MC-SS for Personal Area Networks –
A Combined PHY and MAC Approach

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Abstract—**Future personal networks (PN) will be complemented by personal area networks (PANs), which are considered as a building block for 4G communication systems [1]. PANs establish an ad-hoc network of personal devices around a person with the possibility to associate other devices in reach as well. A connection to infrastructure networks or other PANs will be established on demand. Air interfaces for personal area networks [2] need to be flexible and adaptive as well as robust against interference as no dedicated frequency band will be assigned to PAN services. MC-SS is a PHY layer technique that provides all these features with respect to PANs with multimedia support. A promising standard for medium access control (MAC) is the IEEE 802.15.3 standard, which establishes power and spectrum efficient high data rate communications in ad-hoc networks. However, this standard does not incorporate a suitable physical layer so far. This paper presents a new PHY layer scheme for PANs along with considerations for the MAC in the context of the IST-MAGNET project.**

I. INTRODUCTION

Personal area networks (PANs) have encountered increased interest in the research community during the last years. It is assumed that in future people will own various personal devices that will connect on demand in an ad-hoc fashion forming a Personal Network (PN). In the IST project MAGNET the PAN is seen as a short-range building block for personal communications within a PN [1]. Due to the variety of services and channel conditions PAN air interfaces have to be adaptive and scalable up to high data rates. Efforts in the development of novel standards, especially the IEEE 802.15.3, try to satisfy the need for high data rate multimedia standards for PANs. However, the high data rate PHY layer extension for IEEE 802.15.3, IEEE 802.15.3a, has not been finalised so far and moreover, interference issues of the high data rate UWB system to existing systems are not solved yet. The recent formation of a SIG concerning one of the IEEE 802.15.3a proposals, the Multi Band OFDM Alliance, shows promise at a resolution, but demonstrates the disagreement within the research and industrial community on the issue of a WPAN PHY. Also the lack of adaptability and scalability requires an alternative approach.

The paper is organised as follows. The remainder of this section introduces the PAN concept and the PAN environment with a discussion on the terminology. Section II presents the highly scalable and flexible physical layer scheme based on MC-SS including simulation results on the performance. In section III the IEEE802.15.3 MAC will be introduced and adaptability in the PAN environment will be considered. Results on the throughput with respect to the number of simultaneous data streams and supported traffic types are given. Finally, section IV concludes the paper.

A. *PAN Concept*

Radio Domains are a peculiarity of wireless communications and it is only possible to establish communications between devices if they communicate (even if only temporarily) in the same Radio Domain.

Figure 1 illustrates some aspect of the views of the lower layers.

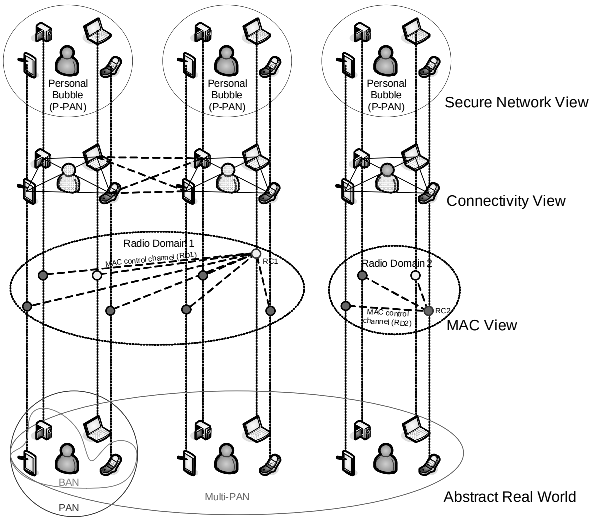

Figure 1: The PAN concept – Views

In the Abstract Real World View device types and Personal Operating Spaces can be identified. The second view shows the

MAC control domain. Medium access, resource coordination and interference from different radio domains can be identified; the Radio Domains depend on the range of devices and are established for coexistence purposes and are individually coordinated by a single Coordinator.

The Connectivity View reflects the network layer and Data/Network Links (i.e., which dev can send data to which device). Regardless of the underlying views, the Private PAN (P-PAN) is formed at this stage if security is taken into account.

II. MC-SS PHY LAYER

A. *Basic Overview*

Achieving low to high data rate transmission through wide-band radio channels along with being robust against interference and limited complexity is a very challenging research target.

