Performance Analysis of a Multiple Antenna Concatenated DMT-FMT Scheme in the Uplink

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***Abstract*—In this paper we analyze a recently proposed concatenated multitone system for application in the asynchronous multiple access channel (wireless uplink). We study the robustness of the scheme to the users' time offsets, carrier frequency offsets, and channel time/frequency selectivity. A comparison with multiuser OFDM and MC-CDMA is reported which shows that increased robustness and better performance can be achieved with the proposed scheme. It is based on the concatenation of an inner filtered multitone (FMT) modulator with transmission over multiple antennas, and an outer space-time cyclically prefixed discrete multitone (ST-CP-DMT) modulator. The inner modulator is used to efficiently realize frequency division multiplexing of the users by partitioning the FMT sub-channels among them. The outer modulator copes with the residual sub-channel intersymbol interference and it further implements a form of transmit diversity. Frequency and space diversity is exploited via direct sequence (DS) data spreading across the DMT tones.**

Keywords—Filtered multitone modulation, Multiuser systems, Multiple Antennas, OFDM., Wireless uplink.

I. INTRODUCTION

In this paper, we consider an air-interface for the asynchronous multiple access channel (uplink) that combines concatenated multitone modulation with multiple antenna transmission [1]. The reverse link poses several challenges that are due to the asynchronous nature of this link. That is, the communication channels of distinct users can be considered independent and they experience propagation delays, carrier frequency offsets, Doppler from movement, and transmission power limitations. These impairments may translate into multiple access interference (MAI) that severely affects performance. Among the various transmission technologies, multicarrier modulation and in particular orthogonal frequency division multiplexing (OFDM), has proven to be effective in simplifying the equalization task in severely dispersive fading channels. In OFDM multiplexing of the users can be obtained by partitioning the available OFDM tones among the active users. However, it should be noted that OFDM, referred to as discrete multitone (DMT) modulation in this paper, is severely affected by time misalignments and carrier frequency offsets that can be large in the reverse link [2]-[3]. This is due to the fact that in conventional OFDM, sub-channels exhibit a *sinc* like frequency response, therefore their orthogonality can be easily lost in the absence of precise synchronization. In an asynchronous multiuser environment, increased robustness and better performance is obtained with filtered multitone (FMT) modulation architectures where the sub-channels are shaped with time-frequency concentrated pulses and are partitioned among the users [4]-[5]. The frequency concentrated sub-channels allow to avoid the intercarrier interference (ICI) and get low intersymbol interference (ISI) contributions. With uniformly spaced sub-carriers and identical sub-channel filters, an efficient digital implementation of an FMT modulator/demodulator is possible. As described in [6] it is based on a fast Fourier transform (FFT) and low rate sub-channel filtering.

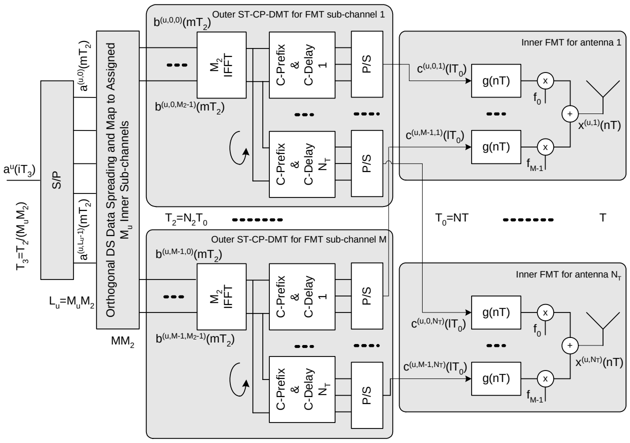

Fig.1. Concatenated multiple antenna DMT-FMT transmitter.

The scheme (Fig.1) that we describe and analyze in this paper combines an inner FMT modulator with an outer cyclically prefixed DMT modulator with multiple antenna transmission [1]. The inner modulator is used to efficiently realize frequency division multiplexing by partitioning the FMT sub-channels among the users. The outer modulator is used to cope with the residual ISI of the FMT sub-channels and to provide a form of transmit diversity. It is here referred to as space-time cyclically prefixed DMT (ST-CP-DMT) [7]. Frequency and space diversity is exploited via direct sequence data spreading across the DMT tones that fall within the FMT sub-channels that are assigned to a given user.

