Multiuser Detection/Decoding in Asynchronous Multitone Multiple Access Systems

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Abstract

We devise the optimal detection scheme in multiuser multicarrier based systems. We focus on the critical uplink scenario where several multicarrier signals belonging to distinct users propagate through independent time-variant frequency selective fading channels, and experience independent time offsets and carrier frequency offsets. We consider an efficient discrete-time system implementation and we refer to it as multitone multiple access. When channel coding is deployed we propose to accomplish decoding through the turbo multiuser detection and decoding approach. A simplified detection method is also described.

Keywords

Filtered multitone modulation, multicarrier multiple access, multiuser OFDM, optimal detection.

INTRODUCTION

The potentiality of multicarrier modulation for application to wireless communication systems with high data rate requirements has been widely recognized. The basic principle behind MC modulation is to transmit a high data rate signal through a number of parallel narrow band sub-channels such that the equalization task at the receiver can have lower complexity. Most of the work has concentrated to single user or synchronous multiuser applications. In this paper we consider an asynchronous multiple access channel, and more specifically the uplink of a wireless communication system [5], [3]. Multiple users share the same spectrum and are multiplexed with a combination of frequency division multiple access and multicarrier modulation. That is, a number of sub-carriers are allocated inside the available spectrum. Then, subsets of carriers are assigned to the users. Each user runs multicarrier modulation over its set of sub-carriers. Each sub-channel can be shaped with a sub-channel filter. When the sub-carriers are uniformly spaced and the sub-channel filters are identical, an efficient digital implementation of the transmitter is possible and referred to as filtered multitone multiple access (FMT-MA) [8]. It comprises the cascade of the following stages: sub-carrier mapping, IFFT, low-rate sub-channel filtering, and P/S conversion. Discrete multitone multiple access (DMT-MA) is a particular implementation that deploys rectangular time domain filters such that sub-channel filtering is avoided [6], [7].

In general the temporal selectivity and the frequency selectivity of the channel introduce intercarrier (ICI) and intersymbol (ISI) interference at the receiver side. The loss of system orthogonality is even more severe in a multiple access asynchronous fading channel since distinct users transmit their signal through independent channels, and experience distinct time offsets and carrier frequency offsets. The time offsets are due to propagation delays of users at different distance from the receiver, while the carrier frequency offsets are due to misadjusted oscillators, or Doppler from movement. Therefore, multiple access interference (MAI) is also generated at the receiver. The appropriate design of the sub-channel filters and the tone allocation strategy across users has the potentiality of reducing the interference components [8], [10]. In an FMT system we subdivide the spectrum in a number of sub-channels that do not overlap in the frequency domain, such that we can avoid the ICI and get low ISI contributions [2]. In a DMT system (often referred to as orthogonal frequency division multiplexing, OFDM) the insertion of a cyclic prefix longer then the channel time dispersion is such that ISI and ICI are eliminated and the receiver simplifies to a simple one-tap equalizer per sub-channel. Further, the channel temporal selectivity can also introduce ICI as a result of a loss of the sub-channels orthogonality. This happens when the channel is not static over the duration of the FFT block.

In such a scenario the optimal detector has to search for the maximum likelihood (ML) solution taking into account the presence of the ICI, the ISI, and the MAI. That is, it has to implement a form of multichannel, multiuser detection [9], [13]. We study the performance limits of the optimal maximum likelihood detector in a single user channel in [12]. In particular, in [12] we show that with optimal detection both temporal and frequency diversity gains can be achieved and depend on the sub-channel time/frequency response and the sub-carrier spacing. In this paper we extend the optimal algorithm to the asynchronous multiuser scenario. We consider a discrete-time system model and show that efficient digital implementations are possible. The optimal multitone multiuser detector relies on a metric that can be used in both the ML and the maximum a posteriori (MAP) algorithm [1]. Assuming to deploy channel coding, the latter can be used to compute optimal a posteriori bit/symbol probabilities and can be concatenated in an iterative fashion with the channel decoders. That is, it can be used to implement a form of turbo multiuser detection and decoding which is particularly effective when interleaving is also deployed [4]. The complexity of the optimal algorithm grows in general exponentially with the number of sub-channels and the sub-channel memory. However, the deployment of appropriate sub-channel filters and tone allocations can translate into reduced complexity. Further, simplified detection algorithms based on reduced state techniques can also be deployed.

