Block interleaving for soft decision Viterbi decoding in OFDM systems

Van Duc Nguyen and Hans-Peter Kuchenbecker
University of Hannover, Institut für Allgemeine Nachrichtentechnik
Appelstr. 9A, D-30167 Hannover, Germany
Phone: +49-511-762-2842, e-mail: nguyen@ant.uni-hannover.de

Abstract— **In this paper, frequency and time interleaving algorithms used for soft decision Viterbi decoding for OFDM systems, performed on frequency-selective and time-selective channels respectively, are investigated.To achieve optimal performance in terms of Bit Error Rate (BER), the size of the interleavers must be specified depending on the properties of the channel and the characteristics of the code. Under these aspects, new frequency- and time interleaving algorithms are proposed. To get the lowest BER, we have found that the frequency interleaving length should be chosen in the range of the decoding constraint length. On the other hand, the time interleaving depth should be derived from the coherence time of the channel.**

Keywords— **Interleaving, soft decision Viterbi decoding, OFDM.**

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation technique, which can easily prevent the Inter Symbol Interference (ISI) by using a guard interval. Because the frequency responses of sub-carriers are overlapped and orthogonal, the system possesses higher spectral efficiency than single carrier systems. The splitting of the total bandwidth of the system into N_C narrow bands makes sub-carriers almost flat fading (or non frequency- selective).

In the frequency- and time-selective transmission environment, the Channel Transfer Function (CTF) of the mobile channel does not change significantly in one OFDM symbol or one OFDM sub-carrier, however it changes from sub-carrier to sub-carrier in the frequency domain and symbol to symbol in the time domain. When the mobile channel is in a deep fading, some sub-carriers as well as some OFDM symbols will suffer from strong noise interference, where the amplitude of CTF is strongly attenuated. At the receiver, the Signal-To-Noise Ratio (SNR) at these positions decreases causing excessive burst-errors.

To overcome this problem, OFDM typically applies coding and interleaving which exploit different diversity methods. To achieve BER requirements for a given scenario and a required data rate, each system parameter must be optimized.

In this paper, the influences of interleaving parameters in the frequency and the time directions used for soft decision Viterbi decoding on the BER are investigated. New frequency and time interleaving algorithms are proposed to achieve low BER.

The paper is organized as follows: In section II, frequency and time interleaving algorithms are explained. The calculation of Channel State Information (CSI) used for soft decision Viterbi decoding is briefly introduced in section III. Section IV presents computer simulation results. Finally, section V concludes the work.

II. Frequency and time interleaving algorithms

A. Frequency interleaving algorithm

Frequency interleaving is used to exploit the frequency diversity in wide-band transmissions. After frequency interleaving, the local deep fading is averaged over the whole bandwidth of the system.

We design the frequency interleaver as a block interleaver which is a matrix with B_f rows and N_f columns. The coded symbols are written into the matrix by rows and read out afterwards by columns. The deinterleaver takes the coded symbol into a matrix with same size (B_f rows and N_f columns), but the symbols are written by columns and read out by rows. We define the number of rows B_f as the interleaving depth, and the number of columns N_f as the interleaving length.

It is well known that in block interleaving, the interleaving depth B_f should be chosen to be larger than maximum burst-error length b_f , the interleaving length should be chosen to be larger than the decoding span [2]. In a block code, decoding span equals the code length. In a convolutional code, the decoding span is defined as the decoding constraint length [2]. In addition, the interleaver requires memory and causes delay, so the dimension of the interleaver is a compromise between the delay and the performance of the system. Some authors (e.g. [10]) derive frequency and time interleaving parameters from system parameters, such as the number of sub-carriers N_C and the number of OFDM symbols in one OFDM frame N_F. However, these parameters do not relate to the burst-error length and the characteristics of the code.

The frequency interleaving should be implemented for all the data symbols in a single OFDM symbol. This means, that the data symbols of two neighbouring OFDM symbols should not be interleaved in one iteration. For this reason, the dimension of the frequency interleaver should be equal to the number of data symbols in a single OFDM symbol, which means

$$N_C = N_f \cdot B_f \tag{1}$$

According to [2], the decoding constraint length L strongly depends on the characteristics of the code and can be derived from the code constraint length ν (see definition in [1]) as follows:

$$L \approx k \cdot \nu \tag{2}$$

k is an integer number which depends on each code. For example in [2], satisfactory performance of BER for the code with $R = 1/2$ is achieved, if the decoding constraint length L is about 5ν. The required decoding constraint length L for the code with $R = 2/3$ is approximately 8ν, and for the code with $R = 3/4$ is about 10ν.

