Journal of Theoretical and Applied Information Technology
10th October 2014. Vol. 68 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

LTE STANDARD: CHANNEL ESTIMATION ALGORITHMS FROM THE BASE STATION TO THE TERMINAL

ABDELHAMID LARAKI & DRISS EL OUADGHIRI, ABDELLAH JAMALI
Dept. of computer Science and Mathematics, My Ismail University-Meknes, FSM, Morocco
Dept. of Computer Science and Mathematics, Hassan 1st University-Settat, ESTB, Morocco
E-mail: abdelhamid-laraki@hotmail.fr & dmelouad@gmail.com, Abdellah.Jamali1@gmail.com

ABSTRACT

This report deals with the LTE downlink transmission scheme, from the base station to the terminal (the mobile phone), which is based on multicarrier modulation: OFDM (Orthogonal Frequency Division Multiplexing). LTE also supports the use of multiple antennas at both the base station and the terminal to improve communication performance: Multiple Input – Multiple Output (MIMO) antenna processing.

The project focuses on the different methods for estimating the time-varying channel between the transmitter and the receiver: to carry out coherent demodulation, the mobile terminal requires estimates of the downlink channel, and to allow this, known symbols are inserted in the transmitted signal.

Keywords: *Analog Baseband - Orthogonal Frequency-Division Multiplexing (OFDM) - End Module - LTE*

1. INTRODUCTION

This document is a summary of work on the articles published in the proceeding of MoMM2013 conferences: International Conference on Advances in Mobile Computing & Multimedia 2.

The investigated methods of Channel estimation algorithms for MIMO-OFDM systems are evaluated by simulations in Matlab, using various channel models, and the best algorithm, in terms of performance, is developed in C/C++. Another important point concerning this estimation is to take into account the MIMO technology: either each channel between two antennas is estimated independently from the others, either spatial correlation is taken into account.

This report presents five different algorithms for channel estimation. In the last part the best method is determined and the MIMO aspect is studied.

In order to detect the received signal correctly, an accurate channel estimate is necessary and it is important to choose a fitted algorithm. A comparative investigation on five different channel estimation methods is thus presented here, concerning SISO (Single-Input Single-Output) systems.

The Matlab program will use existing C programs that create the emitted signal, the channel, and the received signal. This C code is integrated with Matlab thanks to Mex-files (Matlab Executable files): they allow to call C programs directly from Matlab as if they were Matlab built-in functions. The channel theoretical response is available thanks to the channel generation part, and it will be compared with the estimated one.

2. STUDY OF DIFFERENT ALGORITHMS

For the five estimation methods that have been chosen, the interpolation is realized each subframe, it corresponds to two slots or fourteen OFDM symbols. The frequency interpolation is first performed, with different algorithms, and allows to estimate the channel on all the subcarriers of the OFDM symbols that contain pilot symbols. Common for all methods is then the utilization of linear interpolation [1] in the time-domain. This allows to estimate the channel on the OFDM symbols that do not contain any pilot symbols, by using the two neighboring OFDM symbols with pilot symbols.

In all the cases, the results of the frequency interpolation of the previous iteration are saved in order to allow the time interpolation of the last symbols (number 13 and 14) as illustrated in Figure 1. Indeed, for this interpolation, the previous iteration is not needed as the first OFDM symbol includes pilot symbols, but the next iteration is required for the two last symbols (13 and 14) which do not have any pilot symbols.

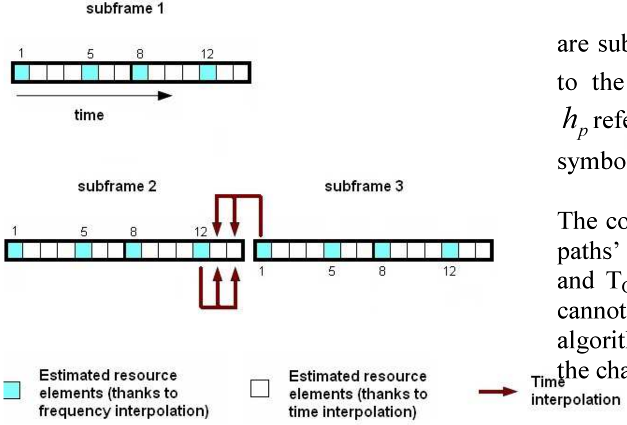

Figure 1 : Time interpolation for symbols 13 and 14

In all these methods, $\widetilde{H}$ refers to the least squares channel estimate in frequency domain at pilot positions, with P the number of pilot symbols:

$$\widetilde{H}_p = X_p^{-1} Y_p$$

for p = 1 to P

It allows to evaluate channel estimation by simply dividing the received data by the transmitted data (when they are known, i.e. on pilot carriers), but it gives a noisy channel estimation as the noise signal is not taken into account.