CDMA provides an efficient way of achieving diversity as well as mitigating interference due to spreading. But, in multi path fading channels CDMA systems suffer from multiple access interference. On the other hand, OFDM systems achieve good performance in this kind of channels along with reasonable complexity. An efficient combination of both schemes, namely MC-CDMA, has been investigated in several projects [4][5][6][7]. In MC-CDMA channelisation is feasible in the time and frequency domain together with the code domain. Figure 2 shows the allocation of spread symbols in code and frequency domain.

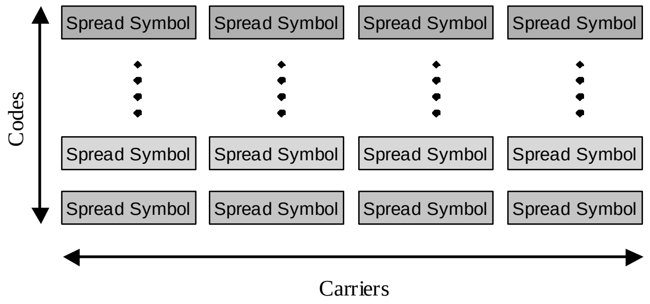

Figure 2: Spread Symbols in Code and Frequency Domain

But recent results from MAGNET have shown [8] that device separation in code domain does not show promising results in PAN environments. Due to the decentralised system approach data that one device receives suffers from severe multiple access interference (MAI), which cannot be equalised easily. In contrast to a cellular uplink system the particular device has no knowledge of the channel for signals received from interfering devices. Further, the device does not need to decode the data of the other devices. Considering the required simplicity of the devices, complex multi user detectors are to be avoided if possible. Consequently, device separation in code domain is not foreseen. In the multi carrier spread spectrum (MC-SS) system all spread symbols within one OFDM symbol will be allocated to one particular device. In this case, spreading will be used to enhance flexibility and scalability as well as to mitigate interference. Equalisation becomes simple as all spread symbols are affected by the same channel and the system will suffer from less MAI. Regarding the multiple access scheme the MS-SS technique foresees TDMA, which is supported by the considered IEEE802.15.3 based MAC.

B. *Frequency Band Selection*

The 2.4 GHz is crowded and not designated for radio systems (i.e. ISM band), while the 5.15-5.35 and 5.47-5.725 GHz (the 5 GHz band) is designated for WAS (Wireless Access Systems), including WLAN [9]. The 5 GHz band is thus a license exempt band. Following the regulatory constraints regarding the 5 GHz band a PAN could be seen as a subset of WLAN. The constraints and limitations to keep in mind for the 5 GHz band are:

- Output power restrictions
- Transmitter power control
- Dynamic frequency selection
- Load balancing over the band

Although the 2.4 GHz band is seen as a possibility, the heavy occupancy of the band is evident and yet another communications system might overcrowd the band just further. The 5 GHz band is seen as a possibility; however, the regulatory issues mentioned above would have to be met.

In contrast, the 17 GHz band is virtually untouched with respect to regulations and thus also radio systems. But, the suitability of this band for PANs has to be further investigated in terms of radio propagation.

Within the framework of the IST-MAGNET project, the 5GHz band is assumed to be most appropriate. Table 1 presents regulatory details of the 5GHz band (EU specific).

Band	**Max EIRP**	**PSD**	**Remarks**
5150 – 5250 MHz	200mW	4dBm/MHz	Indoor only
5250 – 5350 MHz	200mW	4dBm/MHz	Indoor and outdoor Mitigation is required
5470 – 5725 MHz	1W	11dBm/MHz	Indoor and outdoor Mitigation is required
5725 – 5850 MHz	25mW		Indoor to outdoor Point to multi-point
5725-5850 MHz	200W		Indoor to outdoor Point to Point

Table 1: Clarification of the 5GHz band [9]

C. *Transmitter and Receiver Architecture*

Based on the considerations in chapter II.A the transmitter and receiver architecture has been developed as shown in Figure 3.