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MULTITONE MULTIPLE ACCESS

We consider a system where N_U users wish to communicate with a receive station, i.e., uplink communications. The total available spectrum is $W=1/T$ inside which M carries are allocated. Modulation and multiplexing of the users' signals are obtained through a combination of frequency division multiplexing and multicarrier modulation. Essentially, each user is assigned a sub-set of carriers that are used for multicarrier modulation. Distinct users access the media at the same time and in the same spectrum. A number of tone allocation methods are possible. For instance, the spectrum can be partitioned into a number of blocks of carriers. A given block is assigned to a given user. We refer to it as *block allocation*. Another strategy is to interleave the carriers across users, and we refer to it as *interleaved allocation*.

The multicarrier modulated signal (complex lowpass representation) transmitted by user u can be written as

$$x^u(t) = \sum_{k\in\mathcal{K}_u}\sum_{l\in\mathbb{Z}} a^{u,k}(lT_0)\, g(t-lT_0)\, e^{j2\pi f_k t} \tag{1}$$

where $a^{u,k}(lT_0)$ is the sequence of complex data symbols, e.g., M-QAM, of user u transmitted on sub-channel k at rate $1/T_0$ with $T_0=NT$; $g(t)$ is a sub-channel shaping filter (*prototype filter*), and $\mathcal{K}_u \subseteq \{0,\ldots,M\text{-}1\}$ is the set of sub-carrier indices k assigned to user u. The sub-channel carrier frequency is f_k, and in general $N \geq M$. An efficient discrete-time implementation is possible when the sub-carriers are uniformly spaced, i.e., $f_k = k/T_1$ with $T_1 = MT$. In this paper we consider the case $M=N$, i.e., $T_0=T_1$, such that the sub-carriers are minimally spaced and the discrete-time MC signal can be rewritten as

$$x^u(iT) = \sum_{k\in\mathcal{K}_u}\sum_{l\in\mathbb{Z}} a^{u,k}(lT_0)\, e^{j\frac{2\pi}{M}ki}\, g(iT-lT_0)\,. \tag{2}$$

If we define the *sub-channel transmit filter* as $g_T^k(t) = g(t)e^{j2\pi f_k t}$ we can rewrite (2) as follows

$$x^u(iT) = \sum_{k\in\mathcal{K}_u}\sum_{l\in\mathbb{Z}} a^{u,k}(lT_0)\, g_T^k(iT-lT_0)\,. \tag{3}$$

Now let $\mathcal{K}=\{0,\ldots,M\text{-}1\}$, and let $a^{u,k}(lT_0)$ be set to zero in correspondence to unassigned tones. Then, the polyphase decomposition[1] of (2) yields (for $n=0,\ldots,M\text{-}1$, $m=-\infty,\ldots,\infty$)

$$x^{u,n}(mT_0) = \sum\nolimits_{l\in\mathbb{Z}}\sum\nolimits_{k\in\mathcal{K}} a^{u,k}(lT_0)\, e^{j\frac{2\pi}{M}kn}\, g^n(mT_0-lT_0)\,. \tag{4}$$

with $g^n(mT_0)=g(nT+mT_0)$. Therefore, the discrete-time MC modulator (referred to as multitone, MT, modulator in the following) comprises: carrier mapping, M-point IFFT, low rate filtering, P/S conversion. The prototype filter is designed with the goal of minimizing the inter-carrier, inter-symbol, and multiple access interference [5].

[1] The polyphase decomposition is here defined in the time domain as a serial to parallel conversion of a high rate signal $x(iT)$, $i=-\infty,\ldots,\infty$ into M low rate signals $x^n(mT_0)=x(mT_0+nT)$, $T_0=MT$, $n=0,\ldots,M\text{-}1$, $m=-\infty,\ldots,\infty$.

