STATISTICAL ADAPTIVE MODULATION FOR FILTER BANK MULTICARRIER (FBMC) WIRELESS COMMUNICATION SYSTEMS

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ABSTRACT:-*In this paper, statistical adaptive modulation is applied to a downlink filter bank multicarrier (FBMC) wireless communication system operating over a frequency selective fading channel. A subcarrier allocation algorithm is proposed, in which multiuser diversity is utilized. A simple, low computational complexity bit loading algorithm is proposed for finding the number of bits to be assigned to each user on each one of the subcarriers assigned to the user. It is shown that the proposed algorithms improve the overall system performance without increasing the total power transmitted by the base station (BS).*

KEYWORDS–*Wireless Communications; multiuser communications; adaptive modulation; FBMC modulation.*

I. INTRODUCTION

The basic idea of MCM is based on breaking the wideband channel into a number of parallel narrowband channels, called the sub-channels. MCM is a widely-used technique in mobile environments, known to be able to combat frequency selective fading. MCM is usually used to achieve high data rates in wireless systems and to mitigate the harmful consequences of intersymbol interference (ISI).

MCM was initially used in military HF radio systems [1]. MCM has been used in applications like audio and video broadcasting [2]. It has also been used in digital subscriber lines (DSL) in the form of discrete multitone (DMT) modulation [3]. Among the latest application areas of MCM are mobile wireless broadband services [4] and fixed wireless broadband services [5]. MCM is a promising candidate for the air interface in next generation cellular systems [6] [7].

OFDM is the most widespread type of MCM. OFDM systems generally use one of two modulation formats. The first is quadrature amplitude modulation (QAM), while the second is Offset-QAM (OQAM) [3][8][9][10][11]. Following other recent research, we will refer to OFDM/OQAM as filter bank multicarrier modulation (FBMC).

The major difference between FBMC modulation and OFDM/QAM is its improved frequency selectivity [12]. OFDM exhibits large ripples in the frequency domain. In contrast, the filter bank frequency response has negligible response beyond the center frequency of the adjacent sub-carriers. The FBMC approach has the following features, compared to OFDM:

- No guard time, or cyclic prefix, is needed.
- Absence of leakage in the frequency domain enables high resolution spectral analysis.

Adaptive modulation is generally used for the purpose of optimizing the channel utilization of communication systems. The idea of Adaptive modulation was introduced in [13]. Practical channel adaptation algorithms have been proposed for DMT in [14] [15]. In [16], the authors attempted to use adaptive modulation to minimize the outage probability, assuming perfect CSI at the transmitter. Different adaptive power allocation and bit loading schemes have been investigated in [17] [18]. In [18], the authors attempted to minimize the total base station transmit power for multiuser OFDM through combined subcarrier, bit, and power allocation under a fixed BER requirement. In [19], the ultimate goal of the authors was to maximize the minimum user capacities under overall transmit power constraints and zero delay.

This paper is organized as follows. In Section II, we present the channel model. In Section III, the system under consideration is discussed. In Section IV, the proposed subcarrier allocation, bit loading, and power allocation algorithms for multiuser FBMC systems are explained. Performance evaluation and comparisons for FBMC systems are provided in Section V through computer simulation. Section VI is devoted to outline the major conclusions of the paper.

II. CHANNEL MODEL AND SYSTEM DESCRIPTION

Consider an L-tap multipath fading channel. The l-th path ($l = 1, 2, \cdots, L$) is characterized by a time-varying complex channel gain g_l^t and a path delay τ_l. Thus, the channel impulse response (CIR) may be written as:

$$h(t) = \sum_{l=1}^{L} g_l^t \delta\left(\tau - \tau_l\right) \qquad (1)$$

where the channel gain is a zero mean complex Gaussian random variable [20], with real and imaginary parts $g_{l,R}^{t}$ and $g_{l,I}^{t}$, respectively, i.e.,

$$g_{l}^{t} = g_{l,R}^{t} + jg_{l,I}^{t} \tag{2}$$

Consider a multiuser multicarrier system with statistical adaptive modulation operating over a frequency selective channel. For a given user, the subcarriers which experience deep fades are not power efficient to carry data and may not be used by that user [18]. Typically, the signals transmitted over the channel by different users experience mutually independent fading processes. The probability that all user signals experience simultaneous deep fades on a specific subcarrier is extremely low [21].