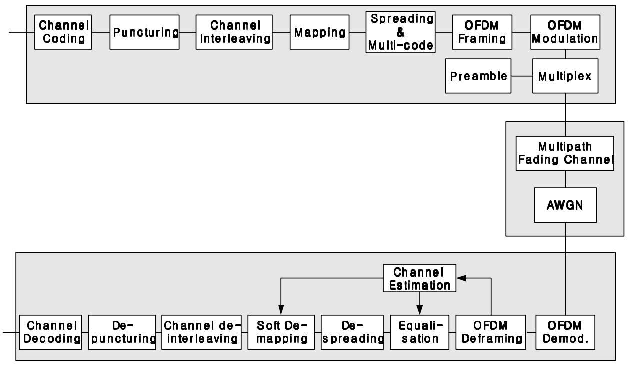

Figure 3: Transmitter - Receiver Architecture

First, bits received from MAC layer are channel coded, punctured and interleaved. The mapping block maps a certain number of bits to complex symbols; QPSK, 16-QAM and 64-QAM modulation are foreseen. The spreading and multi-code transmission is depicted in more detail in Figure 4. Incoming symbols are separated into different streams and spread in the frequency domain. The spread symbols are added afterwards and mapped onto OFDM carriers. As the IFFT length is a multiple of the spreading factor several frequency-spreading blocks (FSB) can be transmitted within one OFDM symbol. The receiver encompasses the inverse operations of the transmitter plus channel estimation and equalisation modules.

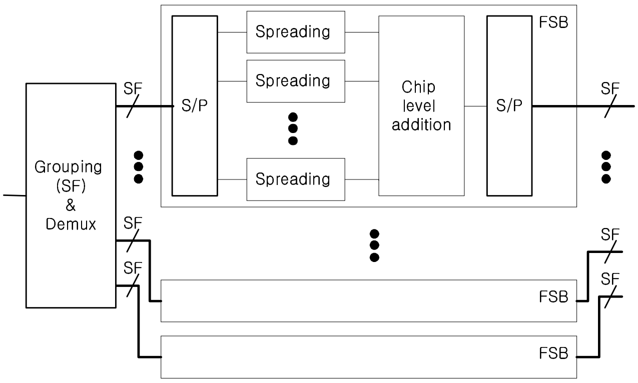

Figure 4: Spreading and Multi-Code Transmission

A preamble symbol is added for channel estimation purpose per each physical layer fragmentation unit. The preamble symbol is followed by a number of OFDM symbols in physical layer.

The system parameters proposed for this system are listed in Table 2. The theoretical system throughput of this system is 150Mbits/s using 50MHz bandwidth and 64-QAM modulation. A spreading factor equal to 8 is foreseen resulting in 12 FSBs per OFDM frame using 25MHz bandwidth and 24 FSBs per OFDM frame with 50MHz, respectively.

Parameter	25MHz	50 MHz
FFT Length	128	256
Subcarriers for guard band	32	64
Subcarriers for data	96	192
Carrier Spacing	195.3 kHz	195.5 kHz
Samples per guard interval	16	32
Total number of samples per burst	144	288
Length data interval	5.12μs	5.12μs
Length of guard interval	0.64μs	0.64μs
Total burs length	5.76μs	5.76μs
Efficiency /burst length / data interval)	0.889	0.889
Spreading factor	8	8
FSBs per OFDM symbol	12	24
Theoretical System Throughput (64 QAM, coding rate ¾)	75 Mbps	150 Mbps

Table 2: System Parameters

D. Adaptive Schemes

Link adaptation (LA) techniques, where the power, modulation, and/or other signal parameters are dynamically adapted to the channel conditions, have recently emerged as powerful tools for increasing the spectral efficiency and performance of wireless data transmission [12],[13]. Adaptability can be achieved by exploiting partial or perfect channel state information (CSI) at the transmitter obtained e.g. from a time-division duplex transmission (TDD) with/without feedback.

In MC-SS systems, the multipath channel affects the orthogonality of the received spreading codes and the resulting interference (MAI) has to be taken into account to design the system.

In the considered system, we assume the receiver to carry out a simple conventional detection and thus rely on the orthogonality of the signals in one FSB. Two adaptive schemes are proposed in order to mitigate the multi-code interference and to improve the average bit-error rate (BER) by an adaptive pre-equalization (APE) and an adaptive bit loading (ABL). In the APE, unlike in OFDM transmission, the main task of the adaptation is the interference mitigation, which is accomplished by the pre-equalization of the channel. The subsequent assignment of the power in each FSB again minimizes the achievable BER. If perfect CSI is available at the transmitter and there are no deep fades, the APE can perfectly equalize the channel in each FSB and the power loading over the FSBs is the same as for OFDM [12]. The ABL module will be based on the resulting equalized channel to select the modulation scheme in each FSB in order to minimize the BER. Both adaptation strategies are subject to a bit-rate and power constraint and can be derived in a similar way as in [12]. The pre-equalization at the transmitter is preferred to the zero-forcing frequency domain equalization (FEQ) at the receiver since it reduces the noise effects at the receiver and keeps the receiver simple.

