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Performance Evaluation of Channel Estimation Techniques for a Mobile Fourth Generation Wide Area OFDM System

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Abstract—**In this paper channel estimation techniques for a mobile fourth generation coherent Orthogonal Frequency Division Multiplexing (OFDM) system are proposed. Coherent detection dictates that a per-subband estimate of the frequency response of the channel is generated for each OFDM symbol. This is achieved by inserting pilot symbols amongst the data symbols in the OFDM modulation grid. With suitable interpolation, the channel estimate at all intermediate symbols can be generated. A number of channel estimation methods with different pilot patterns and interpolation methods are examined for a range of UTRA specified channel environments. Each environment is shown to have an optimal pilot scheme, power level, pattern and density and the paper proposes the use of adaptive pilot processing.**

Keywords—Channel estimation, OFDM, Fourth generation.

I. Introduction

The possible structure of a fourth generation (4G) cellular network is discussed widely in the literature. Enhancements include ad-hoc and self-organising networks, support for mobile IP, interworking with Digital Broadcasting infrastructure and the use of 'software radio' technology [1-4]. Wide area OFDM is identified as a strong contender for use in fourth generation mobile networks. For OFDM to operate in a wide area network, efficient channel estimation techniques are required that operate in fast time varying channels. This paper presents theoretic limitations and performance results for a number of wide area OFDM channel estimation techniques.

The ability of OFDM to efficiently exploit the wideband properties of the radio channel lies at the heart of its popularity. This feature has helped to establish OFDM as the physical layer of choice for broadband wireless communications systems [5-7]. In this paper coherent OFDM is proposed as a possible solution for a fourth generation cellular network. Coherent detection dictates that a per-subband estimate of the frequency response of the channel is generated for each OFDM symbol. This is achieved by inserting pilot symbols amongst the data symbols in the OFDM modulation grid. These pilots are distorted by the wideband properties of the radio channel; however knowledge of their original values enables the distortion at each pilot to be quantified. With suitable interpolation, the channel estimate at all intermediate symbols can be generated [8, 9,10].

Assuming a given pilot pattern, the optimal linear channel estimator (in terms of mean-squared error) is performed as a 2-D Wiener filter. This algorithm has high computational complexity [9] and it is common for simplified alternatives to be applied. A common solution that is considered further in this contribution is to employ separable 1-D filters. Three interpolation methods are investigated. Linear interpolation is the computationally least expensive, but achieves very poor interpolation when the data is known to be non-linear. However, when only two data points are known, this method is the only viable option. Cubic spline interpolation is similar to linear interpolation, but fits a bezier curve to the data, rather than a straight line between the data points. Finally, FFT interpolation [9] is used to transform the data between the time and frequency domains. Using this approach, high delay components beyond that of the maximum excess delay are removed. All three methods are examples of 1-D interpolators that work separately in time and frequency. The use of 1-D filtering offers a distinct complexity advantage over 2D interpolators. For these interpolators, pilots can be arranged in either a grid, or continuous in time or frequency.

This paper is organised as follows: In Section II, the channel environments considered are presented. The OFDM system parameters for a possible fourth generation system are presented in Section III. In Section IV the selection of a pilot scheme, pilot patterns and density are described. A number of channel estimation techniques are proposed. Simulation results are presented in Section V. Finally Section VI discusses the results and concludes the paper.

II. Channel Environments

In order to study the performance of 4G systems it is essential that the transmission channels are satisfactorily characterized. The radio link performance in a mobile environment is primarily limited by Doppler and delay spread. In order to establish some assessment scenarios, the channels proposed in the Evaluation Report for ETSI UMTS Terrestrial Radio Access (UTRA) [11] are considered (Table 1). The channel is time varying, with Doppler rates, f_D, as high as 220 Hz for vehicular operation in the 2GHz band. For the indoor and pedestrian channels, f_D of ~5 Hz are expected.

