An Asynchronous Multitone Multiuser Air Interface for High-Speed Uplink Communications

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***Abstract*—We describe a transmission technology approach that is suited for application to high-speed asynchronous multiuser wireless channels, i.e., reverse WLAN/cellular links. The scheme is based on concatenated multitone modulation and multiplexing. The design parameters are flexible and are chosen to cope with the users' time and frequency offsets, as well as with the time-frequency channel selectivity. Frequency hopping, and DS spreading can also be included for improved diversity and interference averaging benefits. The principles of this modulation and multiplexing approach are illustrated for an asynchronous reverse link over a 3.84 MHz channel. The key aspect of the proposed asynchronous multitone (AMT) air-interface is its intrinsic robustness to multiple access interference, and channel time-frequency selectivity. We emphasize that the approach is applicable to other contexts with wider bandwidths as those available in 802.11a, Hiperlan II, and those that will become available in future 4G cellular systems.**

Keywords - Concatenated multitone modulation, CDMA, DMT modulation, FMT modulation, frequency hopping, multiple access, OFDM.

I. INTRODUCTION

The increasing demand for high-speed wireless communications has attracted considerable research and standardization efforts. Currently, wireless LAN technology (IEEE 802.11a and Hiperlan II) deploys 20 MHz channels supporting data rates up to 54 Mbps, while 3G cellular technology (UMTS, CDMA 2000) deploys 5 MHz channels supporting data rates up to 2 Mbps (up to 10 Mbps in downlink high-speed data packet access recent releases). The gap in offered data rates between the two technologies is quite significant. Different available spectrum and different mobility and coverage requirements in part justify it. It is indeed of great importance to increase current cellular data rates to bridge the gap with WLAN technology and, of more importance, to increase spectral efficiency. We point out that recently a working group (802.20) within IEEE has been established with the objective of accomplishing such a goal. Besides the 3G spectrum limitation, the design of an air interface for a cellular system has to encompass challenging technical requirements such as high mobility, and high coverage. Most of the work has focused on improvements for the forward link rather than the reverse link. This is justified by the general opinion that the traffic is asymmetric since most high-speed services are required in the downlink only, e.g., file downloading, and voice/video streaming services.

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Indeed, it has to be said that the reverse link of a cellular system poses further challenges that are due to the asynchronous nature of this link. That is, the communication channels of distinct users can be considered independent, and experience propagation delays, carrier frequency offsets, Doppler from movement, and transmission power limitations. These impairments/limitations translate into multiuser interference that may severely affect and limit performance. This is a well understood problem, for instance, in CDMA like type of technology that can be mitigated only with the deployment of complex multiuser receivers. It is therefore evident that a technology that allows for deep multiuser interference reduction and that requires moderate receiver complexity is of great importance.

Multicarrier modulation is a mature technology that has proven to be effective in simplifying the equalization task in severely dispersive fading channels. In particular orthogonal frequency division multiplexing (OFDM) has been chosen in 802.11a and Hiperlan II together with a time division multiple access scheme. When multiplexing is done in a time division fashion, the exploitation of the system resources may not exhibit sufficient granularity as required in multiuser bursty and heterogeneous traffic. In other words a combination of both time division and frequency division multiplexing can show better resources utilization and orthogonality properties. Further, 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 a cellular, high mobility environment. This is due to the fact that in conventional OFDM, sub-channels exhibit *sinc* like frequency response, therefore their orthogonality can be easily lost in the absence of precise synchronization [2]-[3], [7], [10]-[13]. In an asynchronous multiuser environment, increased robustness and better performance can be obtained with filtered multitone (FMT) modulation architectures where the sub-channels are shaped with appropriate time-frequency concentrated pulses [1], [7]-[12].

In this paper we present a proposal for an uplink air-interface. It is based on the concept of combined frequency division and time division multiplexing with transmission obtained by the concatenation of two multicarrier modulators. The inner modulator allows for users' frequency division multiplexing by the assignment of a sub-set of the available tones. Each set of tones can be further multiplexed in a time division fashion across users. The outer multicarrier modulator is deployed for achieving better immunity to channel frequency selectivity and simplified detection. The transmitter, as well as the receiver can be efficiently implemented through FFTs and digital polyphase architectures [1]. The key design aspects are the choice of the partitioning of the tones across the concatenated modulators, the tones spacing, and the optimization of the sub-channel pulses. These parameters are determined by the desired characteristics in terms of resources granularity, immunity to propagation delays, carrier frequency offsets, channel Doppler spread and delay spread.