In this paper, adaptive multiuser subcarrier allocation is proposed, such that the subcarriers are assigned to the users based on instantaneous channel gains. A low complexity bit loading algorithm is proposed to determine the number of bits assigned to a given user on each subcarrier. Adaptive multiuser FBMC modulation is considered. In contrast to QAM, OQAM allows for efficient pulse shaping, making it less sensitive to frequency offsets [3]. Adaptive quadrature amplitude modulators are used to generate QAM symbols based on the number of bits assigned to each subcarrier. QAM symbols are transformed into OQAM symbols by an operation called staggering [3]. Using OQAM, data is transmitted alternatingly on the real and imaginary parts of successive symbols. For two successive subcarriers, a time offset of half a QAM symbol period is applied to the imaginary part of QAM symbols on one of the carriers, while it is applied to the real part on the other carrier [3]. The generated OQAM symbols constitute the input of the synthesis filter bank (SFB). Figure 1 illustrates the basic FBMC system configuration.

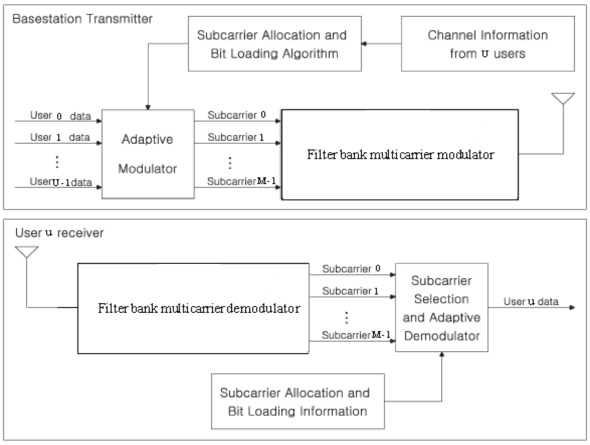

Figure 1: Adaptive multiuser FBMC system

We assume a downlink multiuser FBMC system with M subcarriers and U users. The bandwidth of each subcarrier is assumed to be less than the coherence bandwidth of the channel, so that each subcarrier undergoes flat fading.

In the downlink, the base station (BS) can estimate the instantaneous characteristics of the channel based on channel state information (CSI) obtained from the uplink transmission [18]. As a result, the BS can inform the mobiles about their allocated subcarriers and how many bits have been assigned to each of them.

Generally, adaptive modulation requires instantaneous knowledge of CSI. Obviously, a significant amount of feedback is needed, which may not be practical in many systems. In order to reduce the feedback overhead, we adopt statistical adaptive modulation, which requires only partial knowledge of CSI.

An FBMC symbol consists of contributions from OQAM symbols by all users. Subcarrier and bit allocations are assumed to be used to determine the numbers of bits users can transmit on different subcarriers. Channel characteristics are assumed not to vary over the duration of one FBMC symbol, but to possibly vary from one FBMC symbol to another. In the case of statistical adaptive modulation, the bit and subcarrier allocations are performed once over several FBMC symbols instead of once every FBMC symbol. This reduces the amount of transmission overhead.

III. SUBCARRIER, BIT, AND POWER ALLOCATION

As mentioned earlier, different users will experience different channel gains. Let us define $\alpha_{u,m}$ as the channel gain magnitude at the m^{th} subcarrier as seen by the u^{th} user receiver. Thus, we can construct the $U \times M$ instantaneous channel gain matrix H as

$$H = \begin{bmatrix} \alpha_{0,0} & \alpha_{1,2} & \cdots & \alpha_{1,M-1} \\ \alpha_{2,0} & \alpha_{2,2} & \cdots & \alpha_{2,M-1} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{U-1,1} & \alpha_{U,2} & \cdots & \alpha_{U-1,M-1} \end{bmatrix} \tag{3}$$

A. Subcarrier Allocation Algorithm

We consider the $U \times M$ matrix H and propose an iterative subcarrier assignment algorithm. According to this algorithm, and in each iteration, only the subcarrier with the best channel gain on each user link is exclusively assigned to that user. Only one user can transmit data on any specific subcarrier at any specific time. Then, assignment process is repeated until all subcarriers are assigned to all users.