III. The OFDM System

From Table I, it can be seen that the channel models considered have a wide range of possible delay spreads. Table II, shows the values that were chosen for the proposed OFDM parameters [11]. The OFDM modulation is implemented by means of an inverse FFT with FFT size N=512.

TABLE I. CHANNEL ENVIRONMENTS

Environment Number	Environment Description	RMS delay spread (ns)	Maximum delay spread (ns)	Maximum mobile velocity (km/h)	Maximum Doppler (Hz)
1	Indoor A	70	488	3	5.55
2	Indoor B	125	732	3	5.55
3	Outdoor to Indoor and Pedestrian A	65	488	3	5.55
4	Outdoor to Indoor and Pedestrian B	655	3662	3	5.55
5	Vehicular A	370	2686	120	222
6	Vehicular B	4000	19287	120	222

In order to prevent ISI, a guard interval is implemented by means of a cyclic extension. Thus, each OFDM symbol is preceded by a periodic extension of the symbol itself. The total OFDM symbol duration is $T_{total}=T_g+T$ where T_g is the guard interval and T is the useful symbol duration. When the guard interval is longer than the excess delay of the radio channel, ISI is eliminated. The individual carriers are modulated using either BPSK, QPSK, 16QAM, or 64QAM with coherent detection. The channel encoder consists of a ½ rate mother convolutional code and subsequent puncturing. The physical layer modes with different coding and modulation schemes can provide data rates between 1-13 Mbit/s, in an operating bandwidth of 4.096 MHz. The various transmission modes are selected by a link adaptation scheme. The receiver makes use of soft decision Viterbi decoding. In order to employ coherent detection, channel estimation must be performed. The channel state information is also used in the Viterbi decoder to calculate the metric.

TABLE II. OFDM PARAMETERS FOR 4G.

Parameter	Value
Operating Frequency	2GHz
FFT Size	512
Bandwidth	4096 kHz
Sample period	244 ns
Useful Symbol Duration *(T)*	125 µs
Guard Interval Duration *(T_g)*	$T_g \approx T/6 \approx 20.8$ µs
Total Symbol Duration *(T_{symbol})*	$T_{symbol}=144.2$ µs
Channel Coding	Punctured 1/2 rate convolution code, $K=7$, $\{133, 171\}_{\text{octal}}$
Sub-carrier spacing *(Δ_f)*	8 kHz

For the simulations in this paper, QPSK with ½ rate coding will be used. The guard interval is fixed at ~T/6, although efficiency could be further improved by employing an adaptive guard interval. The packet length is defined as the minimum number of OFDM symbols required to transmit 1200 bits of data. The actual packet length is variable since an integer number of OFDM symbols must be used, but the number of available sub-carriers will depend on the pilot density. A bitwise random interleaver is used across all data bits within a packet in order to mitigate the effects of error bursts, which degrade the performance of the Viterbi decoder. The channel model assumes Rayleigh fading in a classical Doppler spectrum. The channel is correlated within a burst of three symbols, and the bursts are uncorrelated between one another.

IV. PILOT INSERTION AND CHANNEL ESTIMATION

In order to obtain the channel state information (CSI) for all sub carriers at all times, it is necessary to sample the channel according to the Nyquist theorem (if 1-D channel interpolation is to be supported). The equations for the spacing of pilots in time and frequency are as follows:

$$s_f \le \frac{1}{2\Delta f \tau_{\max}} \qquad (1)$$

$$s_t \le \frac{1}{4 f_{D,\max} T_{symbol}} \qquad (2)$$

where s_f and s_t are the pilot spacings in frequency and time respectively, τ_{max} is the maximum excess delay, and $f_{D,max}$ is the maximum Doppler frequency.

