

GLOBECOM '00

IEEE Global Telecommunications Conference

Dr. David Nagel (Chief Technology Officer for AT&T) will be our Keynote Speaker and Dr. Viet Cong (Senior Vice President for MCI Worldcom) will be the Keynote Speaker for our IPv6 workshop which is co-sponsored by the Internet Society and IEEE. The Communications Society will also have several executive business sessions that include executives from telecom service providers, equipment providers and investors.

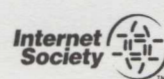
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Volume 2

**San Francisco
27 November–1 December 2000**

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GlobeCom '00—IEEE Global Telecommunications Conference

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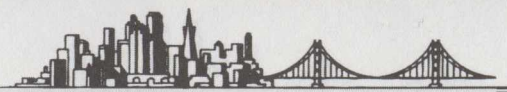
IEEE Catalog Number	00CH37137 (softbound) 00CB37137 (casebound) 00CH37137C (CD-ROM)
ISBN	0-7803-6451-1 (softbound) 0-7803-6452-X (casebound) 0-7803-6453-8 (microfiche) 0-7803-6454-6 (CD-ROM)

Library of Congress 87-640337

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GREETINGS FROM THE GLOBECOM 2000 GENERAL CHAIRMAN

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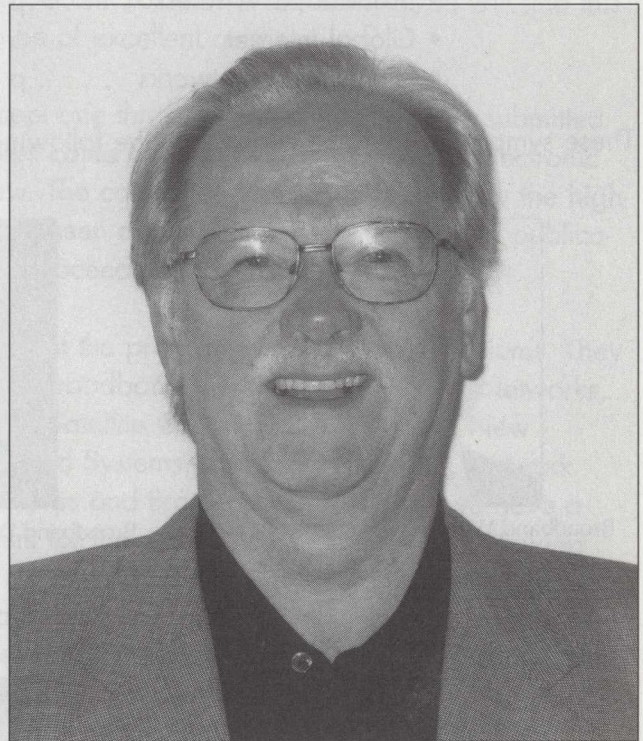
You are invited to attend this annual international communications conference which will feature technical presentations, papers, customized symposiums, tutorials and workshops by more than 300 of the brightest and the best engineers and scientists in the world. We expect attendees from over 40 countries.

To provide attendees both depth and breadth of coverage in high interest areas we have scheduled 6 major symposiums and one special workshop:

- Broadband Wireless
- Global Internet
- High Speed Networks
- Photonic Networks
- Satellite Communications
- Communication Theory
- IPv6 Workshop

Dr. David Nagel (Chief Technology Officer for AT&T) will be our Keynote Speaker and Dr. Vint Cerf (Senior Vice President for MCI Worldcom) will be the Keynote Speaker for our IPv6 workshop which is co-sponsored by the Internet Society and IEEE. The Communications Society will also have several executive business sessions that include executives from telecom service providers, equipment providers and investors.

San Francisco is one of the most beautiful, exciting, enchanting, sophisticated and pleasurable cities in the world. Please join us at Globecom 2000 for an
Interesting, Educational, Enlightening and Enjoyable experience!