II. SYSTEM DESCRIPTION AND ANALYSIS

In this section we describe the proposed transmission architecture. The transmitter (Fig.1) of a given user comprises an inner FMT modulator, an outer ST-CP-DMT modulator, and finally a DS data spreading stage. We use this order

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because the transmitter is modular and can work in principle with the inner FMT modulator only.

A. Concatenated DMT-FMT Multiple Antenna Transmitter

We assume to frequency multiplex N_U uplink users. Each user has an FMT modulated based transmitter that is equipped with N_T transmit antennas. Multiplexing is realized by partitioning the M overall FMT sub-channels among the users [4]-[5]. Each FMT sub-channel is shaped with the real prototype pulse $g(nT)$ that has frequency concentrated response. The FMT sub-channels are centered at frequency f_k, $k = 0,...,M-1,$ with separation $f_k - f_{k-1} = 1/(MT),$ where $W = 1/T$ equals the overall transmission bandwidth. T is assumed as the time unit in the following. The sub-channel symbol period is $T_0 = NT = MT(1+\alpha)$ which corresponds to a non-critically sampled FMT architecture for $\alpha > 0$ [6]. With an ideal root-raised-cosine prototype pulse with roll-off α_1, we can choose $\alpha = \alpha_1 + \alpha_2$ with $\alpha_2 > 0$ such that a frequency guard equal to α_2 / T_0 exists between adjacent sub-channels.

The lowpass discrete-time signal that is transmitted by user u on antenna t can be written as

$$x^{(u,t)}(nT) = \sum_{k=0}^{M-1} \sum_{l \in \mathbb{Z}} c^{(u,k,t)}(lT_0) g(nT - lT_0) e^{j 2\pi f_k nT} \qquad (1)$$

where $f_k = k/(MT)$ and $c^{(u,k,t)}(lT_0)$ denotes the complex symbol that is transmitted at time instant lT_0 by user u over the FMT sub-channel of index $k = 0,...,M-1$ and antenna of index $t = 1,...,N_T$. Distinct FMT sub-channels can be assigned to distinct users. Thus, the symbols are set to zero for the unassigned sub-channels, i.e., $c^{(u,k,t)}(lT_0) = 0$ for $k \notin K_u$, where K_u denotes the set of M_u sub-channel indices that are assigned to user u.

The outer modulator is a modified discrete multitone (DMT) modulator with M_2 tones that is applied serially on each FMT sub-channel (Fig.1) [7]. It is here referred to as space-time cyclically prefixed DMT (ST-CP-DMT). It realizes a form of transmit diversity and, in principle, it allows to obtain a flat frequency response for each FMT inner sub-channel. At the ST-CP-DMT modulator stage of user u and FMT sub-channel k we take a block of M_2 symbols that belong to the PSK/QAM constellation (unless DS data spreading is applied). The block of symbols is denoted as $b^{(u,k,k')}(mT_2) = b^{(u,k,k')}(mN_2T_0)$ for $k' = 0,...,M_2 - 1.$ Each block is transformed by an M_2-point inverse discrete Fourier transform (IDFT). A cyclic prefix of length $\mu \geq 0$ is added to generate an output block of N_2 symbols to cope with the channel time dispersion due to frequency selectivity. The block has transmission period $T_2 = N_2 T_0,$ with $N_2 = M_2 + \mu$. The block at the output of the IDFT is transmitted by an antenna after the insertion of a cyclic delay. In formulae, we generate N_T blocks of N_2 symbols each as follows

$$c^{(u,k,t)}(lT_0) = \frac{1}{\sqrt{M_2 N_T}} \sum_{k'=0}^{M_2-1} b^{(u,k,k')}(mT_2) e^{j\frac{2\pi}{M_2}(n-\mu-\delta^{(t)})k'} \qquad (2)$$