An element of great importance is the deployment of channel coding for error correction and diversity exploitation [7], [9]. In this paper we propose diversity exploitation through the deployment of frequency hopping in conjunction with direct sequence spreading [4].

After having presented general design guidelines, we focus on describing the application of the proposed air-interface to a 3.84 MHz channel. However, the air interface can be upgraded to support wider bandwidths.

II. CONCATENATED MULTITONE MODULATION

The idea behind this air interface is to concatenate in a serial fashion two multitone modulators, Fig. 1. The inner modulator is based on an FMT approach with M sub-channels. It is deployed for users' channelization, i.e., to split the available spectrum into slices that are assigned to distinct users. A given user in a given cell (sector) can be assigned with one or more inner sub-channels according to its data rate requirement. Each inner sub-channel is shaped with a filter having frequency concentrated response, e.g., a squared root raised cosine (s.r.r.c) pulse with roll-off α_1. The inner sub-channels are centered at frequency f_k, with separation $f_k - f_{k-1} = 1/MT$, and have Nyquist bandwidth equal to $1/T_0$ with $T_0 = MT(1+\alpha)$ and $\alpha = \alpha_1 + \alpha_2$. If distinct users deploy non overlapping (in frequency) sub-channels, users' orthogonality is achieved even in the presence of time misalignments across users and channel time dispersion. We choose, in fact, $\alpha_2 > 0$ such that an appropriate frequency guard exists between adjacent sub-channels. This yields protection against carrier frequency offsets across users. Therefore perfect orthogonality between asynchronous users can be achieved in principle with confined sub-channels and frequency offsets between users smaller than α_2 / T_0.

The outer modulator is a discrete multitone (DMT) modulator with M_2 tones that is applied serially over each inner sub-channel and deploys a cyclic prefix of length μ. It is deployed to obtain a flat frequency response for each inner sub-channel. We emphasize that in our design the number of inner sub-channels may not be large enough to obtain a sub-channel bandwidth smaller than the coherence bandwidth.

Assuming a digital implementation, the transmitter of each user can be implemented as shown in Fig. 2. The multitone modulators are implemented with FFTs. The outputs of the IFFT in the FMT modulator are low-rate filtered with sub-channel pulses that are obtained from the polyphase decomposition of a prototype pulse $g(nT)$ [1]. Thus the lowpass discrete-time transmitted signal of user u can be written as

$$x^u(nT) = \sum_{k=0}^{M-1} \sum_{l \in \mathbb{Z}} b^{u,k}(lT_0) g(nT - lT_0) e^{j\frac{2\pi}{M}nk} \quad (1)$$

$$b^{u,k}(lT_0 + mNT_0) = \sum_{k'=0}^{M_2-1} a^{u,k,k'}(mM_2\bar{T}_0) e^{j\frac{2\pi}{M_2}(l-\mu)k'} \quad (2)$$

with $\bar{T}_0 = NT_0 / M_2$, $N = M_2 + \mu$, $l = 0,...,N-1$, and $m \in \mathbb{Z}$. $b^{u,k}(lT_0)$ denotes the symbol transmitted by user u over the inner sub-channel $k = 0,\ldots,M$-1, at time lT_0. Distinct inner-sub-channels can be assigned to distinct users. $a^{u,k,k'}(mM_2\bar{T}_0) = a^{u,k}((k' + mM_2)\bar{T}_0)$ is the data symbol transmitted by user u over the outer sub-channel $k' = 0,\ldots,M_2$-1 that falls within the inner sub-channel k, at time $mM_2\bar{T}_0$.

Note that according to (1) each symbol stream $b^{u,k}(lT_0)$ is filtered with a prototype pulse $g(nT)$ and frequency shifted to frequency $f_k = k / MT$, while (2) basically says: consider the symbol stream to be transmitted over the inner sub-channel k, take a block of length M_2, compute the M_2 points IFFT, add the cyclic prefix of length μ, serially convert the output to obtain the symbol stream $b^{u,k}(lT_0)$. Due to the deployment of the cyclic prefix, sub-channel k has a net date rate of $1/\bar{T}_0$ symb/s.