However, many factors can cause the CSI at the transmitter to become outdated, e.g. a feedback channel with delay in a time-variant environment. Some previous work addressing these issues has been considered in [14],[15]. In order to mitigate the interference arising from imperfect CSI, the FEQ at the receiver will be carried out in any case. If the APE has equalized the channel and perfect CSI is available at the receiver, the FEQ does not change the statistics of the decision variable. If, however, the APE is imperfect, the additional FEQ will help to restore the orthogonality at the expense of a reduced BER performance as compared to an optimal multiuser detection scheme.

E. Performance of PHY layer

The presented PHY layer has been simulated with a system bandwidth of 25MHz. In PHY layer, convolutional coding with rate 1/2, 2/3, and 3/4 have been applied along with QPSK, 16QAM, and 64QAM modulation, and simulation results of selected combinations are shown in Figure 5 in terms of coded BER against Eb/No. In the simulation, each physical layer fragment consists of 5 consecutive OFDM symbols and the numbers specified in the legend represent the number of information bits without considering 8 bits of tail for convolutional encoding. The 5 GHz BRAN-A multi path fading channel defined in [10] has been used with 3km/h velocity. Spreading was performed with a spreading factor equal to 8 and all codes have been used for data transmission. At the receiver, minimum mean square error combining (MMSEC) is used for combining spread signals. MMSE combining is modified ZF combining, where the noise is taken into account, providing a good trade-off between noise enhancements and restoring orthogonality in a non-adaptive system. Mathematical details describing these schemes can be found in [8]. Perfect channel estimation is applied for the simulation and adaptive schemes have not been implemented yet.

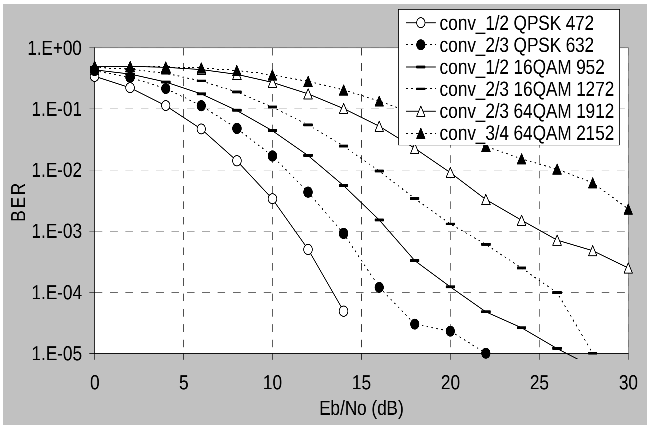

Figure 5: PHY layer performance (non-adaptive)

From the figure, we can clearly see the benefits of having different modulation and coding schemes defined in PHY layer. More realistic system design with non-ideal channel estimation based on preamble, and further enhancing technologies such as MIMO, HARQ, and adaptive transmission algorithms will be further investigated.

III. MC-SS MAC LAYER

A. *Basic Overview*

Although the PHY layer of the IEEE 802.15.3 standard is still rather undefined, a detailed definition of the MAC layer is available [11]. This MAC includes several mechanisms that allow a flexible resource management and support of QoS, which are key requirements for high-data rate PAN devices. Even if the MAC has been originally designed for a single carrier PHY scheme, it can be easily adapted to a MC-SS PHY layer. Nevertheless, to better take advantage of the flexibility offered by a MC-SS system, some modifications to this standard are required. In the remainder of this section, an overview of the 802.15.3 MAC is given, outlining the most important mechanisms for resource management and QoS support. Then, some of the suggested changes to the standard are described.