The total number of subcarriers M in the matrix H may be written, for integer N and K, as:

$$M = NU + K \tag{4}$$

In the First iteration, U distinct subcarriers are assigned to U distinct users. If M is multiple of U (i.e., $K=0$), then N iterations are required to assign all M subcarriers to all U users. Otherwise, after N iterations are completed and NU subcarriers are assigned, each of the remaining K subcarriers, where $K<U$, should be exclusively assigned to the user that has the best channel gain for that subcarrier.

In this paper, we assume M is multiple of U, which means users are assigned equal numbers of subcarriers. The subcarrier assignment algorithm is illustrated in Box 1 below. Let us define $s_{n,u} \in \{0,1,2,........,M-1\}$ as the subcarrier that is assigned to the u^{th} user in the n^{th} iteration, and $S_u \subset \Omega$ as the set of subcarriers assigned to user u, where Ω is the set of all subcarriers.

```
% Initialize all subcarrier sets
1:Set : $\Omega = \{0,1,2,........,M-1\}$
2:Set: $S_u = \phi$ , $\forall u$
% Iterative subcarrier assignment process
%N=M/U ,and N is integer
For $n = 0$ to $N-1$ , % N is the number of iterations required
    For $u = 0$ to $U-1$, % U is the total number of users
        % Select the subcarrier with the best channel gain for user u
        % $s_{n,u}$ is the subcarrier with best channel gain to user u at iteration n
        3: $s_{n,u}$=arg $\max_{m\in\Omega}(\alpha_{u,0}, \alpha_{u,1}, \ldots, \ldots \alpha_{u,M-1})$ ,
        %Update all subcarriers sets
        4: $S_u = S_u + s_{n,u}$ ,% allocate subcarrier $s_{n,u}$ to user u
        5: $\Omega = \Omega - s_{n,u}$ ,% delete subcarrier $s_{n,u}$ from $\Omega$
    End For
End For
% Output all subcarriers sets
% $\forall u$, print out $S_u$
6: Output $\{S_u\}_{u=0}^{U-1}$
```

Box 1: Subcarrier Allocation Algorithm

B. Bit Loading Algorithm

We propose a low computational complexity bit loading algorithm that takes advantages of the CSI. We assume that all users use binary memoryless information sources [22]. In the proposed bit loading algorithm, the serial data of all users are fed into bit allocation blocks. It is assumed that each user has a bit allocation module which determines the number of bits/FBMC symbol assigned to that user on each of the selected subcarriers. Let us define $B_{m,l,u}$ as the number bits/FBMC symbol on the m^{th} subcarrier that are assigned to user u. Let us assume that $B_{m,l,u}$ takes integer values b_0 or b_1, where $b_0 > b1$. Let us further assume that a total number of $2L$ subcarriers are assigned to each user through subcarrier allocation. Note that L is fixed for all users. The bit loading algorithm may be viewed as water filling strategy [22]. In this strategy, b_0 bits are allocated to each one of the L subcarriers (out of $2L$ subcarriers assigned to a given user) with the largest L channel gains, while b_1 bits are allocated to each one of the remaining L subcarriers. The simple bit loading scheme above will be shown to result in reducing the average receiver error probability [23].

C. Power Allocation

Power allocation is not considered in this paper. Instead, we adopt a multiuser multicarrier system with uniform power allocation. The focus is on subcarrier allocation, where a set of subcarriers are assigned to each user based on the channel gains seen by that user. In other words, each one of the subcarriers assigned to a user has a higher channel gain than all subcarriers that are not assigned to that user. Typically, channel gains for the subcarriers that are assigned to a user take values that are relatively close to each other. As a result, power allocation is expected to yield only marginal performance improvement, making it a computational burden. Therefore, use of water filling transmit power allocation is avoided [22]. This means that the distance between adjacent constellation points is fixed during the adaptive modulation process. On the contrary, the constellation size is variable as a requirement of bit loading and modulation format.