For each algorithm, a graph of the estimated and theoretical frequency responses is presented to illustrate the method. This graph is obtained for N_{FFT} = 512, a 15 dB signal to noise ratio, and the same multipath channel called EPA with a Doppler frequency of 70 Hz. The error measured is the mean square error (MSE) between the estimated and the theoretical frequency responses.

I A. ROM

The first method consists in a robust Wiener filtering described in [2]. Only the first stage is implemented, as the other iterations require a decoder. The pilot symbols are used to obtain the estimation of the channel transfer function:

$$\hat{H}_{RWF} = C_{hh_p}\left(C_{h_p h_p} + \frac{\beta}{SNR} I_P\right)^{-1} \widetilde{H}_P$$

In this equation, $\widetilde{H}_P$ is the noisy channel estimate on all pilot symbols (vector of size P), β is a constant that depends on the modulation, I_P is the identity matrix and C_{hh_p} (size N_{FFT}xN_P), $C_{h_p h_p}$ (size N_PxN_P) are subsets of the covariance matrix C_{hh}. h refers to the N_{FFT} subcarriers filled with symbols and h_p refers to the N_P subcarriers that contain pilot symbols.

The covariance matrix is defined assuming that the paths' delays are uniformly distributed between 0 and T_{CP}, the time length of the cyclic prefix. We cannot use the real parameters of the channel as the algorithm has to be robust (it has to work whatever the channel):

$$C_{hh} = \frac{1 - e^{\left(-2j\pi \frac{T_{CP}-1}{T_0} \frac{k-n}{N_{FFT}}\right)}}{2j\pi \frac{T_{CP}-1}{T_0} \frac{k-n}{N_{FFT}}}$$

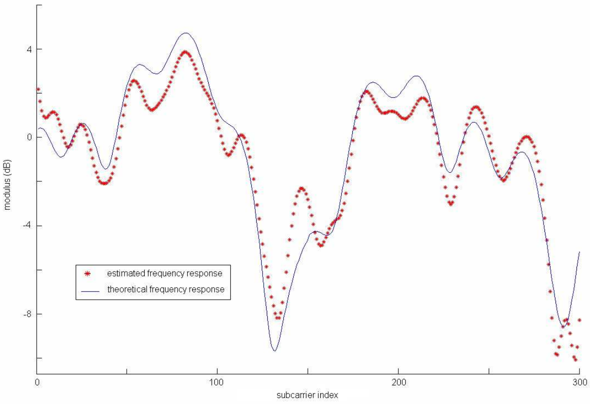

Figure 2 : Channel frequency response for Rom's algorithm

The graph in Figure 2 shows the modulus of the frequency responses depending on the subcarrier index (NSC = 300 different values). In this case, Rom's algorithm gives a good estimation, the MSE equals 0.028448

II B. BELVÈZE

This method is a local interpolation based on Wiener filtering that my supervisor used for the DVB-H. Let be 2P the number of taps in the Wiener filter. This means that to obtain an estimate on carrier n, we will use P noisy estimates on carrier indexes lower than n and P noisy estimates on carrier indexes greater than or equal to n. The vector of 2P noisy estimates is:

As there is one pilot symbol every six subcarriers, six vectors are calculated beforehand and give the estimate of a subcarrier k considering z, its position compared to the nearest previous pilot symbol. They depend on the channel autocorrelation R_n and the variance σ^2 of $\widetilde{H} - H = \frac{N}{X}$:

$$a_z = \begin{bmatrix} R_0+\sigma^2 & R_6 & \dots & R_{12P-6} \\ R_{-6} & R_0+\sigma^2 & \dots & R_{12P-12} \\ \dots & \dots & \dots & \dots \\ R_{-12P+6} & R_{-12P+12} & \dots & R_0+\sigma^2 \end{bmatrix}^{-1} \begin{bmatrix} R_{6P-6+z} \\ R_{6P-12+z} \\ \dots \\ R_{-6P+z} \end{bmatrix}$$

for z = 0 to 5

The subcarrier estimate is then:

$$\hat{H}(k) = \widetilde{H}_{2P,z} \times a_z$$

The channel autocorrelation R_n is evaluated assuming a time distribution of power according to a χ^2 law, as shown in Figure 3:

$$\sigma^2(t) = \frac{2t}{\sum^2} \exp\left(\frac{t^2}{\sum^2}\right)$$

This algorithm required an adjustment in the value of $\sum^2$ that has to be smaller than for the DVB-H. I chose to express it according to the maximum delay of the paths and, after multiple tests, the best value is: ∑=delay_max/2.5.

