$$z^{\hat{t},\hat{k}}(mT_0) = a^{\hat{t},\hat{k}}(lT_0) \beta^{\hat{t},\hat{k}}(mT_0 - lT_0) + w^{\hat{t},\hat{k}}(mT_0) . \quad (14)$$

That is, the matched filter output of index $(\hat{t},\hat{k})$, for $\hat{t} = 0,...,N_T-1$ and $\hat{k} = 0,...,M_T-1$, exhibits a contribution only from the frequency sub-channel of index $\hat{k}$, and the spatial channel of index $\hat{t}$. Therefore, also in this architecture we have orthogonalized the N_T spatial channels. However, some residual ISI can be present which requires some form of temporal equalization, i.e., a bank of independent single channel equalizers.

VII. Channel Coding

In order to exploit spatial and frequency diversity we need to use some form of channel coding in all space-time architectures that we have described. Coding has to take place across the space-frequency sub-channels. It is important to note that while in ST-CP-DMT and ST-FMT the spatial channels overlap, in O-ST-CP-DMT and O-ST-FMT the spatial channels are orthogonalized. For all architectures a possible good coding approach is to use a space-time bit-interleaved encoder [9]. Decoding can be performed via the turbo approach that is based on the iterative concatenation of symbol demapping, de-interleaving, and channel decoding. In ST-CP-DMT we have M flat faded sub-channels each carrying the simultaneous transmission of N_T data symbols. Decoding can be performed with the iterative ST-MAP algorithms in [9]. In ST-FMT we have M sub-channels each carrying the simultaneous transmission of N_T data symbols and each

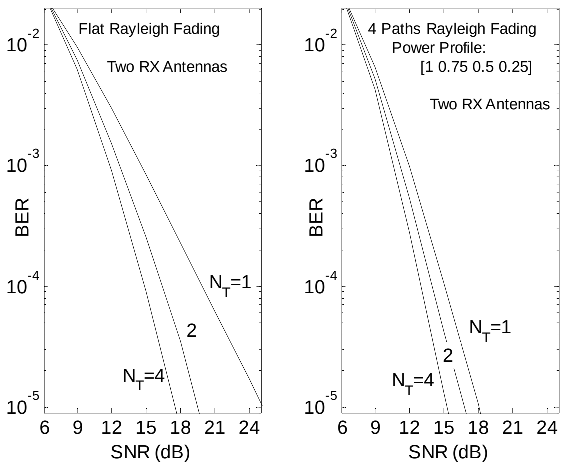

Fig. 5. Performance of O-ST-CP-DMT with outer data spreading. M=64, μ=4, 4-PSK modulation, two receive antennas with ZF detection and MRC combining. Up to N_T=4 transmit antennas.

exhibiting moderate ISI. Decoding can be performed with the iterative ST-MAP equalization algorithms in [12], [13]. In O-ST-CP-DMT we have *M* flat faded sub-channels each carrying a single symbol from a given antenna. Similarly, in O-ST-FMT the spatial channels do not overlap, however some moderate ISI can be present. We emphasize that while for ST-CP-DMT and ST-FMT the complexity of the demapping stage grows exponentially with the number of antennas, in the other two schemes the complexity of each sub-channel demapper is independent from the number of antennas. The penalty is that if we fix the data modulation order in the first two schemes the (peak) transmission rate increases linearly with the number of transmit antennas, while in the latter two schemes is independent of the number of transmit antennas. However, this doesn't necessarily mean that the spectral efficiency is lower in practical scenarios. It has also to be noted that depending on the system design, T_0 is not the same for the four schemes. Typically, a sufficiently long cyclic prefix is deployed in the DMT schemes so that, assuming N_b to be fixed, we have that $R_{O-ST-CP-DMT} \le R_{O-ST-FMT} \le R_{ST-CP-DMT} \le R_{ST-FMT}$. To increase the transmission rate in the latter two schemes we can use higher order modulation, e.g., map $N_T N_b$ bits per modulated symbol.

A. Orthogonal Spreading

Another idea to exploit diversity in the architectures that we have described, is to use data spreading across the space-frequency sub-channels [4]. For space limitations we describe it for O-ST-CP-DMT only. Let us consider an orthonormal matrix, e.g., Walsh-Hadamard matrix, of size *M*. Let $c(i,k)$ for *k*=0,…,*M*-1 be the elements of the *i*-th row. Let $b^i(lT_0)$, *i*=0,…, *M*-1, be a block of data symbols to be transmitted. Then, we apply the orthonormal transform to generate the block of symbols $a^k(lT_0)=\sum_{i=0}^{M-1} b^i(lT_0)c(i,k)$, *k*=0,…, *M*-1, that are transmitted by the O-ST-CP-DMT modulator. According to (11) the output of the demodulator now reads $z^k(lT_0)=H^k \sum_i b^i(lT_0)c(i,k)+w^k(lT_0)$. Assuming knowledge of the channel weights, we can recover the transmitted data symbols, for instance, with simple coherent de-spreading (ZF equalization) as follows

$$z^{\hat{k}}_{despr}(lT_0)=\sum_{k=0}^{M-1} z^k(lT_0) H^{k^*} / |H^k|^2 \, c^*(\hat{k},k) \qquad (15)$$

The above procedure does not add redundancy, i.e., we keep the bit rate equal to MN_b/T_0 bits/s. It implements a form of space-frequency data spreading. It is applied for diversity exploitation. In Fig. 5 we report BER performance for several scenarios assuming double receive diversity and maximal ratio combining. Deep performance improvements are found both in flat fading and in frequency selective fading.

VIII. CONCLUSIONS

We have proposed several ST multitone architectures whose goal is to orthogonalize the time dispersive, with multiple transmit antennas channel. They can be concatenated with outer codes and/or direct sequence spreading. ST-FMT and O-ST-CP-DMT are an interesting option for transmission over uplink multiuser asynchronous channels (see [14]).

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