D. Computer Simulations

To simplify the simulations, only two modulation formats, namely, 4-QAM and 16-QAM, are used in the bit loading process. Note that 4-QAM (16-QAM) is a 2-bit/symbol (4-bit/symbol) modulation technique. When converted to OQAM, half the number of bits goes to one subcarrier, while the other half goes to another subcarrier. This is why it can be referred to OQAM based on 4-QAM (16-QAM) as a 1-bit/symbol (2-bit/symbol) system. Note that this can be summed into the fact that one OQAM symbol is actually one half of a QAM symbol.

ITU Vehicular-A (VEH-A) channel profile (recommended for WiMAX) [20] is adopted. We assume perfect channel estimation and zero forcing block equalization in order to compensate for channel fading experienced by the subcarriers. The FBMC transmission link model in [24] is followed. This model is based on PHYDYAS project filter bank with perfect synchronization in the time and frequency domains [12]. The proposed subcarrier allocation and simple procedure bit loading algorithm are performed over a downlink multiuser FBMC system of 32 users and 128 subcarriers, referred therein as [32*128].

To evaluate the BER of a [32*128] FBMC system, we simulated 4000 independent channels. Initially, we performed the proposed subcarrier allocation (SA) algorithm with fixed modulation schemes (no bit loading). SA was applied on every FBMC symbol. Next, we performed statistical subcarrier allocation (SSA) with fixed modulation schemes, with subcarrier allocation done once every several FBMC symbols. Obviously, SSA is more computationally efficient compared to SA.

In Figure 2 and Figure 3, we compare the theoretical and simulation BERs of fixed modulation and statistical fixed modulation for 4-QAM. The BER increases in the case of statistical fixed modulation because the subcarrier allocation algorithm is based on the statistical average characteristics of the subcarrier channel gains rather than on the instantaneous characteristics.

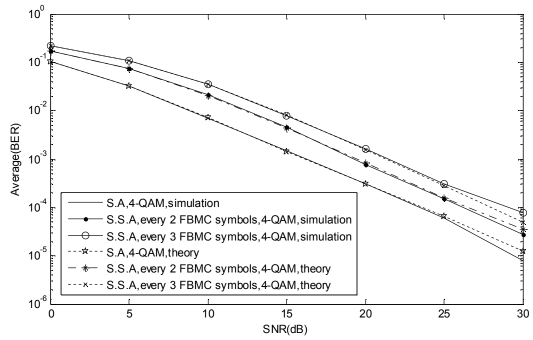

Figure 2: Downlink BER for multiuser FBMC system [32*128], VEH-A channel,vmob=100km/h. comparing SA and SSA with SSA every [2,3] FBMC symybols, fixed modulation scheme of 4-QAM.

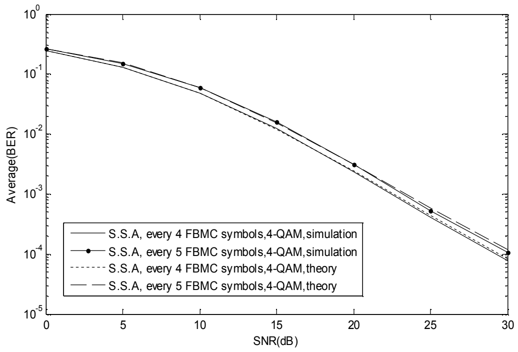

Figure 3: Downlink BER for multiuser FBMC system [32*128], VEH-A channel,vmob=100km/h. comparing SA and SSA with SSA every [4,5] FBMC symbols, fixed modulation scheme of 4-QAM

In Figure 4, the proposed subcarrier allocation algorithm is compared with an allocation algorithm that is based on contiguous subcarrier allocation (CA) [25]. By achieving the best utilization of spectral diversity characteristics, the BER is drastically reduced. There are 4 subcarriers assigned to each of the 32 users of the system. Based on this, a simple procedure bit loading scenario (see Figure 5) is proposed, such that each of the two subcarriers with the largest two channel gains is given 2 bits (complex 16-QAM modulation), while each of the remaining two are given 1 bit (complex 4-QAM modulation). By exploiting the slight variations among the channel gains of the subcarriers assigned for a specific user, we can allocate more bits to subcarriers with larger channel gains and fewer bits to subcarriers with smaller channel gains. This leads to further minimization in average receiver BER.