for $l = n + mN_2,$ $n = 0,...,N_2 - 1,$ $m \in \mathbb{Z}$, and $t = 1,...,N_T$. $\delta^{(t)}$ is an integer delay. The cyclic prefix does not increase with the number of transmit antennas. It should be noted that the symbol stream (2) is fed to the FMT modulator. Essentially, the concatenation of the two modulators generates $L_u = M_u M_2$ narrow sub-channels for user u. The ST-CP-DMT transform can be viewed as a rate one space-time block code, i.e., a transmit diversity scheme, such that the FMT sub-channel k supports a net symbol rate of $M_2/(N_2 T_0)$ symb/s. The goal of the ST-CP-DMT modulator is to increase the diversity resources, i.e., to transform spatial diversity into frequency diversity.

To exploit frequency and spatial diversity we consider in this paper the deployment of DS data spreading across the L_u narrow sub-channels that are obtained via the concatenation of the two modulators of user u (Fig.1). We assume Walsh-Hadamard spreading of length L_u although a shorter code can be used. Thus, starting from a block of L_u PSK/QAM data symbols $a^{(u,i)}(mT_2)$, $i = 0,...,L_u - 1$, of user u, spreading yields

$$b^{(u,k,k')}(mT_2) = \frac{1}{\sqrt{L_u}} \sum_{i=0}^{L_u-1} a^{(u,i)}(mT_2) s(i, k' + C^{(u)}(k) M_2) \qquad (3)$$

with $k' = 0,...,M_2 - 1$, and $C^{(u)}(k) \in [0,...,M_u - 1]$ for $k \in K_u$ is the inverse of the function that yields the indices of the FMT sub-channels of user u. $s(i,n)$ are the elements of the n-th column of the Walsh-Hadamard matrix of size L_u. The procedure implements a form of space-frequency data spreading and it does not add redundancy, i.e., we keep the data rate equal to $M_2/(N_2 T_0)$ symb/s per FMT sub-channel. Different users may have variable length codes that depend on M_u. Equal rate users can have the same spreading codes if they are assigned to distinct FMT channels.

B. Multiuser Channel

In the uplink, the signals of the N_U users propagate through independent time-variant frequency selective fading channels. We assume an equivalent discrete-time lowpass channel model and a receiver that is equipped with N_R receive antennas such that the received sample for receive antenna r at time instant $\tau_i = iT + \Delta_0$ where $i \in \square$ and Δ_0 is a sampling phase, can be written as

$$\begin{aligned} y^{(r)}(\tau_i) = &\sum_{u=1}^{N_U} \sum_{t=1}^{N_T} \sum_{k=0}^{M-1} \sum_{n \in \mathbb{Z}} x^{(u,k,t)}(nT) \\ &\times g_{CH}^{(u,t,r)}(\tau_i - nT - \Delta_\tau^{(u)}; \tau_i) e^{j\left(2\pi\ \Delta_f^{(u)} \tau_i + \phi^{(u)}\right)} + w^{(r)}(\tau_i) \end{aligned} \qquad (4)$$

$$x^{(u,k,t)}(nT) = \sum_{l \in \mathbb{Z}} c^{(u,k,t)}(lT_0) g(nT - lT_0) e^{j 2\pi f_k nT} \qquad (5)$$

where $w^{(r)}(\tau_i)$ is a sequence of i.i.d. zero mean Gaussian random variables, while (5) is the sub-channel signal of index k that is transmitted by antenna t of user u (see also (1)). In this model $g_{CH}^{(u,t,r)}(\tau_1; \tau_2)$ is the equivalent lowpass time-variant impulse response of the broadband channel for the t-th transmit – r-th receive antenna link of user u. It includes the effects of the filters in the digital-to-analog and the analog-to-digital converters at the transmitter and receiver sides. Furthermore, $\Delta_\tau^{(u)}$, $\Delta_f^{(u)}$, $\phi^{(u)}$ are respectively the time offset, the carrier frequency offset (assumed much smaller than $1/T$), and the phase offset of user u. We assume the uplink users to have independent fading channels and time/frequency offsets.