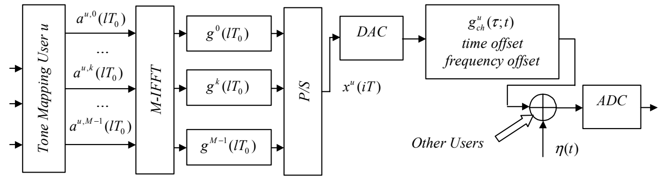

Fig. 1. Multitone lowpass transmission model.

ASYNCHRONOUS MULTIUSER CHANNEL

The MT signal (4) is D/A converted, RF modulated, and transmitted over the air. The received signal is first RF demodulated. Let $g_E^{u,k}(\tau;t)$ be the time-variant baseband impulse response that comprises the cascade of the sub-channel transmit filter $g_T^k(t)$, the analog filter in the D/A converter, and the time-variant radio channel $g_{ch}^u(\tau;t)$ of user u. Then, the composite lowpass received signal is

$$\tilde{y}(t) = \eta(t) + \\ + \sum_{u\in\mathcal{U}}\sum_{k\in\mathcal{K}}\sum_{l\in\mathbb{Z}} a^{u,k}(lT_0)\, g_E^{u,k}(t-\Delta t_{u,k}-lT_0;t)\, e^{j(2\pi\Delta f_{u,k}t+\phi_{u,k})} \tag{5}$$

where $\mathcal{U}$ is the set of active user indices u, $\Delta t_{u,k}$, $\Delta f_{u,k}$, and $\phi_{u,k}$ are the time offset, the carrier frequency offset, and the phase offset of sub-channel k of user u. $\eta(t)$ is zero mean AWGN. The received signal is A/D converted. The analog filters in the D/A and A/D are assumed to approximate an ideal Nyquist filter with bandwidth $1/T$. If we further assume the propagation media to be time-invariant over the duration of the A/D filter, and the frequency offsets $\Delta f_{u,k} << 1/T$, then the sequence of samples at the output of the A/D converter is

$$y(iT) = w(iT) + \\ + \sum_{u\in\mathcal{U}}\sum_{k\in\mathcal{K}}\sum_{l\in\mathbb{Z}} a^{u,k}(lT_0)\, g_R^{u,k}(iT-\Delta t_{u,k}-lT_0;iT)\, e^{j(2\pi\Delta f_{u,k}iT+\phi_{u,k})} \tag{6}$$

where $w(iT)$ are i.i.d. Gaussian with zero-mean and variance N_0, and $g_R^{u,k}(\tau;t)$ is the equivalent *sub-channel receive impulse response* that includes the A/D filter.

OPTIMAL MULTITONE MULTIUSER DETECTION

From (6), the optimal maximum likelihood multitone multiuser detector searches for the data sequences $\{b^{u,k}(lT_0)\}$, of all users and sub-channels, that minimize the Euclidean distance

$$\Delta = \sum_{i\in\mathbb{Z}} \Big| \, y(iT) - \sum_{u\in\mathcal{U}}\sum_{k\in\mathcal{K}}\sum_{l\in\mathbb{Z}} b^{u,k}(lT_0)\, \cdot \\ \cdot\, g_R^{u,k}(iT-\Delta t_{u,k}-lT_0;iT)\, e^{j(2\pi\Delta f_{u,k}iT+\phi_{u,k})} \Big|^2 \,. \tag{7}$$

We can partition the metric (7) as follows

$$\Delta \sim -\mathrm{Re}\Big\{\sum_{l\in\mathbb{Z}}\sum_{u\in\mathcal{U}}\sum_{k\in\mathcal{K}} b^{u,k^*}(lT_0)\Big[2z^{u,k}(lT_0) - \sum_{l'\in\mathbb{Z}}\sum_{u'\in\mathcal{U}}\sum_{k'\in\mathcal{K}} b^{u',k'}(l'T_0)\, s^{k,k',l,l'}(l;l')\Big]\Big\}$$

$$z^{u,k}(lT_0) = \sum_{i\in\mathbb{Z}} y(iT)\, g_R^{u,k^*}(iT-\Delta t_{u,k}-lT_0;iT)\, e^{-j(2\pi\Delta f_{u,k}iT+\phi_{u,k})}$$

$$s^{k,k',l,l'}(l;l') = \sum_{i\in\mathbb{Z}} e^{-j(2\pi\Delta f_{u,k}iT+\phi_{u,k}-2\pi\Delta f_{u',k'}iT-\phi_{u',k'})}\, \cdot \\ \cdot\, g_R^{u,k^*}(iT-\Delta t_{u,k}-lT_0;iT)\, g_R^{u',k'}(iT-\Delta t_{u',k'}-l'T_0;iT) \tag{8}$$