$$\widetilde{H}_{2P,n} = \left(\widetilde{H}_{n-6P} \quad \widetilde{H}_{n-6P+6} \quad \dots \quad \widetilde{H}_n \quad \dots \quad \widetilde{H}_{n+6P-12} \quad \widetilde{H}_{n+6P-6}\right)$$

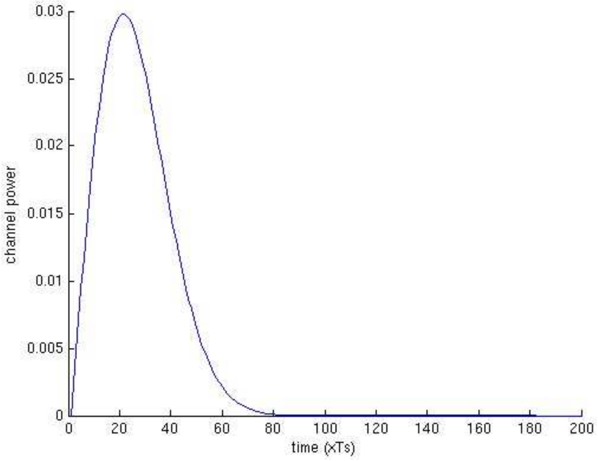

Figure 3 : Channel power for NFFT = 1024 i.e. TS = 65ns

Considering the simulation results, the best performance is obtained for P=2 i.e. 4 pilot symbols used for estimating the channel on each subcarrier.

The graph on Figure 4 shows that the estimation is rather good with a MSE of 0.027246.

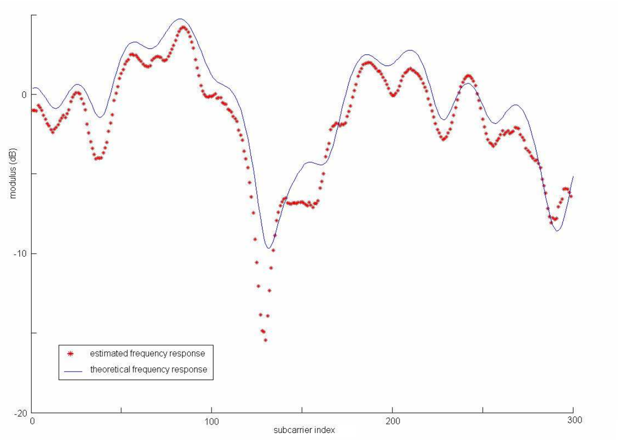

Figure 4 : Channel frequency response for Belvèze's algorithm

III C. MANOLAKIS

The authors propose in [3] a local interpolation based on the two pilots in the resource block plus the two neighboring pilots as illustrated in Figure 5. This constitutes a compromise as using all the pilot symbols is of too high complexity for real time implementation, and only using the two pilots of the resource block degrades considerably the performance.

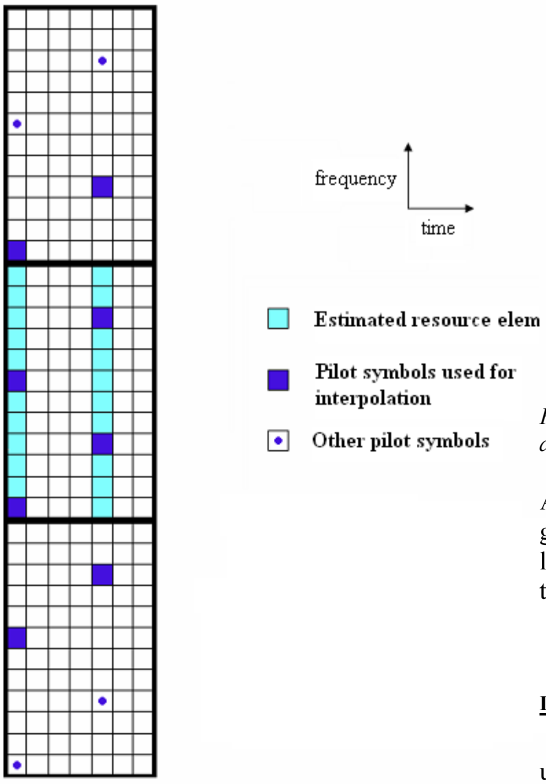

Figure 5 : Local interpolation on a resource block

$$\hat{H}_{RWF} = F_{CL} R_{hh} F_{PL}^{*} (F_{PL} R_{hh} F_{PL}^{*} + \frac{I}{snr})^{-1} H_{pilots}$$

The interpolation is then performed with a linear minimum mean square error (LMMSE) filter which depends on the channel autocorrelation matrix R_{hh} and on the FFT matrices:

Considering the results, this method gives a good estimation with less complexity, especially if the channel is almost constant.