III. ASYNCHRONOUS MULTIPLE ACCESS CHANNEL

In an uplink scenario the signals of N_U users propagate through independent time-variant frequency selective fading channels. We assume an equivalent discrete-time lowpass channel model that results from the concatenation of the DAC transmit filter, the channel, and the ADC receive filter. Assuming the channel slow with respect to the length of the ADC filter, the composite lowpass received signal can be written as follows [7]-[8], and [11]:

$$y(iT) = w(iT) + \sum_{u=1}^{N_U} \sum_{k=0}^{M-1} \sum_{l \in \mathbb{Z}} b^{u,k}(lT_0) \sum_{n \in \mathbb{Z}} \{ g(nT - lT_0) \times g_{ch}^u(iT - nT - \Delta t_{u,k}; iT) e^{j[\frac{2\pi}{M}nk + 2\pi \Delta f_{u,k} iT + \phi_{u,k}]} \} \quad (3)$$

where the time offset due to propagation delay of user u and sub-channel k is denoted with $\Delta t_{u,k}$, the frequency offset is denoted with $\Delta f_{u,k}$ (assumed much smaller than $1/T$), and finally the phase offset is denoted with $\phi_{u,k}$. Further $w(iT)$ is a sequence of i.i.d. zero mean Gaussian r.v., while $g_{ch}^u(mT; iT)$ is the equivalent lowpass time-variant channel impulse response that comprises the DAC-ADC filters.

A. Demodulation

We herein consider a two stage receiver that first performs demodulation for the inner FMT modulator and eventually DMT demodulation for each inner sub-channel (see below).

Optimal multiuser FMT demodulation is accomplished by acquiring time and frequency synchronization with each active user, and running a bank of matched filters that are matched to the individual sub-channels [7]-[8], [11]. If we assume the media to be time-invariant over the duration of the prototype pulse, we can run filtering with pulses that are matched to the sub-channel transmit filters. In formulae, the (inner) sub-channel *k'* of user *u'* matched filter output reads

$$\begin{aligned} z_{inner}^{u',k'}(l'T_0) &= \sum_{i\in\mathbb{Z}} y(iT+\Delta t_{u',k'})g^*(iT-l'T_0)e^{-j[\frac{2\pi}{M}ik'+2\pi\Delta f_{u',k'}iT]} \\ &= \sum_{u=1}^{N_U}\sum_{k=0}^{M-1}\sum_{l\in\mathbb{Z}} b^{u,k}(lT_0)g_{EQ}^{u,u',k,k'}(l'T_0-lT_0;l'T_0)+\eta^{u',k'}(l'T_0) \end{aligned} \tag{4}$$

$$g_{EQ}^{u,u',k,k'}(mT_0;l'T_0)=\sum_{n\in\mathbb{Z}}\sum_{i\in\mathbb{Z}} g(nT+mT_0-l'T_0)g^*(iT-l'T_0)$$

$$\times g_{ch}^{u}(iT-nT-\Delta t_{u,k}+\Delta t_{u',k'};l'T_0+\Delta t_{u',k'})e^{j[\frac{2\pi}{M}(nk-ik')+2\pi(\Delta f_{u,k}-\Delta f_{u',k'})iT+\hat{\phi}_{u,k}]}$$

with $\hat{\phi}_{u,k}$ being an appropriate phase offset. In practice, the time and frequency offsets have to be estimated. Let $g_{ch}^{u}(iT-\Delta t_{u,k}+\Delta t_{u',k'};l'T_0+\Delta t_{u',k'})=\sum_p \alpha_p^u(l'T_0)\delta(iT-pT-p_{u,k}T+p_{u',k'}T)$ with $p_{u,k}=\lfloor \Delta t_{u,k} \rfloor$, then we obtain

$$\begin{aligned} g_{EQ}^{u,u',k,k'}(mT_0;l'T_0) &= \sum_p \alpha_p^u(l'T_0)\sum_{i\in\mathbb{Z}} g(iT-pT-p_{u,k}T+p_{u',k'}T \\ &+mT_0-l'T_0)g^*(iT-l'T_0)e^{j[\frac{2\pi}{M}(ik-pk-ik')+2\pi(\Delta f_{u,k}-\Delta f_{u',k'})iT+\tilde{\phi}_{u,k}]}. \end{aligned} \tag{5}$$