C. Receiver

Detection is accomplished on a user by user base with a three stage receiver that first performs demodulation for the inner FMT modulator, then it runs ST-CP-DMT demodulation, and finally it applies despreading and data decision.

In the FMT demodulation stage we first acquire time/frequency synchronization with each active user. Then, for each user, we run FMT demodulation via a bank of filters that is matched to the transmitter bank and we sample the outputs at rate $1/T_0$. Assuming knowledge of the time and frequency offsets (that have in practice to be estimated [8]), the sequence of samples at the front-end filter output of FMT sub-channel $\tilde{k}$ of user $\tilde{u}$ and receive antenna r that compensates the time offset $\Delta_\tau^{(\tilde{u})}$, and the frequency offset $\Delta_f^{(\tilde{u})}$ of only user $\tilde{u}$, can be written as

$$\begin{aligned} z_{inner}^{(\tilde{u},\tilde{k},r)}(mT_0) &= \sum_{i\in\mathbb{Z}} y^{(r)}(iT+\Delta_\tau^{(\tilde{u})}) g^*(iT-mT_0) e^{-j2\pi\left(f_{\tilde{k}}+\Delta_f^{(\tilde{u})}\right)iT} \\ &= \sum_{u=1}^{N_U}\sum_{t=1}^{N_T}\sum_{k=0}^{M-1}\sum_{l\in\mathbb{Z}} c^{(u,k,t)}(lT_0) g_{EQ}^{(u,k,t),(\tilde{u},\tilde{k},r)}(mT_0-lT_0;mT_0)+\eta^{(\tilde{u},\tilde{k},r)}(mT_0) \end{aligned} \tag{6}$$

where $\eta^{(\tilde{u},\tilde{k},r)}(mT_0)$ are the filtered noise samples, and

$$\begin{aligned} g_{EQ}^{(u,k,t),(\tilde{u},\tilde{k},r)}(lT_0;mT_0) = \sum_{n\in\mathbb{Z}}\sum_{i\in\mathbb{Z}} & g(nT+lT_0-mT_0)g^*(iT-mT_0) \\ & \times e^{j2\pi\left(f_k nT - f_{\tilde{k}} iT\right)+j2\pi\left(\Delta_f^{(u)}-\Delta_f^{(\tilde{u})}\right)iT+j\phi^{(u),(\tilde{u})}} \\ & \times g_{CH}^{(u,t,r)}(iT-nT-\Delta_\tau^{(u)}+\Delta_\tau^{(\tilde{u})};iT+\Delta_\tau^{(\tilde{u})}) \end{aligned} \tag{7}$$

with $\phi^{(u),(\tilde{u})}=\phi^{(u)}+2\pi\Delta_f^{(u)}\Delta_\tau^{(\tilde{u})}$, is the multi-channel time-variant impulse response between the input sub-channel of indices (u,k,t) and the output sub-channel of indices $(\tilde{u},\tilde{k},r)$. In general, the sub-channel filter output of index $\tilde{k}$ may suffer from ISI, ICI (from the sub-channels of index $k\neq\tilde{k}$ that are assigned to user $\tilde{u}$), and MAI (from all sub-channels that belong to the other users) as a consequence of frequency overlapping sub-channels, time/frequency offsets, and channel time/frequency selectivity. Using Parseval theorem it can be shown that the multi-channel impulse response (7) differs from zero only for $k=\tilde{k}$ if the following conditions hold true:

C1. $G(f)=0$ for $(1+\alpha_1)/(2T_0)\leq |f| \leq 1/(2T)$

C2. $|\Delta_f^{(u)}|\leq\alpha_2/(2T_0)$ for all u

where $G(f)$ is the Fourier transform of the prototype pulse (assumed to be real). In other words, if the prototype pulse has a confined frequency response and the carrier frequency offsets of the users are smaller than half the frequency guard, the FMT sub-channels do not overlap (despite the frequency shift) such that we do not get any ICI at the filter bank output. In this case that can be met with the appropriate system design, (6) reads

$$\begin{aligned} z_{inner}^{(\tilde{u},\tilde{k},r)}(mT_0) = \sum_{u=1}^{N_U}\sum_{t=1}^{N_T}\sum_{l\in\mathbb{Z}} & c^{(u,\tilde{k},t)}(lT_0) g_{EQ}^{(u,\tilde{k},t),(\tilde{u},\tilde{k},r)}(mT_0-lT_0;mT_0) \\ & +\eta^{(\tilde{u},\tilde{k},r)}(mT_0) \end{aligned} \tag{8}$$