Assume an OFDM symbol which is located in a deep time fading. This OFDM symbol is strongly attenuated and the data symbols on all sub-carriers are probably in error. Thus, the maximum burst symbol error in frequency domain is equal to the number of sub-carriers. Furthermore, as frequency and time interleaving are implemented successively, the symbol errors in a OFDM symbol are transfered by the time interleaving to other OFDM symbols. Consequently, the length of burst-errors caused by the frequency selectivity of the channel are not predictable after the time interleaving. For this reason, it is not a reasonable task to design the interleaver under condition of a channel model, namely the maximal burst-errors in the frequency domain.

We derive the frequency interleaving algorithm from the decoding constraint length and the number of sub-carriers, as explained by the following two steps:

1. Choose the interleaving length N_f to be approximately equal to the decoding constraint length L of the applied code.
2. After determining the interleaving length, the interleaving depth B_f is derived from eq.(1) as follows:

$$B_f = \lfloor N_C / N_f \rfloor \tag{3}$$

where $\lfloor N_C/N_f \rfloor$ denotes the maximal integer, smaller or equal to N_C/N_f.

B. Time interleaving algorithm

Time interleaving is used to exploit the time diversity of the channel. After the time interleaving, the local time deep fading in some OFDM symbols is averaged over all OFDM symbols.

The block interleaving used for the time interleaving has the size of B_t rows and N_t columns. The definitions of their dimension are the same as in the case of the frequency interleaving.

As mentioned in sect.[II-A], the time interleaving depth B_t should be chosen larger than the maximum burst-error in time domain b_t. Obviously, the maximum burst error depends on the channel model, namely the vehicle speed. At very low velocity, the channel is slow fading and the burst-error becomes longer than at high velocity.

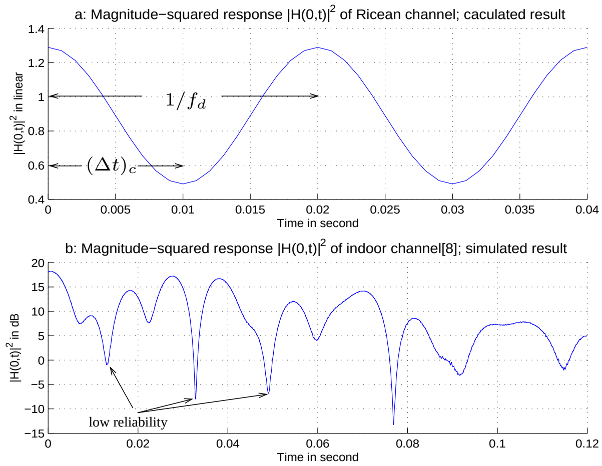

Fig. 1. Magnitude-squared response of the CTF in the time direction and according to the null sub-carrier.

Assume that the mobile channel consists of a direct path and a single path with delay τ_0 relative to the direct path. This channel is called Ricean fading channel defined in [9]. The channel impulse response of such a channel is modeled as

$$h(\tau, t) = \alpha\delta(\tau) + \beta e^{j(2\pi f_d(t)t + \theta_0)}\delta(\tau - \tau_0) \tag{4}$$

where α and β are the attenuation factor of each path. Furthermore, we assume that the channel is modeled for constant Doppler frequency f_d (the receiver moves with constant speed and unchanged direction). The CTF for this channel model in baseband is expressed as

$$H(f, t) = \alpha + \beta e^{j(2\pi f_d t + \theta_0)} e^{-j2\pi f \tau_0} \tag{5}$$