Using Parseval theorem it can be shown that with the conditions

a. $|G(f)|=0 \quad for \quad |f|>(1+\alpha_1)/2T_0$, b. $|\Delta f_{u,k}|\le \alpha_2/2T_0$,

relation (5) differs from zero only for $k=k'$. In other words the inner sub-channels do not overlap, and they have zero cross-correlation. In such conditions that can be met with the appropriate system design (see Section V), we obtain that

$$z_{inner}^{u',k'}(l'T_0)=\sum_{u=1}^{N_U}\sum_{l\in\mathbb{Z}} b^{u,k'}(lT_0)g_{EQ}^{u,u',k',k'}(l'T_0-lT_0;l'T_0)+\eta^{u',k'}(l'T_0) \tag{6}$$

that is, we get MAI only if the same sub-channel is assigned to more than one user. However, the inner sub-channels see ISI.

If we assume to assign distinct tones to distinct users which can be done in a given cell (sector), we obtain

$$\begin{aligned} z_{inner}^{u',k'}(l'T_0) &= \sum_{l\in\mathbb{Z}} b^{u',k'}(lT_0)\underbrace{\sum_p \alpha_p^{u'}(l'T_0)\kappa_g(l'T_0-lT_0-pT)e^{-j\frac{2\pi}{M}pk'}e^{j\tilde{\phi}_{u',k'}}}_{\beta_{l'-l}^{u',k'}(l'T_0)}+\eta^{u',k'}(l'T_0) \\ &= \sum_{l\in\Im} \beta_l^{u',k'}(l'T_0)b^{u',k'}(l'T_0-lT_0)+\eta^{u',k'}(l'T_0) \end{aligned} \tag{7}$$

where $\kappa_g(mT)=\sum_i g(iT)g^*(iT-mT)$ is the prototype pulse autocorrelation, and $\Im$ is the set of tap indices that can be assumed practically finite. Thus, the *k'-th* sub-channel of user *u'* sees ISI, however, depending upon the sub-channel bandwidth the number of taps can be small (note that the taps are now spaced by multiples of T_0). The presence of ISI requires in general sub-channel equalization [5]. However, in order to completely remove the inner sub-channel ISI we deploy the outer DMT modulator. Under the conditions:

c. μT_0 longer than the sub-channel time dispersion,

d. time-invariant channel over a window of length NT_0,

it is easy to show that at the output of a conventional DMT demodulator that comprises a block that disregards the cyclic prefix, and an M_2 points FFT, we obtain

$$z_{outer}^{u',k',k''}(mM_2\bar{T}_0)=\mathrm{A}^{u',k',k''}(mM_2\bar{T}_0)a^{u',k',k''}(mM_2\bar{T}_0)+n^{u',k',k''}(mM_2\bar{T}_0) \tag{8}$$

$$\mathrm{A}^{u',k',k''}(mM_2\bar{T}_0)=\sum_{l\in\Im}\beta_l^{u',k'}(mM_2\bar{T}_0)e^{-j\frac{2\pi}{M_2}lk''}. \tag{9}$$

That is, the k''*-th* FFT output $z_{outer}^{u',k',k''}(mM_2\bar{T}_0)=z_{outer}^{u',k'}((k''+mM_2)\bar{T}_0)$ is the data symbol transmitted on that outer sub-channel weighted by the frequency response of the equivalent inner sub-channel.

B. Avoiding the Outer Modulator in High Mobility Scenarios

The deployment of the outer DMT modulators allows for simple one-tap equalization in certain mobility conditions. For high mobility users, condition d. above might be not fulfilled. For such users we can avoid deploying the outer modulator. Instead, at the output of the FMT demodulator we can deploy an adaptive sub-channel equalizer. Such an equalizer can have reasonably low complexity since the number of inner channel taps is definitely small. In the rare event that perfect users orthogonalization is not possible, some ISI, ICI, and MAI can be present, e.g., when the frequency offsets exceed the chosen frequency guard, the delay spread exceeds the one used for the system design, the Doppler spread is high. To optimize performance optimal multicarrier multiuser detection can be deployed. Details can be found in [7], [8], and [11].