Thus, MAI is present only if the same FMT sub-channel is assigned to more than one user. Now if we assume a T-spaced broadband channel with taps $\alpha_p^{(\tilde{u},\tilde{k},t,r)}(mT_0)$, $p\in P\subset\mathbb{Z}$ that are time-invariant over the duration of the prototype pulse whose main lobe has duration $\sim T_0$, and we further assume to assign distinct FMT tones to distinct users, (8) becomes

$$z_{inner}^{(\tilde{u},\tilde{k},r)}(mT_0)=\sum_{t=1}^{N_T}\sum_{q=-N_{Q1}}^{N_{Q2}}\beta_q^{(\tilde{u},\tilde{k},t,r)}(mT_0)c^{(\tilde{u},\tilde{k},t)}(mT_0-qT_0)+\eta^{(\tilde{u},\tilde{k},r)}(mT_0)$$

$$\beta_q^{(\tilde{u},\tilde{k},t,r)}(mT_0)=\sum_{p\in P}\alpha_p^{(\tilde{u},t,r)}(mT_0)\kappa_g(qT_0-pT)e^{-j\frac{2\pi}{M}p\tilde{k}+j\phi^{(\tilde{u}),(\tilde{u})}} \tag{9}$$

where $\kappa_g(mT)=\sum_i g(iT)g^*(iT-mT)$ is the prototype pulse autocorrelation, and $N_Q T_0=(N_{Q1}+N_{Q2}+1)T_0$ is the duration of the T_0-spaced sub-channel with taps $\beta_q^{(\tilde{u},\tilde{k},t,r)}(mT_0)$. N_Q depends on the channel delay spread, the prototype pulse, and the number of FMT tones, but, practically, it can be considered small. Therefore, at the receiver, the FMT sub-channel $\tilde{k}$ of user $\tilde{u}$ sees ISI and the superposition of the signals that are simultaneously transmitted by the N_T antennas. If we do not use the outer ST-CP-DMT modulator we need to accomplish data detection at this stage. Since there is ISI, sub-channel space-time equalization is required [9]. However, for the particular transmit diversity scheme that we consider in this paper the spatial channels are orthogonal as we show in the following.

Let us start from (9) and let us collect the FMT front-end output samples of receive antenna r and sub-channel $\tilde{k}$, into blocks of N_2 samples that we denote as $z_{inner}^{(\tilde{u},\tilde{k},r)}(nT_0+lN_2T_0)$ for $l\in$ □ , $n=0,\ldots,N_2-1$. Now, for each receive antenna and FMT sub-channel, ST-CP-DMT demodulation is accomplished by dropping the cyclic prefix in the block $z_{inner}^{(\tilde{u},\tilde{k},r)}(nT_0+lN_2T_0)$ and applying an M_2-point discrete Fourier transform (DFT). Then, under the conditions

C3. μT_0 larger than the sub-channel time dispersion $(N_Q-1)T_0$,

C4. time-invariant channel over a window of duration N_2T_0,

the DFT output of index $k'=0,\ldots,M_2-1$ reads

$$z_{outer}^{(\tilde{u},\tilde{k},k',r)}(lT_2)=H^{(\tilde{u},\tilde{k},k',r)}(lT_2)b^{(\tilde{u},\tilde{k},k')}(lT_2)+n^{(\tilde{u},\tilde{k},k',r)}(lT_2) \tag{10}$$

$$H^{(\tilde{u},\tilde{k},k',r)}(lT_2)=\frac{1}{\sqrt{N_T}}\sum_{t=1}^{N_T}\sum_{q=0}^{N_Q}\beta_q^{(\tilde{u},\tilde{k},t,r)}(lT_2)e^{-j\frac{2\pi}{M_2}(q+\delta^{(t)})k'}. \tag{11}$$