If θ_0 is 0, then the magnitude-squared of the CTF on subcarrier zero ($f = 0$) is

$$|H(0,t)|^2 = \alpha^2 + \beta^2 + 2\alpha\beta\cos(2\pi f_d t) \tag{6}$$

$|H(0,t)|^2$ is plotted in figure 1.a, where it is easy to see the deep attenuation in time domain created by the Doppler effect. In this simplified channel model, the distance from a local maximum to a next local minimum of the amplitude of the CTF is equal to the coherence time of the channel derived from Doppler frequency as follows [9]:

$$(\Delta t)_c \approx \frac{1}{2 f_{dmax}} \tag{7}$$

The time interleaving parameters are specified in such a way, that the long runs of the data symbols with low reliability corresponding to the low amplitude of the CTF are avoided. For this reason, the time interleaving depth B_t should be chosen larger than the coherence time of the channel as follows:

$$B_t \geq \frac{(\Delta t)_c}{T_S} \tag{8}$$

where T_S is the OFDM symbol duration. In reality, the run of the CTF is plotted in figure 1b, where the distance of a local maximum of the amplitude of the CTF to a next local minimum of the amplitude of the CTF is also time-variant. Therefore, there is no formula given here to specify the time interleaving parameters. However, we have concluded, that the time interleaving depth B_t needed for slow fading channels is longer than for fast fading channels. The time interleaving process is performed over a specified number of frames, which depends on the required maximal delay caused by the time interleaver. If K is the number of frames to be applied, then the time interleaving length is given as follows:

$$N_t = \lfloor K \cdot N_F / B_t \rfloor \tag{9}$$

III. Calculation of CSI used for Viterbi decoder

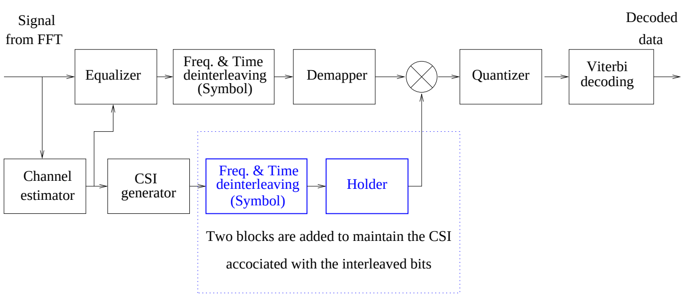

Fig. 2. Viterbi decoding using CSI

Figure 2 shows the modified version of CSI generation method from [4]. Not only the data symbols are needed to be deinterleaved at the receiver, but also the calculated CSI, to maintain the value of CSI associated with data symbols. Hence, an interleaver used for the CSI value is added parallel with the symbol interleaver.

Ref. [4] proposed a CSI calculation method which is derived from the calculation of MSE (mean square error). The MSE at the positions of pilot symbols is obtained by the information of the estimated channel and the noise power. Then these values are inverted and normalized. The calculated values above are interpolated to get the CSI at the positions of the data symbols.

We did not apply this method, but do propose another method, which is more easier to implement and is without any loss of BER performance. Only the data symbols located at deep fading of the channel are needed to multiply with the CSI before entering the Viterbi decoder. The data symbols associated with the strong CTF are assumed to be correct symbols and decoded with the CSI being 1. Therefore, the CSI is obtained by the comparison of the channel power with the noise power as follows:

$$CSI = \begin{cases} |H|^2 & \text{if} \quad |H|^2 \leq P_n \\ 1 & \text{otherwise} \end{cases} \tag{10}$$

where H is the channel transfer function, which is obtained by the channel estimator introduced in [5], and P_n is the noise power.

IV. Simulation results and discussion

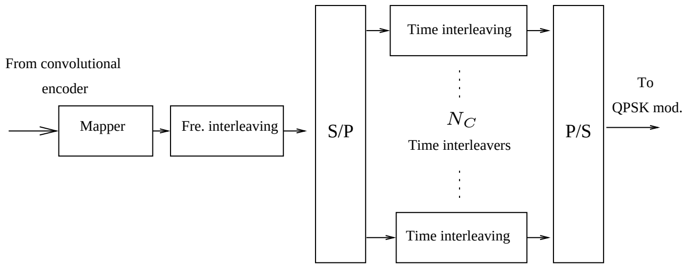

Fig. 3. Block diagram of frequency and time interleavers.

Figure 3 shows the block diagram of the time and frequency interleavers at the transmitter. At first, the coded symbols of each OFDM symbol are taken into the frequency interleaver. After frequency interleaving, the coded symbols are converted to N_C parallel paths. On each parallel path, the time interleaving is performed over a specified number of frames. At the receiver, the deinterleaver performs the inverse function of the interleaver (not shown for brevity).