Terry E. F. Kero

Senior Vice President, Business Development
Telesys

General Chairman's Reception

Monday, 27 November

6:00 pm – 9:00 pm

Fairmont Hotel – Gold Room

Terry E. F. Kero

General Chairman, Globecom 2000

COMMUNICATION THEORY SYMPOSIUM

Symposium Chair: Moe Win, AT&T Labs - Research, USA; Andrea Goldsmith, Stanford University, USA

ComSoc Technical Committee Sponsors: Communication Theory; Radio Communications; Signal Processing for Storage; Signal Processing and Communication Electronics

Stanford Court Hotel, Ballroom Room (West)
Tuesday, 9:00 AM– 2:00 PM

Session CT-1 OFDM I

Organizers: Andreas F. Molisch, Technical University of Wien; Bruce McNair, AT&T Labs–Research, USA

Chair: Leonard J. Cimini, AT&T Labs–Research, USA

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Stanford Court Hotel, Ballroom Room (West)
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Chair: George Chrisikos, USA

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Chair: Dariush Divsalar, Jet Propulsion Laboratory, USA

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Chair: Desmond P. Taylor, University of Canterbury, UK

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Chair: Abhijit Shanbhag, MorphICs Technology, Inc., USA

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Chair: TBA

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Organizer: Moe Z. Win, AT&T Labs—Research, USA
Chair: Norman C. Beaulieu, Queens University, UK

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Organizers: Marco Chiani, University of Bologna, Italy; Jack H. Winters, AT&T Labs-Research, USA
Chair: Ranjan K. Mallik, Indian Institute of Technology, India

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Stanford Court Hotel, Ballroom Room (West)
Thursday, 8:30-11:30 AM

Session CT-9 Space Time Codes

Organizers: Vahid Tarokh, AT&T Labs-Research, USA; Bertrand Hochwald, Bell Labs, Lucent Technologies, USA
Chair: G. Jerry Foschini, Bell Labs, Lucent Technologies, USA

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Chair: Costas Georgiades, Texas A&M University, USA

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Chair: Moe Z. Win, AT&T Labs–Research, USA

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SATELLITE COMMUNICATIONS SYMPOSIUM

Symposium Chair: Sastri Kota, Lockheed Martin, USA

ComSoc Technical Committee Sponsors: Satellite Communications

Stanford Court Hotel, India Room (Blue & Gold)
Wednesday, 8:30–11:30 AM

Session S-2 Satellite Network Protocols and IP QoS

Organizer: Sastri Kota, Lockheed Martin, USA

Chair: C. K. Toh, Georgia Institute of Technology, USA

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Stanford Court Hotel, India Room (Blue & Gold)
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Organizer: Walter Ciesluk, The MITRE, USA

Chair: Satchandi Verma, Motorola, USA

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PHOTONIC NETWORK TECHNOLOGIES ARCHITECTURES & PROTOCOL SYMPOSIUM

Symposium Chair: Jaafar Elmirghani, University of Wales Swansea, UK

ComSoc Technical Committee Sponsors: Transmission and Access and Optional Systems, Ltd.

Mark Hopkins, Room of the Dons
Tuesday, 9:00 AM–12:00 PM

Session P-4 Performance of Optical Networks

Organizers: Mounir Hamdi, Hong Kong University of Science & Technology, Hong Kong;
Jaafar Elmirghani, University of Wales Swansea, UK

Chair: Mounir Hamdi, Hong Kong University of Science & Technology, Hong Kong

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Mark Hopkins, Room of the Dons
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Chair: Ian White, University of Bristol, UK

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Organizers: David Smith, Corning Research Centre, UK; Naohisa Ohta, Sony, Japan

Chair: Jaafar Elmirghani, University of Wales Swansea, UK

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Mark Hopkins, Room of the Dons
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Organizers: Ken-ichi Sato, NTT, Japan; Jaafar Elmirghani, University of Wales Swansea, UK

Chair: Jacek Chrostowski, Cisco Systems, Canada

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Comparison of Amplitude Distributions for Hadamard Spreading and Fourier Spreading in Multi-Carrier Code Division Multiplexing

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Abstract— In this paper we investigate amplitude distributions of transmit signals for multi-carrier spread spectrum (MC-SS) transmission methods based on orthogonal frequency division multiplexing (OFDM), also called multi-carrier code division multiplexing (MC-CDM). In particular we compare Fourier spreading with the commonly used Walsh-Hadamard spreading. As a basis for the comparison we describe a general model. Both up- and downlink of multiple access transmission schemes employing either multi-carrier code division multiple access (MC-CDMA) or multi-carrier frequency division multiple access (MC-FDMA) are compared.