According to (10) the DFT output of index k' is equal to the superposition of a noise contribution with the data symbol $b^{(\tilde{u},\tilde{k},k')}(lT_2)$. The data symbol is weighted by an equivalent channel transfer function $H^{(\tilde{u},\tilde{k},k',r)}(lT_2)$ that is obtained by a transform of the fading channel responses of all antennas that we assume to be statistically independent. Therefore, each DFT output sees a single-input single-output flat faded channel, i.e., the multiple transmit antenna system is transformed into a single transmit antenna system where the spatial diversity translates into increased frequency diversity.

We accomplish despreading with a minimum mean square error (MMSE) approach on a per sub-channel basis, such that the decision metric for the *i*-th data symbol $a^{(\tilde{u},i)}(lT_2)$ is as follows

$$z_{despr}^{(\tilde{u},i)}(lT_2)=\frac{1}{\sqrt{L_u}}\sum_{\tilde{k}\in K_u}\sum_{k'=0}^{M_2-1}\frac{\sum_{r=1}^{N_R} z_{outer}^{(\tilde{u},\tilde{k},k',r)}(lT_2)H^{(\tilde{u},\tilde{k},k',r)}(lT_2)^*}{\sum_{r=1}^{N_R}|H^{(\tilde{u},\tilde{k},k',r)}(lT_2)|^2+\sigma_\eta^2} \qquad (12)$$
$$\times s^*(i,k'+C^{(\tilde{u})}(\tilde{k})M_2)$$

where σ_η^2 is the variance of the noise.

The ST-CP-DMT modulator allows to increase the diversity resources that can be limited when a small number of FMT sub-channels are assigned to a user. It should be noted that without channel coding or DS data spreading no diversity exploitation is possible since the concatenation of the outer and inner modulators generates, for user *u*, $L_u = M_2 M_u$ non-overlapping flat faded channels. We point out that if the conditions C1-C4 that led to (12) do not hold true some interference components can be present. In particular, C1-C2 grant the absence of ICI and MAI at the output of the FMT receiver filter bank. The interference at the FMT front-end output propagates to the output of the ST-CP-DMT demodulator. Furthermore, when C3-C4 do not hold true, the DFT output experiences ICI and ISI. In conclusion, if for simplicity we assume ZF detection, (12) can be manipulated to obtain $z_{despr}^{(\tilde{u},i)}(lT_2) = a^{(\tilde{u},i)}(lT_2) + ISI + ICI + MAI + noise$. The evaluation of the signal-to-inference power ratio shows that it is high with the appropriate system design.

III. PERFORMANCE

We report bit-error-rate (BER) performance as a function of the average symbol-energy-to-noise ratio (SNR). We assume the parameters in Table I with a truncated root-raised-cosine prototype pulse for the FMT modulator. In the proposed architecture, distinct users and antenna links have independent channels. Further, the users have independent uniformly distributed time offsets in $[0, \varepsilon_T]T_0$, and carrier frequency offsets in $[-\varepsilon_F, \varepsilon_F]/(MT)$, that are assumed to be constant over the transmission of a frame of several outer DMT symbols. The users deploy 4-PSK modulation and have equal average power and number of antennas. The system is fully loaded (all sub-channels are used) with users having the same rate. The FMT sub-channels are allocated in an interleaved fashion. We assume perfect knowledge of the channel and ideal time/frequency synchronization when we demodulate the desired user.