IV. Data Modulation and Frequency Hopping

So far we have not talked about the data modulation, i.e., the data symbols to be fed to the outer modulator, or directly to the inner modulator. A typical choice comprises M-QAM, M-PSK, or differently encoded M-PSK constellations. The latter allows for avoiding channel estimation when the outer modulator is deployed, i.e., the sub-channel response is flat.

A. Combined DS Spreading, Frequency Hopping, and Concatenated Mutitone Modulation

An important question concerns diversity exploitation. In order to do so, we need in general to deploy channel coding, which allows for both temporal and frequency diversity exploitation. In order to maximize the diversity exploitation we can deploy frequency hopping. A possible hopping pattern comprises cycling across the inner sub-channels, Fig. 3. That is we can allocate the inner sub-channel to the users in an interleaved fashion, and then we can cycle (cyclically shift by one inner sub-channel) the users as the time goes on.

Another idea to exploit the frequency diversity is to use DS spreading both in time and frequency [4]. We herein propose to deploy combined orthogonal spreading, frequency hopping, and concatenated multitone modulation as follows, Fig. 3 and Fig. 4.

Let us assume an outer multitone modulator with M_2 tones and an inner multitone modulator with M tones, then the available number of sub-channels is M_2M. As explained before, let partition the tones in M groups of M_2 consecutive tones. Further, to simplify the exposition let us assume to multiplex M users each deploying a single inner sub-channel that is sliced into M_2 outer sub-channels. At time instant, say, $lM_2\bar{T}_0$ user 1 is assigned to the group of tones 1, user 2 to group 2 and so on. At time instant $(l+1)M_2\bar{T}_0$ each user frequency hops to the adjacent group of tones, i.e., user 1 is assigned to group 2, user 2 to group 3, …, user M to group 1. This procedure implements a full frequency hopping cycle, and it requires M time slots of duration NT_0 each. It can be generalized to the case of $N_U<M$ and of more than a single inner sub-channel per user.

It has to be emphasized that frequency hopping requires hopping synchronization across users in order to preserve orthogonality. However, synchronization is not required if the number of frequency bins (inner sub-channels) M is at least equal to $2N_U$, so that users can hop to free bins.

Now, joint direct sequence spreading and frequency hopping is implemented as follows. Let us consider a Walsh-Hadamard matrix of size M_2M whose rows are orthonormal. Let $c(i,j)$ for j=0,…,M_2M-1 be the elements of the i-th row, and let partition it in M portions as follows: $c(i,k'+lM_2)$, k'=0,…,M_2-1, l=0,…,M-1. Let $a^u(m)$, m=0,…,M_2M-1 be the u-th user data symbols to be transmitted over M time slots (recall that we assume one inner sub-channel per user) that we index with l. Then, at time slot l, we feed sub-channel k' of the outer modulator with $\sum_{m=0}^{M_2M-1} a^u(m)c(m,k'+lM_2)$. After the cyclic prefix insertion, we obtain N samples that are transmitted over the inner sub-channel $k(l)$ according to the FH pattern.

According to (8) the output of the DMT demodulator now reads $z_{out}^{u,k(l),k'}(lM_2\bar{T}_0) = A^{u,k(l),k'}(lM_2\bar{T}_0)\sum_m a^u(m)c(m,k'+lM_2)$ $+n^{u,k(l),k'}$. Assuming knowledge of the channel weights, we can completely eliminate the self interference, for instance, with simple coherent de-spreading (ZF equalization), i.e.,

$$z_{despr}^{u}(m) = \sum_{k'=0}^{M_2-1}\sum_{l=0}^{M-1} z_{out}^{u,k(l),k'}(lM_2\bar{T}_0)\frac{\mathrm{A}^{u,k(l),k'}(lM_2\bar{T}_0)^*}{|\mathrm{A}^{u,k(l),k'}(lM_2\bar{T}_0)|^2}c^*(m,k'+lM_2). \quad (10)$$

The above procedure does not add redundancy, i.e., we keep the data rate equal to $1/\bar{T}_0$ symb/s per inner-sub-channel, and we assign the same codes to all users. It implements time-frequency spreading by partitioning a spreading sequence over time and frequency, and it is applied for diversity exploitation, as the performance results of Section V will show.