I. INTRODUCTION

Multi-carrier code division multiplexing (MC-CDM) [1] is an interesting candidate for the physical layer in wireless high data rate local area networks. When compared to orthogonal frequency division multiplexing (OFDM), the additional spreading of MC-CDM produces a signal space diversity which improves power efficiency especially for high code rates [2]. A Hadamard transform is used for spreading in most MC-CDM system descriptions, e.g. [1]. However, further choices for orthogonal spreading are possible. With Fourier spreading [3], which can be implemented by a discrete Fourier transform (DFT) operation, it is clear that it can cancel the inverse discrete Fourier transform (IDFT) of an OFDM transmitter when spreading is done over all subcarriers, such that the result is a simple serial block transmission with cyclic extension [4]. This serial transmission can be regarded as a spread spectrum transmission, since the entire transmission bandwidth is covered by each transmitted symbol. The peak-to-average power ratio (PAPR) of a serial transmission is much lower than that of an OFDM transmission. The question that arises is: how is the situation when spreading is done not over all OFDM subcarriers but only over groups of carriers?

The aspect of comparison treated here is the amplitude distribution of the transmit signal when employing different spreading methods. This is an important topic when RF power amplifiers suffer from nonlinearity, which is in practice always the case to some extent. The nonlinear characteristic produces harmonics which result in out-of-band radiation. The best option to avoid out-of-band radiation is to guarantee a suitable amplitude distribution of the transmit signal, with a low PAPR.

In [5] Golay complementary sequences have been used instead of Hadamard sequences for reducing the PAPR in MC-

CDMA transmission, and a scrambling scheme was employed to further improve the amplitude distribution of the transmit signal. In this paper we suggest to employ a DFT for spreading, which can be implemented efficiently as a fast Fourier transform (FFT). Furthermore we extend our considerations to MC-FDMA, as introduced in [6] (named MC-SS-MA there).

Subsequently we describe a model of a MC-CDM transmitter. In a multiple access context, this model is valid for both, MC-CDMA and MC-FDMA. We describe the methods used for computation of the amplitude distribution and the PAPR of the transmit signal. It is shown that, given the transmit symbol alphabet and the corresponding symbol probabilities, both amplitude distribution and PAPR are uniquely determined by a single matrix which describes the transmitters linear mapping from transmitted symbols to the transmit signal. Based on simulation results, we discuss the suitability of Hadamard and Fourier spreading for MC-CDM transmission methods.

We use the following notation: random variables are written in bold type, vectors have a single underline, matrices have a double underline.

II. MODEL OF A MC-CDM TRANSMITTER

The model in Fig. 1 depicts a transmitter for MC-CDM based on OFDM. An OFDM transmitter is extended by an additional spreading, described by the transform matrices $\underline{T}$, and by an interleaver. The OFDM transmitter consists of an IDFT, a cyclic prefix insertion CP, a parallel-to-serial conversion, and the conversion to continuous-time using an ideal Dirac sampler and a basic waveform $e(t)$, which is a Nyquist impulse. The delivered baseband transmit signal is $s(t)$. The number of OFDM subcarriers is N , the cyclic prefix has length L , transmit signal samples are indexed by c , and the Dirac sampler generates an impulse every T_c seconds.

OFDM breaks down the transmission bandwidth into narrow subcarriers which can be regarded as flat fading channels; they are modeled as Rayleigh fading channels. The fading behavior of neighbored OFDM subcarriers is correlated, according to the power delay profile of the transmission channel. When looking at two different subcarriers within the OFDM transmission bandwidth, the fading behavior becomes less correlated when the two channels are separated further in frequency. By spreading over several fading channels which are not fully correlated, a diversity gain is achieved.

Spreading is done by transforming a vector of M symbols

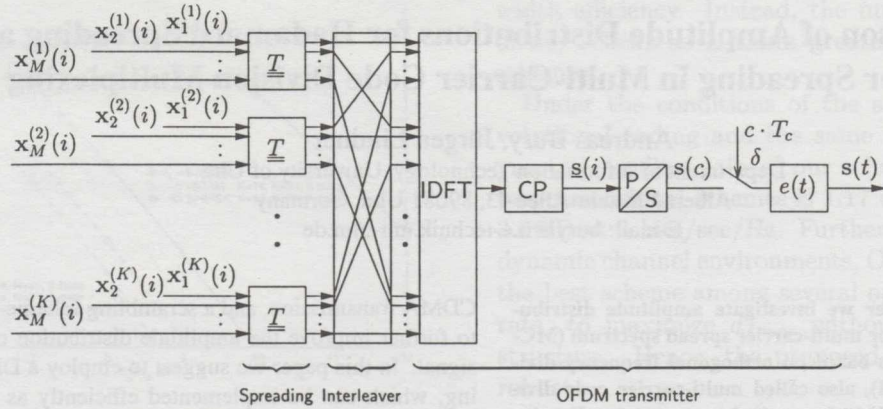


Fig. 1. Model of transmitter for OFDM-based MC-CDM.