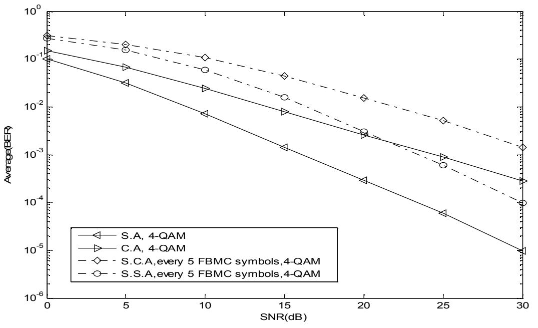

Figure 4: Downlink BER for multiuser FBMC system [32*128], VEH-A channel,vmob=100km/h comparing SA and CA and SSA with SSA every 5 FBMC symbols, fixed modulation scheme of 4-QAM

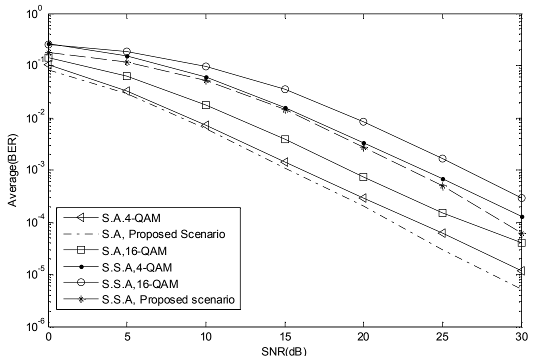

Figure 5: Downlink BER for multiuser FBMC system [32*128], VEH-A channel, vmob=100km/h. comparing SA with SSA every 5 FBMC symbols for 4-QAM and 16-QAM with proposed bit loading scenario

In multiuser FBMC systems, the total data rate of the system is a contribution of all users bits divided by the FBMC symbol duration; it may be written as:

$$R = \frac{1}{T_F} \sum_{u=0}^{U} \sum_{m=0}^{M-1} b_{m,u} = \frac{B}{M} \sum_{u=0}^{U} b_u \qquad (5)$$

where B is the total bandwidth, M is the number of subcarriers, T_F is the FBMC symbol duration, given by $T_F = M / B$, U is the number of users, and b_u is the number of bits/user.

In the proposed system, each user transmits data over only 4 distinct subcarriers. Thus, b_u is independent of u

, with values in the set b= {4, 6, 8} that, respectively, represent complex 4-QAM, proposed scenario, and complex 16-QAM modulation schemes. Equation (5) can be rewritten in the form

$$\frac{R}{B}=\frac{Ub}{M} \tag{6}$$

Based on (6), for any FBMC system characterized by $M = 4U$, the average data rate/bandwidth takes values of {1, 1.5, 2} with modulation schemes {4-QAM, proposed scenario, 16-QAM}, respectively. In obtaining Figure 6, each user has been assumed to transmit data over 4 distinct subcarriers. Therefore, b_u in (5) is independent of u, because the number of bits is decided by which of the four modulation schemes is used. Hence, b= {4, 6, 8} represents the sums of the numbers of bits transmitted over 4 subcarriers, according to (6). The result seen in Figure 6 is that applying the proposed bit loading scenario improves system performance, compared to fixed modulation.

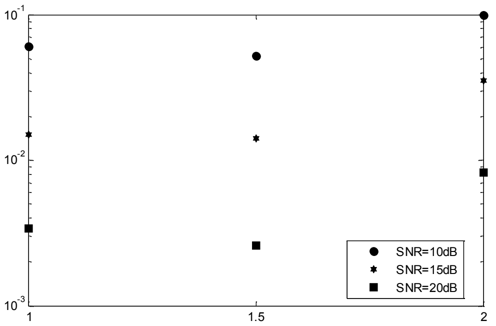

Figure 6: Downlink BER versus Average R/B for multiuser FBMC system [32*128], VEH-A channel,vmob=100km/h. SNR=10,15,20 dB, statistical adaptive modulation every 5 FBMC symbols.

An interesting result can be seen in Figure 7 and Figure 8, where a comparison is made between different numbers of users and subcarriers. In the three systems, each user is allowed to transmit data over four subcarriers. It is found that the overall system BER decreases as the number of users increase. This result is best explained based on multiuser diversity effect [26]. Since each subcarrier channel fading is independent of the others, it is more likely to find subcarriers with larger channel gains in case of larger multiuser multicarrier FBMC systems.