V. System Design and Parameters Choice

As we said above, the system design pursues the goal of orthogonalize asynchronous uplink users. We do not force the users to adjust their timing, and carrier frequency such that they appear the same at the base station. Indeed we assume a much softer synchronization approach that is based on simply making the users adjusting their timing based on the downlink frame. In such a case, at the base station distinct users signals will still experience time offsets and carrier frequency offsets relatively to the base station reference signal. The time offsets are equal to the two-way propagation delay, i.e., $\Delta t(r) = 2r/c = 6.67\ \mu s/km$, while the frequency offsets are equal to the frequency Doppler shift due to the mobiles movements, i.e., $\Delta f(v) = vf_C/c = 0.93\ Hz/GHz/km/h$. For instance with up to 5 km cell radius $\Delta t \le 33.3\ \mu s$, while with $f_C = 2.5\ GHz$, and $v \le 200\ km/h$ we have $\Delta f \le 463$ Hz. Indeed we could also deploy transmit carrier frequency adjustment, i.e., compensation of the frequency offset at the transmitter at the expense of increased complexity [2].

Now if we turn our attention to the propagation media, the coherence bandwidth, and the coherence time are related to the rms delay spread σ_τ, and the maximum Doppler spread f_D, through the following relations [6] $B_{ch} = 1/(2\pi\sigma_\tau)$, and $T_{ch} = 9/(16\pi f_D)$. With $\sigma_\tau \le 10\ \mu s$, and $f_D \le 465$ Hz, we obtain that $B_{ch} \ge 15.9$ kHz, and $T_{ch} \ge 0.38$ ms. Keeping this in mind, we choose a number of inner sub-carriers such that a tradeoff in terms of large coherence bandwidth and coherence time with respect to the transmission parameters is safely fulfilled. We also have to emphasize that since the users are frequency multiplexed, a sufficient number of tones have to be chosen to grant an appropriate level of granularity in terms of simultaneously active users and transmission rate per user.

A. W=3.84 MHz Bandwidth

We report system parameters in Table I. The parameters have been chosen assuming a transmission rate of 3.84 MHz (as in UMTS). To allow system flexibility we assume both frequency and time multiplexing in a dynamic fashion which can be handled by the MAC layer. That is, simultaneous transmission is performed across distinct tones, thus supporting up to 64 users. The minimum burst duration is 0.3817 ms. Further, each tone can be shared in a time division mode every MAC frame that comprises a certain number of bursts.

Although not discussed here, a similar transmission approach can be deployed in an FDD mode for the downlink where higher transmission rates can be achieved for instance with larger bandwidths, say, in the order of 20 MHz in future 4G systems.

B. BER Performance

We report in Fig. 5 the average BER performance assuming uncoded 4-PSK, and s.r.r.c sub-channel pulses for the FMT inner modulator with the parameters in Table 1. We assume to assign one inner sub-channel per user. In particular we consider a slow (quasi-static) Rayleigh faded channel with exponential power delay profile, and rms delay spread σ_τ=2 μs. Further, we assume double receive diversity with ZF equalization, and maximal ratio combining. Users are time asynchronous and have $\Delta f \le 463$ Hz. The curves aim at highlighting the diversity effect which is clearly higher when spreading and FH is deployed. The BER with spreading but without FH (spreading over a single sub-channel) is also shown. With the outer modulator and no spreading, simple one-tap equalization is required, however no frequency diversity is exploited. When the inner modulator is only deployed, we run ZF equalization. There is some complexity increase, but some diversity exploitation is possible [9]. For all cases, further improvements are possible with other equalization approaches.

CONCLUSIONS

We have presented an air-interface approach for uplink wireless communications. It is based on concatenated FMT modulation and DMT modulation. Further, it can be combined with frequency hopping and direct sequence spreading.

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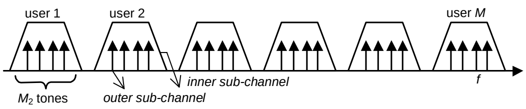

Figure 1. User channelization via inner FMT concatenated with outer DMT.