Using equations (1) and (2) with the parameters in Tables I and II yields the following maximum pilot spacings for the system under study:

TABLE III. PILOT SPACINGS FOR TEST SYSTEM

Environment	s_f (maximum)	s_t (maximum)	s_f (used)	s_t (used)
1	128	313	128	-
2	85.3	313	64	-
3	128	313	128	-
4	17.1	313	16	-
5	23.2	7.5	16	2
6	3.2	7.5	4	2

In order to meet the packet length requirement (>1200 bits), 3 OFDM symbols will be used for QPSK 1/2 rate. From Table III, it can be seen that in the low Doppler environments (environments 1-4), the maximum distance between pilots in time is 313 OFDM symbols. Hence, it is clear that over a 3-OFDM symbol (or even larger) packet, the channel can be assumed correlated in time (and therefore no temporal interpolation is required). In our scheme, the second symbol of the three will contain the pilots. The second symbol is used since intuitively the extracted pilots will be highly correlated to those required in symbols 1 and 3. In the high Doppler environments (5 and 6) the separation of pilots in time must be less than 7.5 symbols. Therefore two cases will be investigated: a) pilots on symbols 1 and 3, and linear interpolation between them in time to obtain the estimate for symbol 2 and b) using only one row of pilots. Hence, the performance degradation of using only one row of pilots in the high Doppler channel will be shown.

The spacing in frequency is chosen to be the highest power of 2 that is less than or equal to the optimal value calculated (see Table III). The power-of-2 condition is necessary for the FFT interpolation to work effectively.

Table IV, shows the packet sizes for the different environments, after pilot insertion is taken into account. The overall data rate (assuming a guard interval of ~T/6) is also shown. Inserting pilots will incur a performance penalty since a portion of the transmit energy is diverted from the user data. This performance loss is also shown in table IV. It can be seen that only environment 6 has a significant degradation due to pilots (≈0.8dB).

TABLE IV. PACKET SIZES AND PILOT DENSITIES

Environment	No. of Pilots	Bits per packet	Data Rate (Mbit/s)	Eb/No loss (dB)
1	4	1526	3.53	0.01
2	8	1522	3.52	0.02
3	4	1526	3.53	0.01
4	32	1498	3.46	0.09
5	64	1466	3.39	0.18
6	256	1274	2.94	0.79

Three interpolation schemes are now investigated:

A. FFT Interpolation

In this scheme the time domain channel estimate is windowed to suppress noise and interpolation between the known frequency domain values is performed. The initial frequency domain channel estimate is transformed into the time domain by use of an IFFT. This yields a copy of the time domain profile, echoed along the delay axis. If all the delay components that are higher than the longest known delay tap are suppressed, and then the time domain profile is transformed back to the frequency domain (by use of an FFT), a full channel estimate can be achieved. In the noiseless case, this estimate will be without error.

B. Spline Interpolation

This scheme operates solely in the frequency domain. The real components of the known sub-carriers are taken and a Bezier curve [13, 14] is fitted between them. This is then repeated for the imaginary components and the two are combined to create a final frequency domain estimate for all sub-carriers. Spline interpolation requires a minimum of 3 known points.

C. Linear Interpolation

In linear interpolation (which also operates solely in the frequency domain), the intermediate estimates are calculated by the linear sum of the known components on either side. It performs very poorly as an interpolator across frequency, but is often the only option for interpolation in time, since it only requires 2 points to be known.

V. PERFORMANCE RESULTS

Fig. 1 shows the bit error rate (BER) performance for the various environments with perfect channel knowledge at the receiver, with pilots included in the packets (and therefore the Eb/No loss due to pilots included).

From Fig.1, it can be seen that the channels with the least delay spread (environments 1-3) perform significantly poorer than those with higher delay spread (environments 4-6), due to the higher frequency diversity that accompanies a richer delay spread environment [15]. Although environment 6 has the highest delay spread, its performance is not the best due to the Eb/No loss resulting from the large number of pilots required.