To proceed let us define the following index relations[2]: $m = u + kN_U + lM_1 - 1$, with $M_1 = MN_U$, $l(m) = m \text{ div } M_1$, $k(m) = (m \bmod M_1) \text{ div } N_U$, $u(m) = (m \bmod M_1) \bmod N_U + 1$ for k=0,…,M-1, u=1,…,N_U, l=-∞,…,∞, m=-∞,…,∞. Then,

$$\Delta \sim -\sum_{m\in\mathbb{Z}} \mathrm{Re}\left\{ b_m^* \left[2z_m - \sum_{m'\in\mathbb{Z}} b_{m'} s_{m,m'} \right] \right\} \tag{9}$$

where $b_m = b^{u(m),k(m)}(l(m)T_0)$, $z_m = z^{u(m),k(m)}(l(m)T_0)$, and $s_{m,m'} = s^{u(m),u(m'),k(m),k(m')}(l(m)T_0, l(m')T_0)$. Since $s_{m,m'} = s^*_{m',m}$ we can rewrite (9) as follows

$$\Delta \sim -\sum_{m\in\mathbb{Z}} \mathrm{Re}\left\{ b_m^* \left[2z_m - b_m s_{m,m} - 2\sum_{m'>0} b_{m-m'} s_{m,m-m'} \right] \right\}. \tag{10}$$

It follows that the search of the maximum likelihood transmitted sequence can be implemented with a Viterbi algorithm. The transition metric is defined as:

$$\Delta_m = -\mathrm{Re}\left\{ b_m^* \left[2z_m - b_m s_{m,m} - 2\sum\nolimits_{m'>0} b_{m-m'} s_{m,m-m'} \right] \right\}. \tag{11}$$

while the state is defined as $S_m=\{b_m,\ldots,b_{m-L+1}\}$ for some finite L. Several considerations can be made at this point:

A. The optimal multiuser detector has been derived from the discrete time model (6). It can be derived from the continuous time model (5) as well, see [5], [11].

B. The proposed detection algorithm is applicable also in a single user system, i.e., it is the optimal detector for multitone modulated signals [12].

C. The computation of the transition metric requires the computation of the z and s parameters. In turn, such a computation requires an estimate of both the channel impulse response and the time/frequency/phase offsets of all users. Assuming a tapped delay line channel model the front-end part can be efficiently implemented. In fact, if the cascade of the D/A, the channel, and the A/D has an impulse response $h^u(\tau;t) = \sum_p \tilde{\alpha}^u(p;t)\delta(\tau - \tau_p)$, the sub-channel impulse response reads $g_R^{u,k}(\tau;t) = \sum_p \tilde{\alpha}^u(p;t) g_T^k(\tau - \tau_p)$. If we assume $\tau_p = pT$, and we denote with $\mathcal{P}$ the set of tap indices p, the discrete-time z-parameters read,

$$\begin{aligned} z^{u,k}(lT_0) = \sum_{n\in\mathcal{K}} e^{-j\frac{2\pi}{M}nk} \sum_{m\in\mathbb{Z}} g^*(nT + mT_0 - lT_0)\cdot \\ \cdot \sum\nolimits_{p\in\mathcal{P}} \psi^{u,k}(nT + pT + mT_0)\alpha^*(p; nT + pT + mT_0) \\ \alpha(p;iT) = \tilde{\alpha}(p; iT + \Delta t_{u,k}) \\ \psi^{u,k}(iT) = e^{-j2\pi\Delta f_{u,k}(iT + \Delta t_{u,k}) - j\phi_{u,k}} y(iT + \Delta t_{u,k}) \end{aligned} \tag{12}$$