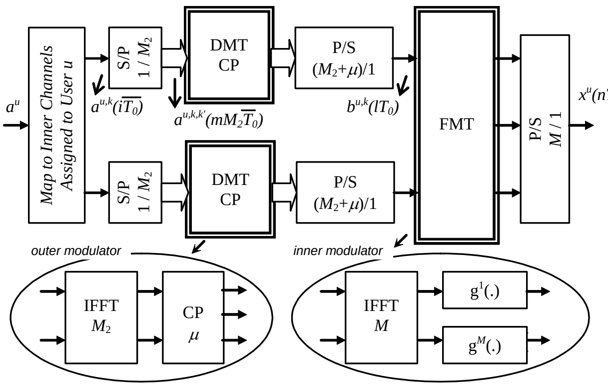

Figure 2. Concatenated MT transmitter user u.

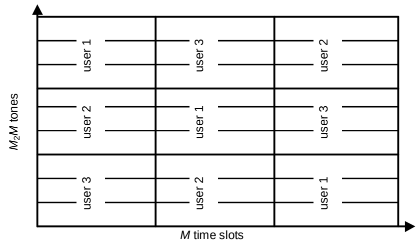

Figure 3. Multiuser frequency hopping (frequency cycling) with M=3.

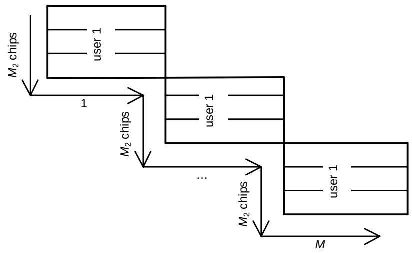

Figure 4. Combined FH and DS spreading.

TABLE I
SYSTEM PARAMETERS W=3.84 MHz f_C=2.5 GHz

M = 64	Number of tones of inner modulator
$1/MT = W/M$ = 60 kHz	Inner Sub-channel bandwidth
$\alpha = \alpha_1+\alpha_2$ = 0.125+0.02 = 0.145	Roll-off + Guard factor inner modulator
$1/T_0 = 1/MT/(1+\alpha)$ = 52.4017 kHz	Inner Sub-channel transmission rate
T_0 = 19.083 μs	Inner Sub-channel symbol period
N_{LS} = 20	Minimum number of symbols per burst
$T_B = 20T_0$ = 0.3817 ms	Minimum burst duration
N_U = 64	Maximum number of users per frame
R_{TOT}= 6.707 Mb/s 4-PSK R_{TOT}= 13.415 Mb/s 16-QAM	Aggregate max transmission rate per sector with inner modulator only
M_2 = 16	Number of tones outer modulator
μ = 4	Cyclic prefix length
$1/(M_2+\mu)/T_0$ = 2.62 kHz	Outer sub-channel transmission rate
R_{TOT}= 5.366 Mb/s 4-PSK R_{TOT}= 10.731 Mb/s 16-QAM	Aggregate max transmission rate per sector with outer modulator

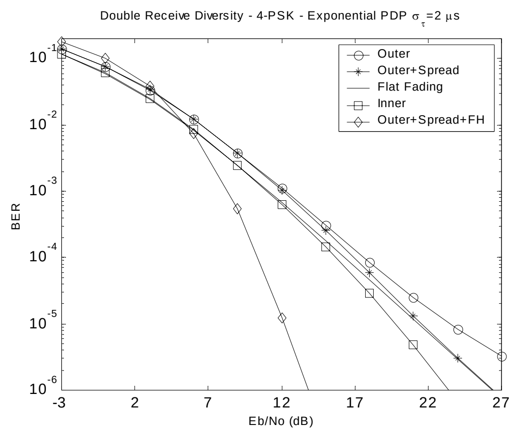

Figure 5. BER performance

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[13] A. Tonello, N. Laurenti, and S. Pupolin, "Analysis of the uplink of an asynchronous DMT OFDMA system impaired by time offsets, frequency offsets, and multi-path fading", *Proc. of IEEE VTC 00-Fall*, Boston, pp.1094–1099, September 2000.