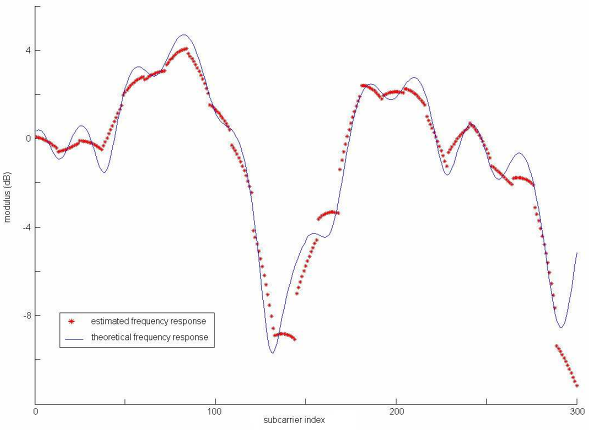

Figure 6 : Channel frequency response for Manolakis' algorithm

As we can see on Figure 6, the results are rather good considering the fact that the interpolation is local: the MSE equals 0.01247 and is even lower than Rom's value.

IV D. LAGRANGE INTERPOLATION

Lagrange interpolation [1] consists in finding the unique L^{th}-order polynomial that exactly passes through L+1 distinct samples of a signal. The estimate value for the subcarrier x equals:

$$\hat{H}(x) = \sum_{i=0}^{L-1} \hat{H}(x_i) l_i(x)$$

where:

$$l_i(x) = \prod_{j=0, j\neq i}^{L-1} \frac{x - n_j}{n_i - n_j}$$

where x denotes the subcarrier position,
where n_i denotes the ith pilot's position,
and where $H(x_i)$ is the estimate value for the pilot i.

But all the subcarriers cannot be taken into account (order 49 for N_{sc}=300), they are divided into smaller parts. In fact the best performance is obtained for order 1, which corresponds to a basic linear interpolation.

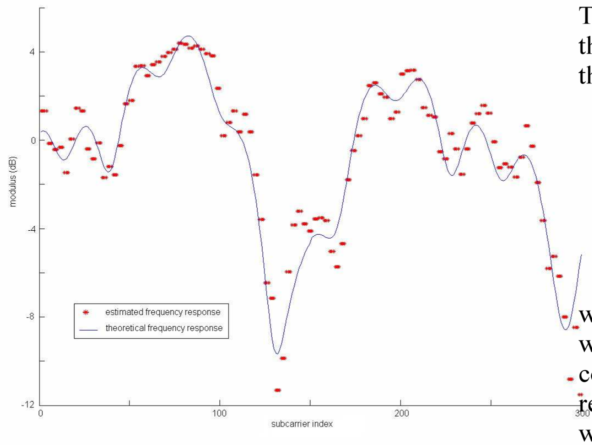

Figure 7 : Channel frequency response for Lagrange's algorithm

This last estimation, illustrated in Figure 7, gives a MSE of 0.018819, which is very satisfying.

V E. ANCORA

Ancora's method described in [4] uses least square (LS) channel estimation but the formula requires the inversion of an LxL matrix which turns out to be ill-conditioned (L is the number of sampling periods corresponding the channel length).

The authors consider an interesting solution: due to the LTE OFDM symbol structure, a large portion of the band is not used (only N_{SC} subchannels over N_{FFT} carry useful information). All the previous methods could estimate the channel on all the N_{FFT} subcarriers whereas this algorithm is suited to reduced channel estimation (only for N_{SC} subcarriers). By decreasing the sampling frequency by a factor of 2/3 (which still ensure the absence of aliasing in all cases, as at least 1/3 of the subcarriers are unused for transmission), the channel could be sounded only in the excited band.