The standard 802.15.3 operates as a centrally controlled ad hoc network, forming piconets. A piconet consists of a piconet Coordinator (PNC) and one or more devices that are synchronised with the PNC. Synchronization is required since the MAC superframe is structured in time slots. Two devices in the piconet can communicate directly by either randomly accessing the time slots in the Contention Access Period (CAP) of the superframe or by accessing the channel in some assigned time slots of the superframe during the channel time allocation period (CTAP). Figure 6 shows the structure of the MAC superframe, which consists of three parts:

- Beacons are the control messages broadcasted by the PNC, which contain information such as timing parameters, assigned time slot for the communication;
- Contention Access Period (CAP), where devices access the channel according to a random multiple access scheme (i.e., CSMA/CA);
- Channel Time Allocation Period (CTAP), where the access to the channel is controlled by the PNC, which assigns the time slots for that communication in response to the request message that contains information about the requested bandwidth, delay constraints and other QoS requirements of the communication to be established.

Two types of time slots can be assigned to one communication: Channel Time Allocation (CTA) time slots, which are used for information data transfer and Management CTA (MCTA), which are used for exchanging management information. According to the beacon settings, management and/or data information can be transmitted in the CAP. The contention free access to the channel is a key element for QoS support of delay-sensitive applications. In the CTA period the access to the channel is based on TDMA.

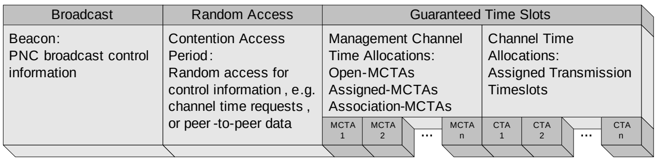

Figure 6: IEEE 802.15.3 MAC Superframe Structure

B. *Adaptability in the PAN Environment*

Adaptation is the ability to match the parameters and modes of operation of the air interface to the link quality. It involves managing the changes in channel conditions, traffic conditions, user requirements and operation conditions of the device. In a PAN environment significant contributions to change in channel conditions are due to fading, shadowing, varying data rates and interference. Traffic characteristics will depend on the application requirements. For example IP services are bursty in nature and their requirement on channel time will vary time to time.

Many PAN technologies are expected to operate in shared spectrum, and at the least a PAN will have to co-exist with other PANs. Efficient medium access control and radio resource management algorithms are to be devised, balancing spectrum efficiency and QoS requirements. The level of coordination between devices needs to be considered, for both the same and different PANs. In most situations a degree of interference has to be accepted, and so the optimisation of the air interface along with interference mitigation processing (in the temporal and spatial domains) need to be considered.

Major aspects of an adaptive resource management scheme are:

- Dynamic channel allocation
- Dynamic management of multiple access schemes including an adaptive superframe structure

– Dynamic soft channel management – involves parametric control over constellation sizes, power levels, code sizes etc.

The adaptation system can be viewed as a measurement and control system in which the context changes are sensed through measurements and adaptations are affected through a closed loop control system. This could be either centralized or distributed across layers.

The adapation of parameters will be based on PHY layer parameters like channel state information (CSI), signal strength, interference level, PHY-layer resources such as spatial processing schemes, number of antenna elements and QoS parameters such as latency, throughput, BER, PER, jitter and associated priority. Due to the flexible structure of the PHY layer optimal configurations can be applied.

C. Performance of MAC Layer

The presented MAC layer has been simulated with NS-2. Two different types of traffic have been modelled, namely MPEG and constant bit rate (CBR) traffic. The average data rate of the MPEG stream was 5Mbps, whereas the CBR stream generated 1 data packet of 1000 bytes each millisecond. The channel capacity was 25 Mbps and 50 Mbps, respectively and perfect transmission in the PHY layer has been assumed. CTA size was fixed (1500 µs) and the superframe size has been set to 30000 µs. The system throughput with respect to number of data streams in depicted in Figure 7.