through a matrix $\underline{T}$. This square matrix is orthogonal, such that the condition

$$\underline{T}^H \underline{T} = \underline{I} \quad (1)$$

is fulfilled. Furthermore, to assure equal energy distribution, we consider only spreading matrices with the property that the absolute value of all matrix elements is constant

$$|t_{i,k}| = \frac{1}{\sqrt{N}} \quad \forall i, k. \quad (2)$$

In literature usually a Hadamard transform is selected for $\underline{T}$; however, further choices are possible, e.g. a DFT.

The total number of N transmit symbols is partitioned into K spreading groups of size $M = N/K$. The interleaver assures that symbols are spread equidistantly over the entire frequency band in order to obtain a maximum diversity gain. Small spreading groups (small values of M) mean that there is little diversity gain, large groups (large values of M) offer a better diversity gain but may result in a higher receiver complexity.

In a multi-user context, the model in Fig. 1 covers two different systems which are described in literature. To be specific, it describes the downlink transmitter for the following transmission methods:

- a) Multi-carrier code division multiple access (MC-CDMA).

Here each user out of a total of M users occupies a certain symbol m in all K spreading groups. User m transmits the symbols $x_m^{(k)}(i) \forall k, i$. Each user is assigned one particular element in each spreading block; if more users are desired, larger spreading blocks are required.

- b) Multi-carrier frequency division multiple access (MC-FDMA).

Here each user out of a total of K users occupies all M symbols of a certain spreading group k . User k transmits the symbols $x_m^{(k)}(i) \forall m, i$. Each user is assigned its

own spreading block; if more users are desired, more (and smaller) spreading blocks are required.

Fig. 1 depicts the *downlink* transmitter for the described transmission schemes. The corresponding *uplink* transmitter of a specific user is obtained from this figure by setting the transmit symbols of all remaining users to zero, thereby omitting the corresponding signal paths.

III. AMPLITUDE DISTRIBUTION OF THE TRANSMIT SIGNAL

For a certain time instant t_0 the complex baseband transmit signal $s(t_0)$ is a random variable which is in general a linear combination of all random transmit symbols

$$s(t_0) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^K \sum_{m=1}^M \alpha_{m,k,i}(t_0) x_m^{(k)}(i). \quad (3)$$

The coefficients $\alpha_{m,k,i}(t_0)$ are derived from $\underline{T}$, $e(t)$, N , L , K , and M , as described subsequently. When the duration of the basic waveform $e(t)$ is finite, the infinite sum over i in this equation can be replaced by a finite sum. Then the probability density function (PDF) of the transmit signal at time t_0 , $f_{s(t_0)}(x)$, is obtained from the PDFs of all contributing transmit symbols.

We assume that all transmit symbols $x_m^{(k)}(i)$ are mutually statistically independent. Then the PDF $f_{s(t_0)}(x)$ is obtained by convolving the densities of all contributing random variables $\alpha_{m,k,i}(t_0) x_m^{(k)}(i)$.

The envelope of the transmitted RF signal is the amplitude of the complex baseband signal, i.e., its absolute value. Given the PDF of the baseband transmit signal, the PDF of its absolute value is determined by the integral

$$f_{|s|(t_0)}(r) = \int_0^{2\pi} f_{s(t_0)}(r \cdot \exp(j\varphi)) \cdot r \cdot d\varphi. \quad (4)$$

With the assumption of statistical independence of all transmit symbols, and assuming identical probability densities of all transmitted symbols, the transmit signal $s(t)$ is cyclo-stationary with period $T_S = T_c(N + L)$. The average PDF of the transmit signal amplitude is obtained through

$$f_{|s|}(r) = \frac{1}{T_S} \int_t^{t+T_S} f_{|s|(\tau)}(r) \cdot d\tau \quad (5)$$

for some arbitrary value of t .