Practically, it means that the channel is not estimated in all the L taps but only in 2 out of 3 taps:

$$\hat{h} = (h_0 \quad h_1 \quad 0 \quad h_3 \quad h_4 \quad 0 \quad h_6 \quad h_7 \quad 0 \ldots)^T$$

This method gives a proper estimation, but only in the band of interest (the N_{SC} central subcarriers), thanks to the Least Square criterion:

$$\begin{cases} \hat{h}_{ds} = (F_{ds}^H A_p^H A_p F_{ds})^{-1} F_{ds}^H A_p^H F \times y \\ \hat{H}_{ds} = F \times \hat{h}_{ds} \end{cases}$$

with F the Fourier matrix of size N_{FFT}xL ;
with F_{ds} the Fourier matrix F where the columns corresponding to the removed taps of h are removed;
with A_p the $N_{FFTx}N_{FFT}$ diagonal matrix containing non-zero elements in the position of the transmitted pilot symbols;
with y the time domain received signal.

For N_{FFT}=2048 points, as the matrix $F_{ds}^H A_p^H A_p F_{ds}$ is badly conditioned, the inversion is replaced with a pseudo-inversion.

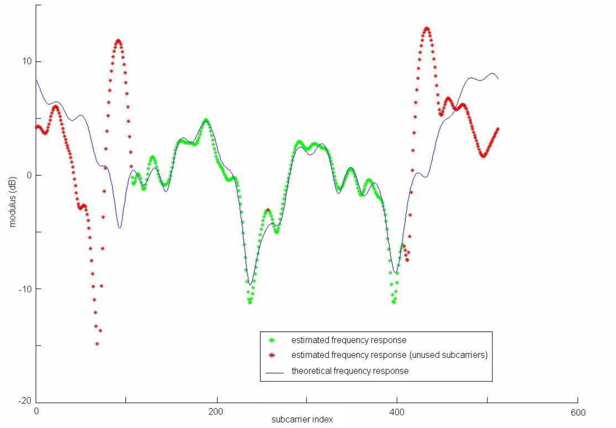

Figure 8 : Channel frequency response for Ancora's algorithm

As we can see in Figure 8, the method gives a proper estimation, but only on the NSC=300 central subcarriers. The estimation is really satisfying: the MSE equals 0.008733.

However here we have seen the results of the five algorithms only in one particular case, a real comparison will be realized in the next part.

3. DETERMINATION OF THE BEST METHOD

3. 1- SIMULATIONS

The best algorithm will be determined by realizing simulations with different parameters varying:

- the size of the FFT (we chose three sizes among the five available: 128 with 6 resource blocks, 512 with 25 resource blocks, and 2048 with 100 resource blocks) ;
- the value of the SNR (5, 10, 15, 20 and 25 dB)
- the channel models.

In order to have significant results, simulations are realized on extended duration (50 seconds if f_D=5 Hz, 10 seconds otherwise, i.e. 50000 or 10000 iterations).

The LTE standard [5] proposes five channel models representing different multipath propagation conditions. They consist of two parts: the delay profile and the maximum Doppler frequency. The delay profile gives, for each path, the travel delay and the power relatively to the emitted signal power.

There are three delay profiles selected to be representative of low, medium and high delay spread environments: Extended Pedestrian A model (EPA) Extended Vehicular A model (EVA) Extended Typical Urban model (ETU). The ETU model, with a large maximum travel delay, applies to some extreme urban, suburban and rural cases which occur seldom but which are important in evaluating LTE performance in the most challenging environments. These delay profiles are combined with a maximum Doppler frequency to define the five channel models that will be used for the simulations:

In order to simplify the comparison, the delays are expressed in number of sampling periods, so if two values cannot correspond to two different numbers of sampling periods, they are merged into one and their normalized power are added ; there are thus 2 paths for EPA, 5 paths for EVA and for ETU.

The performance is measured using the mean square error (MSE) between the theoretical and the estimated frequency response.

3. 2 - Simulation Results

The best algorithm has to be determined considering simulation results but also considering its complexity, i.e. the resources used to estimate the channel frequency response.

Concerning the channel model EPA, the best results are obtained for Manolakis' and Ancora's algorithms. For N_{FFT} = 128, Ancora's MSE is more than 5 dB better than Manolakis for high values of SNR, whereas for N_{FFT} = 512 (cf. *Figure 11*) and N_{FFT} = 2048, Manolakis' MSE is, in average, around 2 dB better