The parameters of HIPERLAN type 2 as defined in [3] are used for simulation. The number of sub-carriers N_C is assumed to be equal to the FFT length N_{FFT}. The FFT length is varied to stress out that the necessary frequency interleaving length is independent of the FFT length. Varying N_{FFT} , i.e. varying symbol duration affects the performance of the system [6]. While designing interleaving parameters we consider the sole aspect of interleaving performance.

Simulations are performed under the typical office environment, channel model A, which is described in [8]. The channel consists of 18 paths with a maximal time delay of 390 ns. The maximum Doppler frequency on each path is 50 Hz according to the pedestrian's speed of 3 m/s and the carrier frequency at 5GHz. The effect of the frequency interleaving length on BER for different N_{FFT} is tested. In this phase, the time interleaver is not applied. The modulation in the baseband and on each sub-carrier is QPSK. The convolutional code with parameters R=1/2, $\nu = 6$ is used. The results, which are plotted in figure 4, show that the lowest BER is achieved when the frequency interleaving length is approximately the decoding constraint length. For instance, the R $= 1/2$, $\nu = 6$ code has the decoding constraint length $L \approx 5\nu$, and therefore the frequency interleaving length should be in the range of 30. This result is independent of the FFT length. However, increasing FFT length is equivalent to increasing the OFDM symbol duration T_S. Thus, the effective energy per bit is increased, if the guard interval length is kept constant. At the same SNR level, when the results

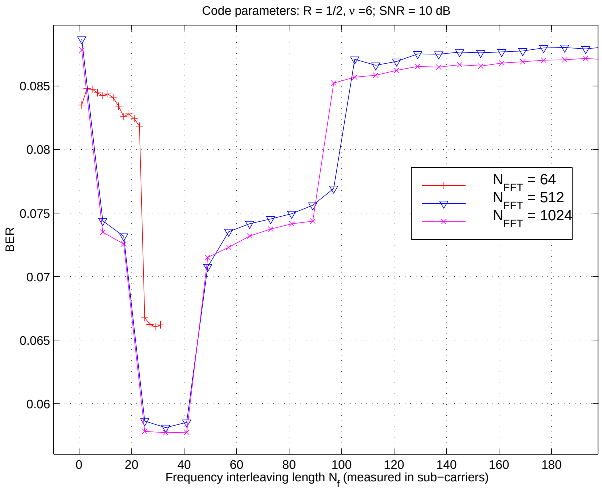

Fig. 4. Influence of the frequency interleaving length N_f on the BER tested for different N_{FFT} length

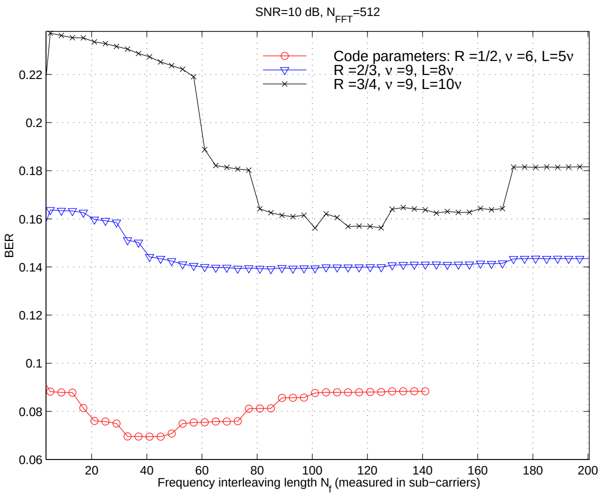

Fig. 5. Influence of the frequency interleaving length N_f on the BER tested for different codes

of $N_{FFT} = 64, 512, 1024$ are compared, increasing FFT length improves BER performance.

In figure 5, the influence of the frequency interleaving length on BER is tested for different codes with parameters: $R = 1/2, \nu = 6$; $R = 2/3, \nu = 9$ and $R = 3/4, \nu = 9$. The necessary frequency interleaving lengths taken from simulation results are compared with the necessary decoding constraint lengths in Table I.

The frequency interleaving length need not be chosen exactly equal to the decoding constraint length. However in this range the satisfactory performance of BER can be achieved. With the increase of N_f over the range of the decoding constraint length, B_f resulting from (1) decreases. This leads to the increase of the BER as shown in figure 5.

If higher modulation levels like 16-QAM and 32-QAM are used, the necessary frequency interleaving lengths for

TABLE I

COMPARING DECODING CONSTRAINT LENGTH WITH NECESSARY FREQUENCY INTERLEAVING LENGTH.