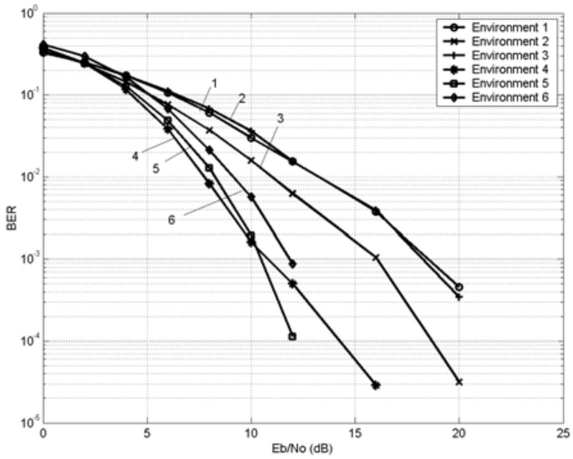

Figure 1. BER Performance for Perfect Channel Knowledge

A. Comparison of Interpolators

Fig. 2 shows the BER performance for the various environments with the FFT and spline interpolators as described in the previous sections. The pilot spacings and the number of pilots are shown in Tables III and IV respectively.

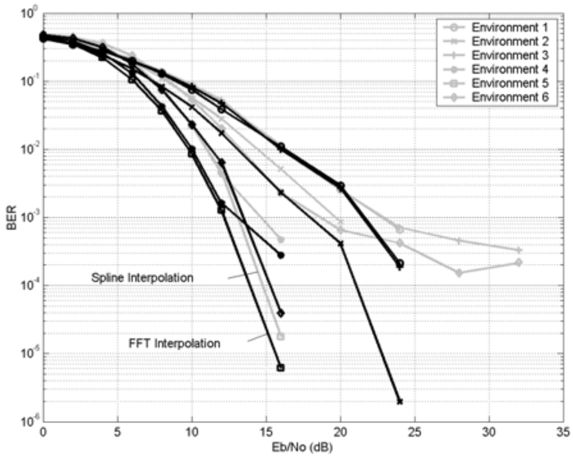

Figure 2: BER performance for FFT and Spline interpolators

From fig. 2, it can be seen that the FFT interpolator performs significantly better in all environments, and that the performance benefit is particularly evident in the higher delay spread channels. In particular, environment 6 has a large performance drop in the spline interpolator due to the channel being slightly undersampled (see Table III). The FFT interpolator is clearly able to handle undersampling much better than the spline interpolator. The power of the FFT interpolator is that it exploits the strictly delay limited nature of the multipath in the frequency domain, assuming the maximum excess delay is known. The spline interpolator on the other hand, will introduce high delay 'harmonics' (using the time-frequency duality) that are known not to exist, but which are not removed by this technique.

B. Boosted Pilots

Of particular importance is the effect of noise on the pilots and hence on the channel estimate. Fig. 3 shows the performance of the FFT interpolator on channels 1 and 5, for the cases of pilots affected by noise, and with noiseless pilots.

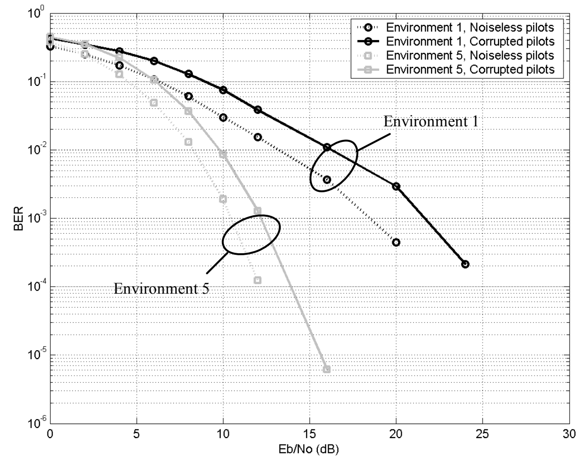

Figure 3: BER Performance for noiseless vs noisy Pilots, Environments 1 & 5.

There is clearly a 2-3dB degradation in performance due to noise on the pilots. The degradation is worse for environment 1 as the channel estimate is based on just four pilot samples; therefore if one of these is heavily corrupted the channel estimate will be strongly influenced. The higher delay channels utilize more pilots and so are less affected by noise, although significant degradation still occurs.