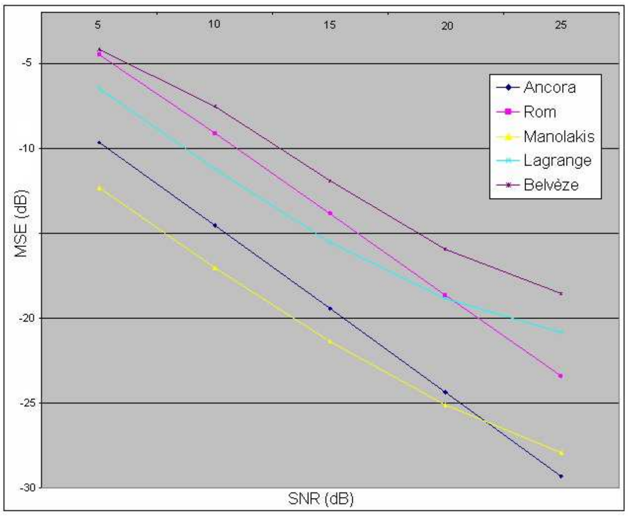

Figure 9 : Values of MSE for channel model EPA 5Hz and NFFT = 512

Concerning the channel model EVA, the best results are also obtained for Manolakis' and Ancora's algorithms, but for N_{FFT} = 2048 (cf. *Figure 12*), Manolakis' MSE notably increases for high values of SNR (the difference with Ancora can reach 12 dB).

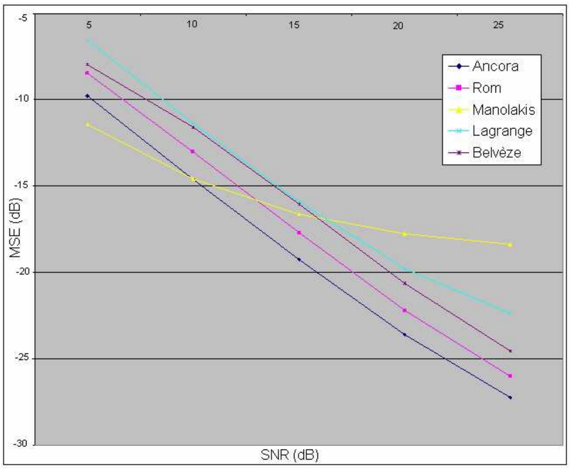

Figure 10 : Values of MSE for channel model EVA 70Hz and NFFT = 2048

Concerning the channel model ETU, Ancora's algorithm gives good results whatever the FFT size. Manolakis is rather good for low values of N_{FFT} and Belvèze is very satisfying for N_{FFT} higher than 512 (cf. *Figure 13*)

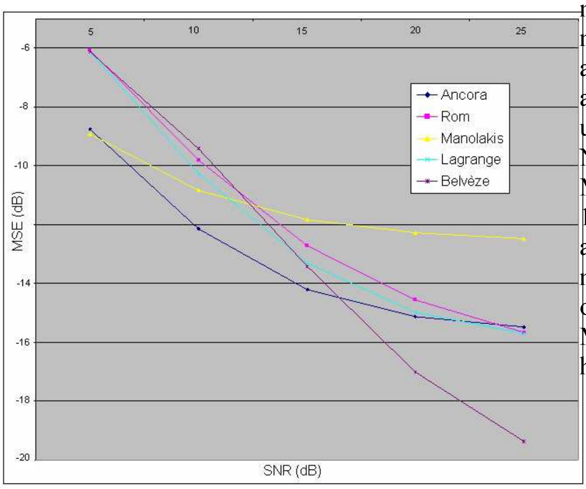

Figure 11 : Values of MSE for channel model ETU 300Hz and NFFT = 512

	Ancora	Rom	Manolakis	Lagrang	Belvèze
Mean MSE	0.0431	0.1277	0.0499	0.0864	0.1335

The mean value of all the MSE (for the five channel models, the five values of SNR and the five FFT sizes) shows that Ancora's algorithm gives the best results and its advantage compared with Manolakis' is that it gives good results in all the cases:

3. 3 - Complexity Study

The complexity of the algorithms is determined by calculating the number of multiplications and additions realized at each iteration for the five methods. L is the number of sampling periods corresponding to 2/3 of the cyclic prefix, nb_path is the number of paths, N is the number of points of FFT, N_{SC} is the number of useful subcarriers, N_{RB} is the number of resource blocks and N_P is the number of pilot symbols for one OFDM symbol.