Discrete-time computation

At discrete time we consider the signal $s(c)$ instead of $s(t)$. To obtain a simple description we join the spreading, interleaving, IDFT and cyclic extension of the transmitter in Fig. 1 into a single matrix $\underline{U}$, see Fig. 2.

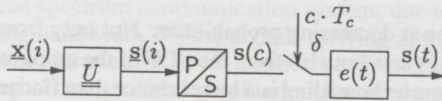


Fig. 2. Equivalent transmitter model.

The discrete-time transmit signal of a *single* OFDM block ($i = 0$) then represents the cyclo-stationary statistics of the transmit signal. We omit the block index i and write

$$\underline{s} = \underline{U} \cdot \underline{x}, \quad (6)$$

with vector elements $x_{(m+M(k-1))} = x_m^{(k)}(0)$ and $s_c = s(c)$. In equivalence to equation (3) we write

$$s_c = \sum_{n=1}^N u_{c,n} x_n. \quad (7)$$

Hence, the PDF at a particular time instant c is related with a certain row in $\underline{U}$.

To obtain the PDF of the amplitude we apply equation (4), and the *average* PDF of the amplitude is obtained as

$$f_{|s|}(r) = \frac{1}{N+L} \sum_{c=1}^{N+L} f_{|s|(c)}(r). \quad (8)$$

From above equations we see that, given the transmit symbol alphabet and corresponding occurrence probabilities, the PDF of the discrete-time transmit signal, $f_{s(c)}(x)$, is determined by the transform matrix $\underline{U}$.

For the case of Fourier spreading, the matrix $\underline{U}$ contains in most cases more zero elements than for Hadamard spreading. This already indicates a better amplitude distribution for Fourier spreading, because fewer random variables are summed.

'Continuous-time' computation

Equation (5) states that the PDF would have to be averaged over an infinite number of times. Because the computational effort for this is also infinite, we consider a discrete-time version of the continuous-time transmit signal $s(t)$. The filter $e(t)$ is implemented as a digital FIR filter at a certain oversampling rate. Because of the duration of this filter impulse response, transmitted symbols of more than only a single OFDM block must be taken into account when evaluating the PDF of the transmitted signal. In matrix notation, convolution with the basic waveform is a multiplication with a Toeplitz matrix. Matrix representations of all blocks in an equivalent discrete-time model are joined to, again, find a *single* transform matrix which determines the PDF of the transmit signal.

IV. PAPR COMPARISON

The PAPR of the transmit signal indicates the maximum amplitude range of the transmit signal for a certain power level. Given the transform matrix of the transmitter, the PAPR can be computed by systematically constructing the worst case instantaneous power, and normalization to the average power. We compute the PAPR at 'continuous' time using three times oversampling. The basic waveform $e(t)$ is a root raised-cosine impulse with $\alpha = 0.2$. For the downlink, full system load is assumed. For the uplink, an average amplitude distribution for all users is computed. Simulation results are given in Fig. 3.

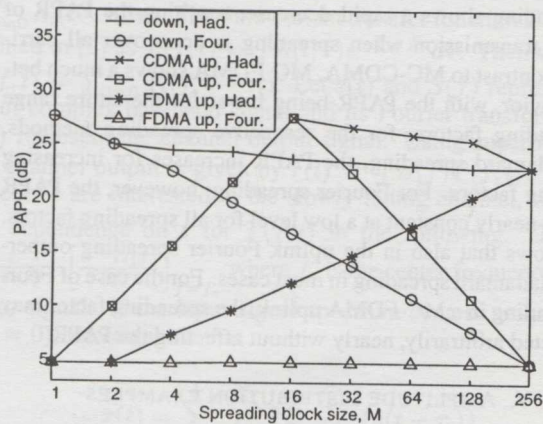


Fig. 3. PAPR as a function of the spreading block size. 4PSK, $N = 256$, $L = 32$, 'continuous' time.