Therefore, the front-end part of the detector can be efficiently implemented using an FFT and low rate sub-channel matched filtering (see also [12]). Note that the time/frequency/phase compensated samples $\psi^{u,k}(iT)$ are

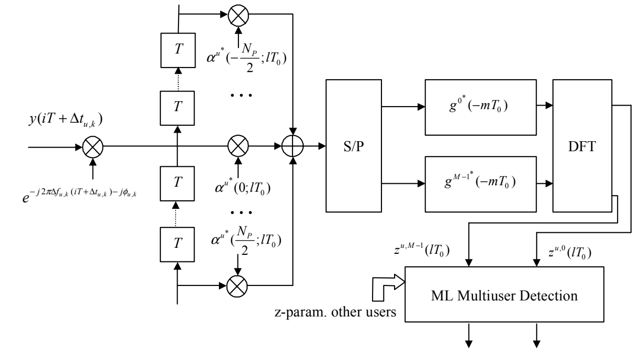

Fig. 2. Optimal Multiuser MT detector in quasi-static multipath channel

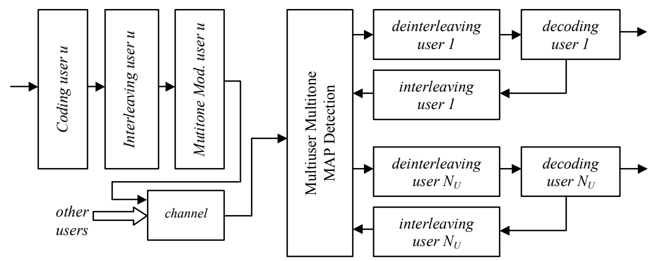

Fig. 3. Turbo multiuser multitone detection.

coherently combined with the time-variant channel taps. This resembles an adaptive RAKE receiver. If the channel is time-invariant over the duration of the prototype filter, the computation of the z-parameters simplifies to

$$\begin{aligned} z^{u,k}(lT_0) \approx \sum_{m\in\mathbb{Z}} g^*(nT + mT_0 - lT_0) \sum_{n\in\mathcal{K}} e^{-j\frac{2\pi}{M}nk}\cdot \\ \cdot \sum_{p\in\mathcal{P}} \alpha^*(p; lT_0)\psi^{u,k}(nT + pT + lT_0) \end{aligned}. \tag{13}$$

Thus, the detector can be implemented as Fig. 2 shows.

D. The metric (11) can be used to implement the MAP algorithm [1]. If we further include the a priori state transition probability, the transition probability to be used in the MAP algorithm becomes:

$$\gamma(z_m, S_m \mid S_{m-1}) \sim e^{\frac{1}{2N_0}\Omega(S_m|S_{m-1})} P(S_m \mid S_{m-1}) \tag{14}$$

$$\Omega(S_m \mid S_{m-1}) = \mathrm{Re}\left\{ b_m^* \left[2z_m - b_m s_{m,m} - 2\sum\nolimits_{m'>0} b_{m-m'} s_{m,m-m'} \right] \right\} \tag{15}$$

$$P(S_m \mid S_{m-1}) = \prod_{m'\geq 0} P(b_{m-m'}). \tag{16}$$

where the a priori transition probability (16), assuming the data symbols to be independent, equals the product of the a priori probability of the data symbols that are associated to the given transition. When channel coding is applied the assumption of independent data symbols holds when interleaving is deployed. Further, the a priori probabilities can be estimated using the redundancy introduced by the channel encoders.

TURBO DETECTION AND DECODING

Let us assume to deploy channel coding (Fig. 3). Here we consider the deployment of bit interleaved codes. Essentially the information bit stream of each user is encoded and

[2] We denote with (a div b) and (a mod b) the integer division and the reminder of the integer division.

interleaved. The encoders are convolutional. The encoded bit stream is parsed into a number of sub-streams equal to the number of assigned carriers. Each sub-stream is mapped into M-QAM data symbols. Finally, multitone modulation takes place.