Concerning Ancora, there is two matrix multiplications (product of a matrix LxN and a matrix Nx1; product of a matrix N_{SC}xL and a matrix Lx1) that have been improved. Belvèze's algorithm needs N_{SC} products of a matrix 1x2M and a matrix 2Mx1 (2M is the number of pilot symbols used for the estimation). Lagrange only requires N_{SC} multiplications and N_{SC} additions. Concerning Manolakis, there are NRB_DL products of a matrix 12x4 and a matrix 4x1. And finally, for Rom's algorithm, a product of a matrix N_{SC} x N_P and a matrix Npx1 is realized each iteration. As a product of a matrix MxN and a matrix NxP consists in MP(N-1) additions and MPN multiplications, we have the complexity results:

	Number of additions	Number of multiplications
Ancora	$(N+N_{SC})(L+2)+12$	$(N+N_{SC})(L+2)+16$
Belvèze	$(2*M-1)\ N_{SC}$	$2*M*N_{SC}$
Lagrange	N_{SC}	N_{SC}
Manolakis	$36N_{RB}$	$48N_{RB}$
Rom	$(N_P - 1)\ N_{SC}$	$N_P * N_{SC}$

Manolakis' algorithm is both simple and adequate; however its performance is greatly reduced for high values of SNR. Ancora's algorithm performs significantly better than the others, whatever the FFT size or the SNR, and its complexity is acceptable: it corresponds to 637 MIPS (million instructions per second) in the worst case ($N_{FFT} = 2048$).

Based on the above results, the best method to estimate the channel is Ancora's algorithm.

4. MIMO

At this point, we have only studied the case of one transmit antenna and one receive antenna. If multiple antennas are used, we can estimate the channel separately for each couple transmit/receive antennas, using Ancora's algorithm.

But, as spatial correlation cannot be avoided in real MIMO systems, we can take it into account to realize the estimation. In Luo's paper [6], a general minimum mean square error (MMSE) channel estimation algorithm is proposed for MIMO-OFDM systems. It can make full use of the channel correlation in space, time and frequency to estimate the channel state information (CSI). In real conditions, time and frequency correlations are unknown but in order to implement this algorithm, we have first considered them as known. The complex formula given in this paper shows that the CSI estimate depends on the mean values and variance of transmit symbols. In our case, as some pilot symbols are inserted with a known pattern, the mean values and the variances are known.

The number of iterations is reduced in order to keep reasonable simulation times: 5000 and 20000 iterations for 2x2 antenna configuration, 2500 and 10000 iterations for 4x4 antenna configuration. The correlation matrices have been set according to the standard [7]

Ancora's algorithm shows almost the same performance for single or multiple antenna transmission, it appears satisfying. For single antenna transmission, Luo's algorithm gives extremely interesting results (the values of MSE are below all others), especially for high values of SNR and high values of FFT size. This method gives better mean square errors than other algorithms in all the cases, as it is based on optimal MMSE (Minimum Mean Square Error) whereas the five algorithms studied before use approximations.

For multiple antenna transmission, Luo's method gives even better results: the use of spatial correlations has really improved the channel estimation (especially when SNR is low), compared with Ancora's algorithm for MIMO systems and also compared with Luo's algorithm for single antenna configuration. For 4x4 antenna configuration, the MSE is even lower than for 2x2 antenna configuration, it shows that using the spatial correlations is very interesting in terms of performance.

The example given in Figure 12 shows that, for the exact same case, Luo's estimation is more accurate: the MSE for Luo's algorithm equals 0.0074, and the MSE for Ancora's algorithm is 0.1000.

However, the complexity of Luo's algorithm is much more important as it constitutes a real Wiener filter. In case of 1x1 antenna configuration, there is a product of a matrix NSC x NSC and a matrix NSC x 1 every iteration, so there are (NSC -1) NSC additions and NSC^2 multiplications, and the number of operations is more than three times as big as for Ancora's algorithm:

	N = 128		N = 512		N = 2048	
	Additions	Multiplications	Additions	Multiplications	Additions	Multiplications
Ancora	1,602	1,606	21,124	21,128	318,31	318,32
Luo	5,112	5,184	89,700	90,000	1438,8	1440,0

Obviously, Luo's method is computationally inefficient for practical applications: it corresponds to 2879 MIPS (million instructions per second) in the worst case and no existing smart phone can execute so many instructions real-time.