Downlink

In the downlink, the PAPR is the same for both MC-CDMA and MC-FDMA. This is obvious because both systems are identical except for the assignment of transmitted symbols to users. For the trivial case of spreading over a single carrier and for the case of spreading over two carriers, both Hadamard and Fourier spreading deliver the same PAPR. In the latter case this

happens because Hadamard and Fourier matrices are identical for spreading over two symbols. In the case of Hadamard spreading, when spreading is done over an increasing number of subcarriers, the PAPR remains nearly constant (with a slight decrease); for Fourier spreading, however, it decreases rapidly and reaches the PAPR of a single carrier transmission when spreading is done over *all* subcarriers. This means that for the downlink Fourier spreading clearly outperforms Hadamard spreading. The larger the spreading factor, the better the PAPR. Furthermore, assuming that a large number of users is desired, we consider the following: Since MC-FDMA requires (at least) one spreading block per user, the spreading blocks must be small in case of many users, resulting in a relatively large PAPR. For MC-CDMA, however, the larger the spreading block, the larger the possible number of users. Here the best choice with respect to PAPR is to use Fourier spreading over all carriers while assigning groups of input symbols for each user, resulting in the lowest possible PAPR.

Uplink

In the uplink we distinguish between MC-CDMA and MC-FDMA. For MC-CDMA the PAPR of both Fourier and Hadamard spreading shows a strong increase for increasing spreading factors, reaching a maximum when the spreading factor equals the square root of the number of subcarriers. When the spreading factor is increased further, Hadamard spreading shows a slight decrease in PAPR while Fourier spreading shows a rapid decrease, reaching the PAPR of a serial transmission when spreading is done over all carriers. In contrast to MC-CDMA, MC-FDMA shows a much better behavior, with the PAPR being lower for the entire range of spreading factors, for the respective spreading methods. For Hadamard spreading, the PAPR increases for increasing spreading factors. For Fourier spreading, however, the PAPR remains nearly constant at a low level for all spreading factors. This shows that also in the uplink Fourier spreading outperforms Hadamard spreading in most cases. For the case of Fourier spreading in a MC-FDMA uplink, the spreading factor may be selected arbitrarily, nearly without affecting the PAPR.

V. AMPLITUDE DISTRIBUTION EXAMPLES

Since the PAPR only describes the worst case amplitude of the transmit signal, the amplitude distribution gives better insight into the occurrence probability of a certain amplitude range. We plot the amplitude distribution in the following way: a normalized threshold power $P_{\text{thresh}}/P_{\text{avg}}$ is defined, and for this threshold value the probability is computed that the instantaneous power exceeds the threshold power; the plot is in logarithmic scale over a range of threshold values. Fig. 4 depicts results for a block size of 16.

The graph shows that, in case of the downlink, Fourier spreading offers a more sharply limited amplitude distribution while Hadamard spreading produces continuously grow-

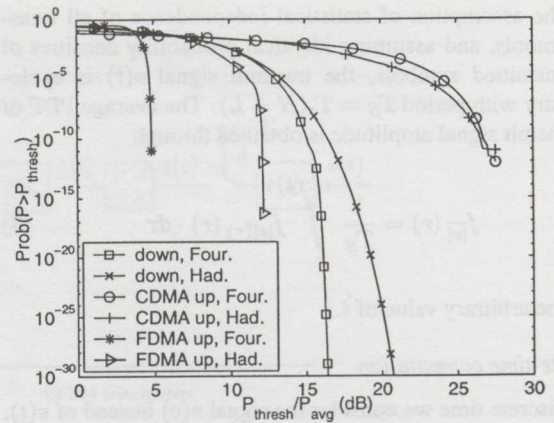


Fig. 4. Example for amplitude distribution.
4PSK, $N = 256$, $L = 32$, $M = 16$, 'continuous' time.

ing amplitudes at decreasing probabilities. Not only from the PAPR point of view, but also from the PDF of the amplitude it is clear that Fourier spreading is a better choice than Hadamard spreading.

VI. CONCLUSIONS

Amplitude distributions of Hadamard spreading and Fourier spreading have been compared for OFDM based MC-CDM transmission methods, using a general matrix model. Comparison has been done for both up- and downlink in MC-CDMA and MC-FDMA multiple access scenarios, and for various spreading factors. For both up- and downlink Fourier spreading delivers a lower or equal PAPR. This superiority increases significantly for larger spreading factors. In the uplink, MC-FDMA delivers lower PAPRs than MC-CDMA. From the amplitude distribution point of view, the best choice is to employ Fourier spreading with MC-CDMA in the downlink and with MC-FDMA in the uplink.

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