When interleaved codes are deployed, practical decoding can be accomplished through the turbo decoding approach [4]. Essentially, we run multiuser-carrier detection, then after de-interleaving we run channel decoding (Fig. 3). Further, we can iteratively concatenate demodulation and decoding by passing feedback information from the decoders. The multiuser detector has now to provide the a posteriori probabilities of the coded bits, which are then de-interleaved and passed to the decoders. This is obtained using the MAP detection algorithm with the metric that we have derived. The decoders are implemented using a MAP decoder for convolutional codes [1] and are capable to deliver new a posteriori probabilities of the coded bits. These are interleaved and passed back to the multiuser detector where they are used to estimate the a priori transition probabilities (16).

SIMPLIFIED DETECTION

Let us denote with *M.O* the modulation order (constellation size), and with L the number of data symbols associated to each state. Then, the complexity of the ML detection algorithm is determined by the number of states that is equal to $|\Sigma|=(M.O)^L$, and the number of transitions to/from each state that is equal to *M.O*. Note that $L \le m_C M N_U$ with m_C being the memory of the sub-channel impulse response. That is, the complexity of the algorithm increases exponentially with the number of users, the number of sub-channels and the memory of the channel. The exact value of L depends on the propagation conditions, the tone multiplexing scheme, and the choice of the prototype filter. For instance, if we allocate to the users distinct tones, we deploy strictly band-limited filters, and there are no frequency offsets, then the optimal ML detector simplifies to a bank M independent sub-channel equalizers. This is because there are no ICI and no MAI terms but only small residual sub-channel ISI. In general, the appropriate design of the prototype filter, and tone allocation strategy helps to minimize the interference components and therefore the complexity of the optimal detector. In turn, such a design affects the overall system performance. The deployment of band-limited filters reduces the intercarrier interference, while the deployment of time limited filters reduces the intersymbol interference. However, optimal detection is capable of exploiting the frequency and temporal diversity provided by time-variant frequency selective channels. It turns out that the band-limited filters are a better option for exploiting the temporal diversity while the time limited filters are a better option to exploit the frequency diversity [12].

Once the tone allocation and the prototype filter are fixed, the ML multiuser-tone detector can be simplified through reduced state techniques. Reducing the number of states implies that some of the branches in the full state 3-D trellis are cut. This is done dynamically as we move through the 3-D trellis, by retaining only a certain amount of states. This is equivalent to force hard decisions on some of the past (in the user-frequency-time sense) transmitted data symbols. A special case of reduced complexity multicarrier detection is obtained when we split the original trellis into independent sub-trellises. Decisions made on each trellis can be iteratively exchanged among them. For instance, we can use single carrier detectors that make symbol-by-symbol decisions and use decision feedback on all other interfering data symbols. This approach basically consists on iteratively cancel the interference terms using hard decisions from other independent detection stages. Symbol decisions can be directly included in the metric (11). We refer to this simplified method as *iterative per-symbol detection*. If channel coding is deployed the detectors and the decoders can be concatenated by performing cancellation with decisions from the decoders. In this case we refer to it as *turbo per-symbol decoding*. To limit error propagation it may be beneficial to use soft symbol decisions. The performance of this simplified approach is evaluated in the next section for both an uncoded and a coded system.

As an example we report the performance of simplified iterative per-symbol detection/decoding in a multiuser scenario with an AWGN channel in the presence of severe time/frequency asynchronism (Fig. 4), and in a single user scenario in the presence of multipath fading (Fig. 5).