Our architecture can work with only the inner FMT stage. In this case it corresponds to a multiuser FMT system [5]. In Fig.2, we compare the inner FMT stage assuming the parameters in Table I.A with a multiuser DMT scheme (OFDMA) that uses 128 tones and a CP of length 32. The two systems have identical data rate. Single transmit-receive antenna is used. Detection is single user based with one tap equalization for the DMT scheme and with MMSE linear equalization with 11 taps for the FMT scheme. 8 full rate users are active. In the DMT scheme the users are multiplexed by partitioning the 128 tones in a block (BLK) or in an interleaved (INT) fashion. We consider quasi static frequency selective Rayleigh fading with rays spaced by T. The rays are independent and have an exponential power delay profile with

TABLE I

	SYSTEM A	**SYSTEM B**
Modulation	*4-PSK*	*4-PSK*
Spreading	*Walsh Hadamard*	*Walsh Hadamard*
Number of tones of inner FMT modulator	$M = 32$	$M = 32$
Maximum number of users per frame	$N_U = 32$	$N_U = 32$
Roll-off root-cosine pulse + guard factor	$\alpha = \alpha_1+\alpha_2 = 0.2+0.05$	$\alpha = \alpha_1+\alpha_2 = 0.0625+0$
FMT sub-channel symbol period	$T_0 = 40T$	$T_0 = 34T$
Aggregate symbol rate with FMT only	$R_{TOT\text{-}IN} = M/T_0 = 0.8/T$	$R_{TOT\text{-}IN} = M/T_0 = 0.94/T$
Number of tones outer ST-CP-DMT	$M_2 = 32$	$M_2 = 32$
Cyclic prefix length	$\mu = 8$	$\mu = 6$
ST-CP-DMT sub-channel symbol period	$T_0(M_2+\mu) = 40T_0$	$T_0(M_2+\mu) = 38T_0$
Aggregate symbol rate with outer mod.	$R_{TOT\text{-}OUT} = 0.64/T$	$R_{TOT\text{-}OUT} = 0.79/T$

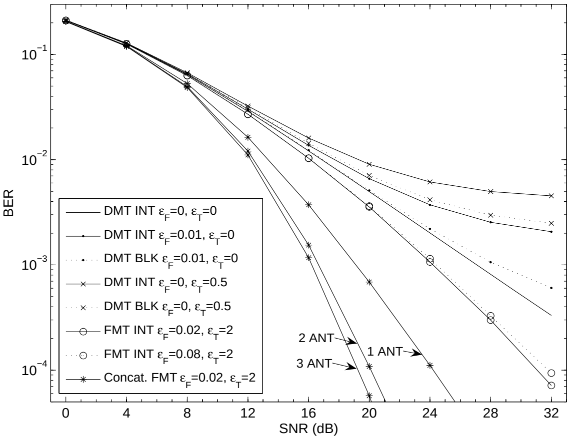

Fig.2. Performance of multiuser DMT, multiuser FMT, and concatenated DMT-FMT with 8 asynchronous users in the uplink. Up to 3 transmit antennas for concatenated DMT-FMT.

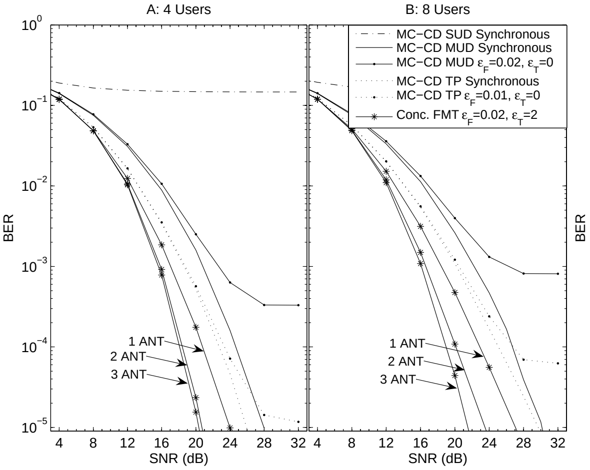

Fig.3. Performance of MC-CDMA, MC CDMA with tone partitioning (MC CDMA TP) and concatenated DMT-FMT with 4 and 8 asynchronous users in the uplink. Up to 3 transmit antennas for concatenated DMT-FMT.

average power $\Omega_p \sim e^{-pT/(\gamma T_0)}$, with $p \in \mathbb{Z}^+$ and $\gamma = 0.1$. The channel is truncated at -20 dB. The BER is averaged over all users. The figure shows that multiuser DMT is severely affected by the MAI that is generated by the users' frequency offsets and by the time offsets (together with the channel dispersion) that exceed the CP length. With the block tone allocation DMT is more robust than with the interleaved allocation [2]. However, DMT performs always worse than the multiuser FMT scheme for all the cases herein considered. For the FMT scheme there is no visible degradation due to the MAI if $\varepsilon_F \leq 0.02$ although we use truncated prototype pulses. While uncoded DMT with synchronous users performs essentially as 4-PSK in flat fading, the FMT sub-channel equalizer yields a diversity gain by the exploitation of the sub-channel frequency selectivity [10].