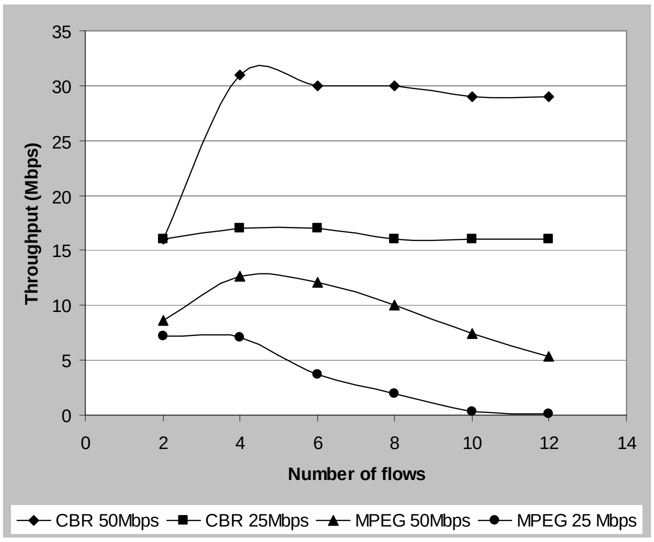

Figure 7: Throughput of MAC layer

Using CBR traffic the throughput increases linearly up to a certain level. With a channel capacity (CC) of 25 Mbps the maximum throughput reaches 16Mbps, whereas with a 25Mbps wide channel the system throughput achieves up to 32 Mbps. Using MPEG traffic the total throughput is much lower, since packet sizes and data rates vary in time domain. Further one can see that the total throughput decreases significantly with increasing number of streams if the maximum throughput has been exceeded.

IV. CONCLUSION

In this paper a new PHY layer concept for personal area networks (PANs) has been presented along with the IEEE802.15.3 MAC layer. Performance results of the new PHY layer were given for different equalization schemes. Moreover, novel adaptive schemes, which are capable to further enhance the system performance, were introduced. The system throughput of the MAC layer was shown with respect to simultaneous data streams and type of traffic. Schemes to further adapt the MAC layer along with the PHY layer to the PAN environment (e.g. in terms of interference, co-existence, QoS) were presented. Future work has to be performed to integrate the novel adaptive PHY layer schemes into the simulation environment and to combine MAC and PHY layer simulations in order to evaluate the overall system performance.

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REFERENCES

[1] R. L. Olsen, F. Fitzek, R. Prasad, J. Saarnio, ’My personal adaptive Global NET – MAGNET’, WWRF8bis, Beijing, China, 26-27 February 2004
[2] M. Presser et al, ‘MAGNET 4G Personal Area Network Air-Interfaces for Personal Networks’, IST Summit 2004, Lyon, June 2004.
[3] M. Presser, R. Tafazolli, K. Schoo, K. Strohmenger, “The MAGNET PAN Environment with respect to air-interfaces”, MAGNET Workshop, Shanghai, China, 11-12 November 2004.
[4] IST-MATRICE Project, www.ist-matrice.org
[5] IST-4More Project, www.ist-4more.org
[6] F. Bauer, E. Hemming, J. Rodrigez, ‘MC-CDMA for next generation systems, The IST projects MATRICE and 4MORE’, WWRF8bis, Beijing, China, 26-27 February 2004
[7] K. Schoo, Balamuralidhar.P, H. Choi, M. Presser, K. Strohmenger, “MC-CDMA in Personal Area Networks – A Combined PHY and MAC Approach”, MAGNET Workshop, Shanghai, China, 11-12 November 2004.
[8] MAGNET Deliverable D3.2.2a
[9] WRC, June 9 to July 4, 2003, Geneva
[10] ETSI BRAN HIPERLAN/2
[11] IEEE 802.15.3 Working Group, “IEEE standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements part 15.3”, 2003
[12] C. Mutti, D. Dahlhaus, T. Hunziker and M. Foresti, “Bit and power loading procedures for OFDM systems with bit-interleaved coded modulation”, IEEE Int. Conf. on Telecomm, (ICT), Papeete, French Polynesia, pp. 1422-1427, Feb. 2003.
[13] C. Mutti, D. Dahlhaus and D. Destefanis, “Adaptive Coding Based on LDPC Codes for OFDM Systems with HD Decoding”, in 13th IST Mobile & Wireless Comm. Summit, Lyon, France, pp. 549-553, June 2004.
[14] T. Hunziker and D. Dahlhaus, “Optimal Power Adaptation for OFDM Systems with Ideal Bit-Interleaved and Hard-Decision Decoding”, in IEEE Proc. Int. Conf. on Comm. (ICC) ’03, vol. 5, pp.11-15, Anchorage, AK, May 2003.
[15] C. Mutti, D. Dahlhaus and C. Mensing, “Channel Prediction for Adaptive Power Loading in MIMO BICM-OFDM Systems”, IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2005), submitted.