Example of System Performance

We start considering an uncoded system with M=16 total carriers. Two users are multiplexed by assigning 8 carriers each and interleaving the tones across them. We assume that the users' signals experience a time misalignment Δt_u that is uniformly distributed in [-8T, 8T], and a frequency offset Δf_u that is uniformly distributed in [-0.125/16/T, 0.125/16/T], relatively to a fixed reference point at the receiver. Note that we assume all sub-channels of a given user to experience identical time/frequency offsets. We compare the system that deploys prototype filters that are rectangular in time (DMT-MA), with the system that uses filters that are Gaussian shaped with a normalized bandwidth equal to 0.33 (FMT-MA) [5]. In DMT no cyclic prefix is added. The Gaussian filters are a good choice to minimize the temporal and frequency overlapping across sub-channels. Both uncoded QPSK and coded QPSK average bit-error-rate performance is shown in Fig. 4, i.e., averaged over the time and frequency offsets statistics. With coding, frames of 80 information bits are encoded with a rate 1/2 convolutional code with memory 2. The resulting 160 coded bits are randomly interleaved, mapped to QPSK symbols, and assigned to the sub-carriers. The reference curve is represented by the BER achieved when all users are synchronous (Bound), or identically when interference cancellation takes place with perfect extrinsic knowledge (optimal multitone detection). The other curves have been obtained with iterative per-symbol detection, or turbo per-symbol decoding. In the latter case, the feedback from the two decoders to the detector is hard. FMT yields better performance than DMT when no channel coding is deployed. With 8 iterations FMT is about 0.5 dB from the bound at BER=10^{-3}. The curves corresponding to the initial iterations exhibit an error rate floor due to error propagation. With coding DMT and FMT yield similar performance. Although not shown, when the block tone allocation scheme is deployed a fewer number of iterations is required to improve performance because lower MAI is introduced.

We now consider an uncoded system where a single user transmits its information via DMT with 8 sub-carriers and 4-PSK modulation. No cyclic prefix is added. Propagation is through a flat Rayleigh fading channel with both static (over the transmission block) and completely temporal uncorrelated fading. We consider also a 2-rays channel with independent, equal power, and Rayleigh faded rays. The second ray is delayed by $3T$. In Fig. 5 we report the performance of optimal multitone detection with perfect cancellation of all interfering data symbols (bound). This is to show that with optimal detection we can exploit both the frequency diversity and the temporal diversity. Note that if we inserted a cyclic prefix and we did conventional DMT detection the performance would be identical to the one in flat fading with no diversity exploitation [12].

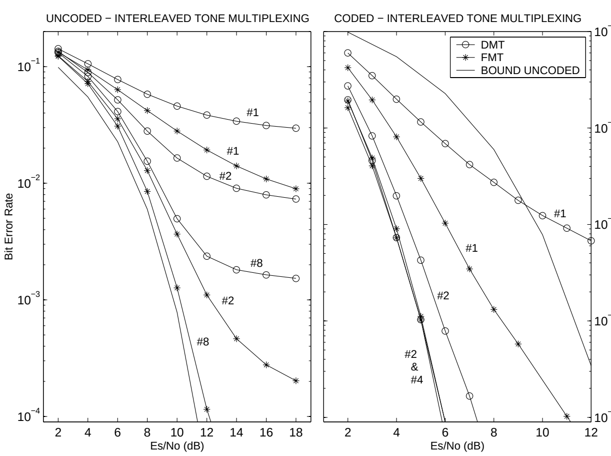

Fig. 4. Average BER performance of iterative per-symbol detection (up to eight iterations) and iterative per-symbol decoding (up to 4 iterations). 2 Users system in AWGN with time and frequency offsets. DMT: rectangular filters, FMT: Gaussian filters.

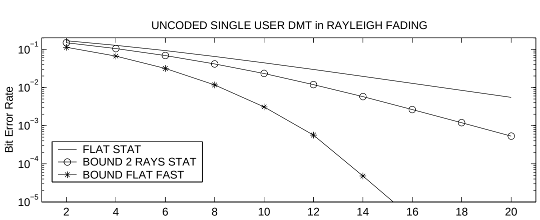

Fig. 5. Average BER performance of optimal multitone detection with perfect interference cancellation (Bounds) in Rayleigh fading.

CONCLUSIONS

We have considered the uplink of a multitone multiple access system and shown that the propagation through independent temporal/frequency selective fading channels in the presence of time/frequency offsets generates ISI, ICI, and MAI. In such a scenario the optimal multiuser/carrier detector searches for the maximum likelihood solution using an appropriate metric. When interleaved codes are deployed the metric can be used in a MAP detector that can be concatenated in an iterative fashion with the channel decoders. The appropriate design of the sub-channel filters and the tone multiplexing across users can reduce the interference components and help to reduce the detector complexity. The optimal detection scheme is capable of exploiting the channel temporal/frequency diversity yielding diversity gains that depend on the choice of the sub-channel transmit filters and sub-carrier spacing as demonstrated in [12].

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