IV. CONCLUSION

In this paper, subcarrier allocation with fixed and adaptive modulation has been investigated. The results show that the proposed subcarrier allocation schemes improve the BER of FBMC systems, compared to contiguous subcarrier allocation with fixed and adaptive modulation formats. The BER increases in case of statistical fixed or statistical adaptive modulation; because subcarrier allocation is based on the average characteristics of the subcarrier channel gains rather than on the instantaneous characteristics.

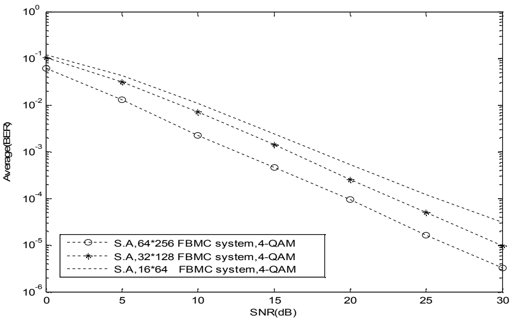

Figure 7: Downlink BER,VEH-A channel, ,vmob=100km/h. comparing SA with different multiuser FBMC systems [16*64], [32*128], [64*256], for 4-QAM modulation.

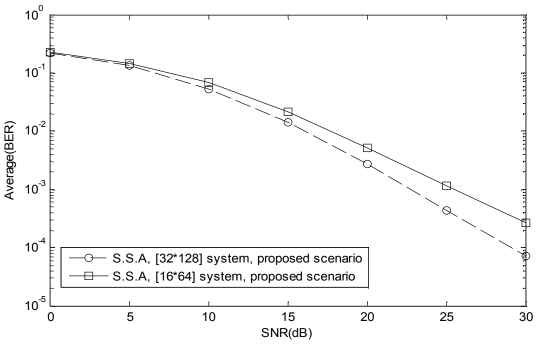

Figure 8: Downlink BER,VEH-A channel, vmob=100km/h. comparing SSA (every 5 FBMC symbols) with different multiuser FBMC systems [16*64], [32*28] proposed scenario modulation format.

Simple procedure bit loading scenario has been studied. The results show that by applying this scenario, we can transmit more data bits at relatively lower BER than that of fixed 4-QAM modulation schemes. Our work includes comparison between different numbers of users and subcarriers of FBMC system. It has been observed that the average decreases in when larger multiuser multicarrier FBMC systems are used.

REFERENCES

[1] S. Hara and R. Prasad, “Overview of multicarrier CDMA,” *IEEE Communications Magazine*, Vol. 45, No. 12, pp. 126–133, December 1997

[2] J. A. C. Bingham, “Multicarrier modulation for data transmission: An idea whose time has come,” *IEEE Communications Magazine*, Vol. 28, No. 5, pp. 5–14, May 1990

[3] P. Siohan, C. Siclet, and N. Lacaille, “Analysis

and Design of OFDM/OQAM Systems Based on Filterbank Theory," *IEEE Transactions on Signal Processing*, Vol. 50, No. 5, pp. 1170-1183, May 2002

[4] G. L. Stüber, J. R. Barry, S. W. Mclaughlin, Y. LI, M. A. Ingram, and T. G. Pratt, "Broadband MIMO-OFDM Wireless Communications," *Proceedings of the IEEE*, Vol. 92, No. 2, pp. 271-294, February 2004

[5] C. Eklund, R. B. Marks, K. L. Stanwood, and S. Wang, "IEEE Standard 802.16: A Technical Overview of the WirelessMAN 326 Air Interface for Broadband Wireless Access, IEEE Commun. Mag., pp. 98–107, June. 2002

[6] W. Lu, "4G Mobile Research in Asia", IEEE Commun. Mag., pp. 104-106, Mar. 2003

[7] T. S. Rappaport, A. Annamalai, R. M. Buehrer, and W. H. Tranter, "Wireless Communications: Past Events and a Future Perspective", IEEE Commun. Mag. Vol. 40, No. 5, pp. 148–161, May 2002