Code parameters	L	N_f
R = 1/2 $\nu = 6$	5ν	30-42
R = 2/3 $\nu = 9$	8ν	70-85
R = 3/4 $\nu = 9$	10ν	90-125

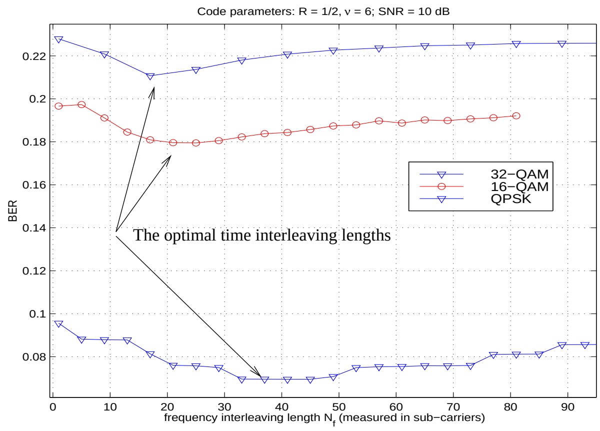

Fig. 6. Influence of the frequency interleaving length N_f on the BER tested for different modulators

a given code becomes shorter as shown in figure 6. This result can be explained: For example one interleaved symbol of 16-QAM corresponds to two interleaved symbols of QPSK. Therefore, the decoding constraint length for a fixed code is constant, but the necessary frequency interleaving length becomes theoretically two times shorter.

The purpose of the simulation as shown in figure 7.a was to determine the effect of the time interleaving depth on the BER. At first, we did not use the frequency interleaver. The time coherence $(\Delta t)_c$ of channel model A in [8] according to eq.(7) is: $(\Delta t)_c = 1/(2f_d) = 0.01$s. This corresponds to $(\Delta t)_c/T_S = 3125$ OFDM symbols. The simulation results show that the performance of BER is improved slowly, i.e. the BER is decreased, until the time interleaving depth reaches around 1950 OFDM symbols (corresponding to 0.00624s). This effect can be explained as follows: If the time interleaving depth is increased, such that data symbols corresponding to a local minimum of the CTF are exchanged to the data symbols corresponding to a local maximum of the CTF, then the burst-error of data symbol is well distributed. On further increasing the time interleaving depth, we see that, in the range of 1950 to 3000 OFDM symbols, the BER is slightly increased. This is so, because in this range the data symbols corresponding to a local minimum of the CTF are exchanged to other data symbols corresponding to another local minimum of the CTF (see the run of CTF in figure 1). In the interleaving matrix, burst-errors appear in the same rows and adjacent columns. Consequently, burst-errors are still

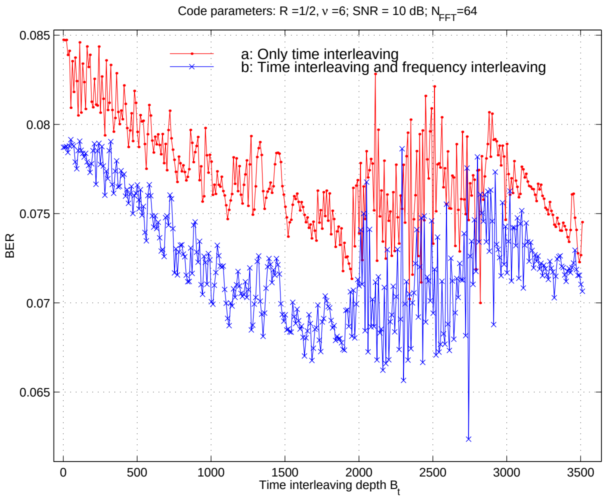

Fig. 7. Influence of the time interleaving depth B_t measured in OFDM symbols on the BER