Now, although the inner FMT scheme allows to implement a robust multiple access system, its performance can be improved by concatenating the outer DMT stage and adding DS spreading. The curve labeled with Concat. FMT in Fig.2 assumes the parameters in Table I.B and it shows that at BER=10^{-4} we obtain about 6.5 dB improvement over the inner FMT scheme and about 12 dB over synchronous DMT with identical data rate. This is due to the capability of the concatenated scheme to exploit the wideband channel diversity. Further improvements can be realized with multiple transmit antennas as Fig. 2 shows.

In Fig.3 we compare the performance of the proposed concatenated DMT-FMT system with multicarrier CDMA (MC-CDMA) assuming a single transmit-receive antenna. MC-CDMA is essentially a DMT scheme where all tones are assigned to all users and multiplexing is obtained by partitioning the codes among the users [11]. Since the data symbols are spread over the whole tones (bandwidth) with a unique code, MC-CDMA can exploit the full frequency diversity. MC-CDMA has proved to be effective in the downlink. In the uplink, it is severely affected by the MAI that is generated both by the independent frequency selective channels and the users' asynchronism. Fig.3 shows an example of the performance of MC-CDMA with 4 and 8 users. MC-CDMA has 128 tones and a long cyclic prefix of length 72 to counteract the propagation delays. Walsh codes of length 128 are used. All spreading codes are assigned such that the data rate is identical for the various schemes herein evaluated. For MC-CDMA single user detection (SUD) is not sufficient in the uplink even with synchronous users such that multiuser detection (MUD) becomes mandatory. Herein we consider MMSE MUD with ideal channel knowledge [11]. Although MC-CDMA has the potentiality of exploiting the full frequency diversity, its performance is limited by the MAI even with MUD and synchronous users. Further, the BER worsens with the users time/frequency asynchronism. To lower complexity and make the scheme more robust in the asynchronous channel we also report the performance of MC-CDMA when we partition in a block fashion the tones across the users [3] (curves labeled with MC-CD TP). In this case, with simpler single user detection the performance improves because tone partitioning reduces the MAI. Nevertheless, the concatenated FMT scheme (with the parameters in Table I.A) has the best performance in all cases here considered (from about 2 to 4 dB gain at BER=10^{-4} over synchronous MC-CDMA), although the users have access to less frequency diversity resources as their number increases.

It should be noted that the performance of the concatenated scheme decreases as the number of users increases because, in our fully loaded system, the number of FMT sub-channels per user decreases and consequently each user cannot exploit the full broadband channel diversity. In this case, multiple transmit antennas can provide spatial diversity benefits. This is shown in Fig.3 assuming 2 and 3 transmit antennas. The ST-CP-DMT with DS spreading provides sensible performance gains. It allows to recover the diversity gain loss for the users that transmit at low rate and occupy a fraction of the overall spectrum.

IV. CONCLUSIONS

We have presented a novel air-interface approach for next generation uplink wireless communications. It is based on the concatenation of an inner FMT modulator and an outer ST-CP-DMT modulator. The scheme exhibits robustness to the users' asynchronism and yields significant performance advantages over multiuser DMT and MC-CDMA. The scheme incorporates a form of transmit diversity that turns out to be very effective in providing spatial diversity benefits for the low rate users that do not have access to high levels of frequency diversity. Furthermore, the proposed scheme is robust to the near-far problem, and it allows to effectively implement synchronization and channel estimation exploiting the separability of multiple users signals in the frequency domain [8].

V. REFERENCES

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