[8] H. Zhang, D. Le Ruyet, and M. Terre, "Spectral Efficiency Analysis in OFDM and OFDM/OQAM Based Cognitive Radio Networks", in Proc. IEEE Vehicular Tech. Conf. (VTC), Apr. 26–29, 2009, vol. 1

[9] A. B. Salem, M. Siala, and H. Boujemaa, "Performance Comparison of OFDM and OFDM/OQAM Systems Operating in Highly Time and Frequency Dispersive Radio-Mobile Channels", in Proc. of IEEE Int. Conf. on Elect., Systems and Circuits (ICECS), Dec. 11–14, 2005

[10] T. Fusco, L. Izzo, A. Petrella, and M. Tanda, "Blind Symbol Timing Estimation for OFDM/OQAM Systems", IEEE Trans. Signal Processing., Vol. 57, No. 12, pp. 4952-4958,2009

[11] B. Hirosaki, S. Hasegawa, and A. Sabato, "Advanced Groupband Data Modem Using Orthogonally Multiplexed QAM Technique", IEEE Trans. Commun. vol. 34, no. 6, pp. 587–592, June 1986

[12] Deliverable D2.1 PHYDYAS ICT-211887, "Blind techniques and strategy for synchronization and initialization," July 2008

[13] I. Kalet, "The Multitone Channel", IEEE Trans. Communication., vol. 37, no. 2, pp.119-124, Feb. 1989

[14] Ranjan V. Sonalkar, Richard R. Shively, "An Efficient Bit-Loading Algorithm for DMT Applications", IEEE communication letters., VOL. 4, NO. 3, MARCH 2000, pp80:82

[15] B.S Krongold, K. Ramchandran, and D. L. Joughns, "Computationally Efficient Optimal Power Allocation Algorithms for Multicarrier Communication Systems", IEEE Trans Commun., Vol. 48, No. 1, pp. 23–27, Jan, 2006

[16] K. M. Kamath and D. L. Goeckel, "Adaptive Modulation Schemes for Minimum Probability in Wireless Syetems", in Pro. IEEE J. Global Commun. Conf. (GlobeCom'01) San Antonio, Texas, Nov. 2001, pp-1267-1271

[17] D. H. Hartogs, "Ensemble Modem Structure for Imperfect Transmission Media", U.S. patents 4679227 July 1987, 4731816 Mar. 1988, 4833706 May 1989

[18] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, "Multiuser OFDM with Adaptive Subchannel, Bit, and Power allocation", IEEE J. Sel. Areas Commun., Vol. 17, no. 10, pp. 1747–1758, Oct. 1999

[19] W. Rhee and J. M. Cioffi, "Increase in Capacity of Multiuser OFDM System Using Dynamic Subchannel Allocation", in Proc. IEEE Vehicular Technology Conf. (VTC 2000), Tokyo, Japan, May 2000, pp. 1085–1089

[20] TU ITU-R M.1225, "Guidelines for Evaluations of Radio Transmission Technologies for IMT-2000", 1997

[21] J. Jang, K. Bok, "Transmit Power Adaptation for Multiuser OFDM Systems", IEEE journal on selected areas in communications., vol. 2, pp. 171-173, Feb.2003

[22] T. M. Cover and J. A. Thomas, Elements of Information Theory, 1st edition, New York: Wiley & Sons, 1991

[23] A. M. Wyglinski, F.Labeau, "Bit Loading with BER-Constraint for Multicarrier Systems", *IEEE Transactions on Wireless Communications* Vol. 4, No. 4, pp. 1383-1387. July, 2005

[24] Deliverable 5.1, "Prototype Filter and Structure Optimization", ICT- 211887 PHYDYAS, July 2008

[25] H. Zhu and J. Wang, "Chunk-Based Resource Allocation in OFDMA Systems—Part I: Chunk Allocation", IEEE Trans. Commun.,Vol. 57, No. 9, pp.2734-2744, Sep.2009

[26] R. Knopp and P. A. Humblet, "Information Capacity and Power Control in Single-Cell Multiuser Communications", in *Proc. IEEE Int. Conf. Communications 1995 (ICC'95)*, Seattle, WA, June 1995, pp. 331–335.