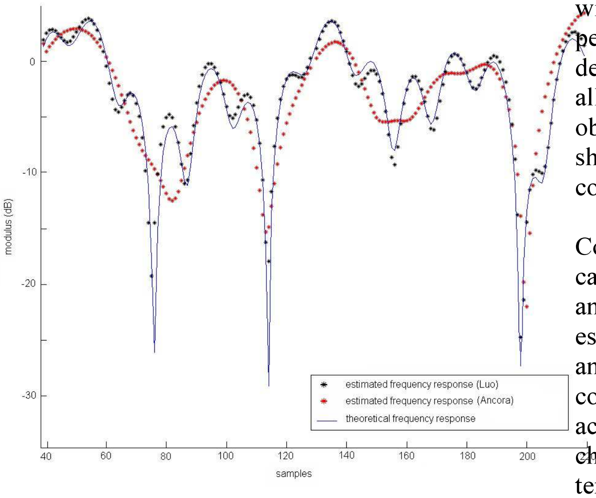

Figure 12 : Channel Estimation For Luo's And Ancora's Algorithms

5. CONCLUSION

In this report, the problem of channel estimation for the downlink of MIMO-OFDM systems in mobile communications is investigated. For the transmission over time-varying and frequency-selective fading channels, the receiver requires an estimation of the channel transfer function in both time and frequency domains. The received pilot signals are used to perform channel estimation, given the fact that pilot symbols are transmitted on predetermined resource elements.

Five robust channel estimation algorithms are described: all methods use linear interpolation in time domain, after different frequency interpolations (local or not). In order to determine the best algorithm, they are all compared, in terms of performance and complexity. Simulations are realized for five channel models (with different delay spreads and different Doppler frequencies), for three FFT sizes and for five values of SNR. The performance of these algorithms is measured thanks to the mean square error between the estimate and the theoretical frequency response, and the complexity is evaluated comparing the number of operations necessary to give the estimate.

Manolakis' algorithm, based on a local interpolation over the four neighbouring pilot symbols, appears simple and rather satisfying, except for high values of SNR. Ancora's algorithm realizes a simplified least square channel estimation and it performs significantly better than the others, with a reasonable complexity. The reliable performance of this proposed method has been demonstrated in single-antenna systems. Based on all the results, the best channel estimation is obtained with Ancora's algorithm: this method shows a good performance and an acceptable complexity, at least for simulation purposes.

Concerning MIMO systems, Ancora's algorithm can be used, considering each couple transmit antenna – receive antenna as a whole channel to estimate. It gives good results for 2x2 and 4x4 antenna configurations. However, there are spatial correlations between antennas that can be taken into account. Luo's algorithm makes full use of these channel correlations and gives excellent results in terms of performance, but has high computational complexity and needs to know the frequency and time correlations of multipath channels. One way to both improve the performance results and keep a reasonable complexity would be to combine Ancora's algorithm with the part of Luo's algorithm concerning the spatial correlations between antennas.

REFERENCES:

[1] Chen Weiwei, Zhu Qi , "Research on interpolation methods for channel estimation in the MIMO-OFDM systems", Wireless Communications, Networking and Mobile Computing, 2007

[2] Luis Ángel Maestro de Temiño, Carles Navarro i Manchón, Christian Rom, Troels B. Sorensen and Preben Mogensen, "Iterative channel estimation with Robust Wiener Filtering in LTE Downlink", Vehicular Technology Conference, 2008

[3] Konstantinos Manolakis, Andreas Ibing and Volker Jungnickel, "Performance evaluation of a 3GPP LTE terminal receiver," in proc. 14th European Wireless Conference, pp. 1-5, June 2008

[4] Andrea Ancora, Calogero Bona and Dirk T.M. Slock, "Down-sampled impulse response least-squares channel estimation for LTE OFDMA", Acoustics, Speech and Signal Processing, 2007

[5] 3GPP TS 36.101 V.8.3.0, "User Equipment (UE) radio transmission and reception

[6] Zhendong Luo and Dawei Huang, "Optimal and robust MMSE channel estimation for MIMO-OFDM systems", Personal, Indoor and Mobile Radio Communications, 2008

Zhendong Luo and Dawei Huang, "General MMSE channel estimation for MIMO-OFDM systems", Vehicular Technology Conference, 2008

[7] 3GPP TS 36.211 V.8.4.0, "Physical Channels and Modulation".

[8] Spécification technique 3GPP TS 36.331, E-UTRA, Radio Resource Control (RRC), Protocol

specification, v8.16.0, décembre 2011.

[9] Spécification technique 3GPP TS 23.401, General Packet Radio Service (GPRS)

enhancements for E-UTRAN access, v8.16.0, mars 2012.

[10] Circuit-Switched Voice Services over HSPA, Qualcomm Incorporated, 2009.

Spécification technique 3GPP TS 25.331, UTRA, Radio Resource Control (RRC), Protocol

[11] specification, v8.18.0, mars 2012.

Spécification technique 3GPP TS 23.272, Circuit Switched (CS) fallback in

Evolved Packet System (EPS), Stage 2, v8.11.0, octobre 2010.