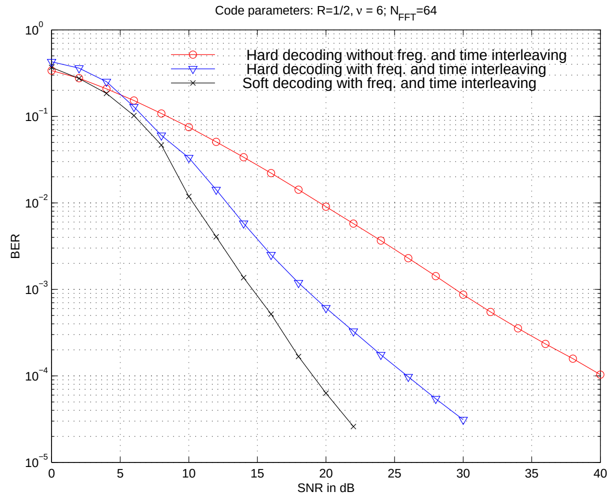

Fig. 8. Time and frequency interleaving are applied for soft decision Viterbi decoding

remaining after interleaving. Above this range of the interleaving depth, the BER will decrease slightly again and so on, until the time interleaving depth is long enough such that the data symbols at the output of the deinterleaver are memoryless. This means the symbol burst-errors are evenly distributed.

Comparing with the results in [7], in which the typical urban channel was performed, it becomes clear that the necessary time interleaving depth in typical office channel is longer than in the typical urban channel. These results are predictable, because the typical office channel simulated in this work is regarded as a slowly fading channel ($(\Delta t)_c$ equivalent to 3512 OFDM symbols), whereas the typical urban channel simulated in [7] is considered as a fast fading channel ($(\Delta t)_c$ is approximately equivalent to 100 OFDM symbols).

In practice, the results which are gained without the frequency interleaving are not relevant because the frequency diversity is not exploited yet. After applying the frequency interleaver, the results in figure 7.b show that when both frequency diversity and time diversity are exploited the BER decreases with an increase of the time interleaving depth. Figure 8 shows the performance of BER for hard- and soft decision Viterbi decoding using CSI information, which is generated by the method in (10). The interleaving parameters used are: $N_f = 32$ (10MHz), $B_f = 2$ (0.625 MHz); $N_t = 64$ (0.2048 ms), $B_t = 3512$ (11.238 ms). To apply soft decision Viterbi decoding, the CSI values have thus to be deinterleaved to keep their values associated with the data symbols before entering the decoder.

V. Conclusion

New frequency and time interleaving algorithms which were derived from the characteristics of the code and the channel profiles are proposed. The frequency interleaving length should be chosen in the range of the decoding constraint length. After interleaving in the frequency domain, the time interleaver is performed in parallel. While designing the time interleaving, the necessary time interleaving depth depends on the individual channel models. The coherence time of the channel should be taken into account while choosing the time interleaving depth. The application of these algorithms for soft decision Viterbi decoding is considered. Furthermore, a simple method used for the calculation of CSI derived from the noise power and the channel power is proposed. The combination of these algorithms leads to satisfactory results concerning the BER.

References

[1] Bossert, M. *Channel Coding for Telecommunications* John Wiley & Sons Ltd, England, 1999.

[2] Clark, G. C.; Cain, J. B. *Error-Correction Coding for Digital Communication* New York, Plenum Press, 1981.

[3] ETSI DTS/BRAN-0023003 *HIPERLAN Type 2 Technical Specification; Physical(PHY) layer.* 1999.

[4] Lee, W.- C.; Park, H.-M; Park, J.-S. *Viterbi decoding method using channel state information in COFDM system* IEEE Trans. on Consumer Electronics, Vol. 45, No. 3, August 1999.

[5] Nguyen, V. D.; Hansen, C.; Kuchenbecker, H.-P. *Performance of Channel Estimation Using Pilot Symbols for a Coherent OFDM System.* WPMC'00, November 2000, Bangkok, Thailand.

[6] Nguyen, V. D.; Kuchenbecker, H.-P. *Intercarrier and Intersymbol interference analysis in OFDM Systems over fading channels.* 6^{th} International OFDM-Workshop 2001, Hamburg. In press.

[7] Nguyen, V. D.; Kuchenbecker, H.-P. *Interleaving algorithm for soft decision Viterbi decoding in OFDM systems over fading channels.* IEEE International Conference on Telecommunication, Juni 2001, Romania.

[8] Medbo, J.; Schramm, P. *Channel Model for HIPERLAN/2 in Different Indoor Scenarios.* ETSI EP BRAN 3ERI085B, 30 March 1998.

[9] Proakis, J.G. *Digital Communications* 3. edition, New York: McGraw-Hill, 1995.

[10] Thibault, L.; Le, M. T. *Performance Evaluation of COFDM for digital audio broadcasting part I: Parametric Study* IEEE Trans. on Broadcasting, Vol. 43, No. 1, March 1997