In order to optimize performance it is important to mitigate the effects of noise on the channel estimate. There are two methods of doing this: firstly, by oversampling the channel with more pilots so that the effects of noise are reduced, since each pilot will now contribute proportionally less to the estimate. However, as more pilots are used the overall data throughput will be reduced due to the sub-carriers being used for pilots rather than user data. The second method is to 'boost' the pilots by giving them more power than the data symbols. This results in a trade-off: with increased power the pilots will have greater noise immunity. However as the total transmitted power must remain constant, the power of the data symbols will be reduced, making them more susceptible to noise. Performance will therefore be improved by a better channel estimate, but reduced by a higher effective Eb/No on the data symbols.

The Eb/No loss due to the extra energy on the pilots can be easily computed. However to calculate the resultant performance gain a simulation must be performed. Hence, BER curves have been produced for various levels of pilot power. Each environment will have a different optimum boost level, since a packet with fewer pilots can be boosted more than a packet with a higher number of pilots, and still achieve the same overall power output. Pilots are positioned at $\pm p$ on the constellation plane. Data symbols have previously been normalized to have an average power of 1, so QPSK symbols would lie at $\pm 1/\sqrt{2} \pm j/\sqrt{2}$. A value of p=1 therefore represents a non-boosted pilot. Fig. 4 shows BER performance for environment 1 for various levels of pilot power. Fig. 4 clearly shows the performance improving as the pilots are boosted, and then degrading as boosting increases and the noise power on the data symbols dominates. For environment 1, a value of p=4 gives the optimum performance, and results in less than 0.5dB degradation over the case of perfect channel knowledge, at a bit error rate of 10^{-2}. This is a considerable improvement on the previous case of non-boosted pilots, where the degradation was approximately 3dB.

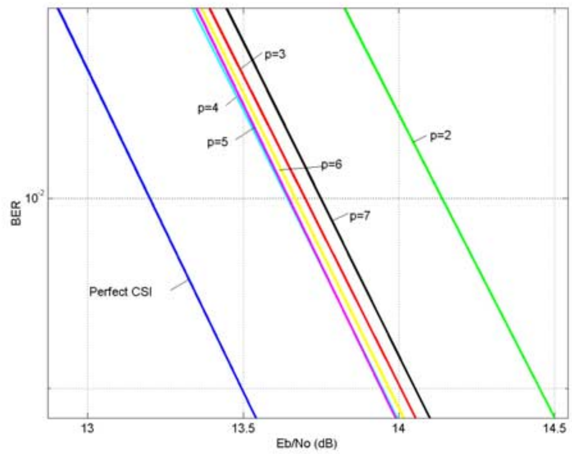

Figure 4: BER Performance for Boosted Pilots, Environment 1

Table V shows the performance improvement of boosting pilots for each environment. The degradation shown is the extra bit energy required over the perfect CSI case to reach a BER of 10^{-2}. The higher delay spread environments benefit less from pilot boosting as each packet will contain more pilots. Therefore, they can be boosted less before the noise degradation on the data symbols dominates the performance.

TABLE V. PERFORMANCE FOR BOOSTED PILOTS

Env	Degradation for non-boosted pilots (dB)	Degradation for boosted pilots (dB)	Improvement (dB)	Optimum boost level, p
1	3.0	0.5	2.5	4.0
2	2.1	0.5	1.9	3.5
3	3.0	0.5	2.5	4.0
4	2.2	0.9	1.3	2.1
5	1.5	0.9	0.6	1.7
6	2.0	1.9	0.1	1.4

C. Interpolation in Time

For all the results above, environments 5 and 6 use linear interpolation in time in order to improve BER performance, since it is assumed that the channel cannot be said to remain constant across the three OFDM symbols. Fig. 5, compares the BER performances for the case where the channel is assumed constant and where time interpolation is used.

It can be seen that BER performance is improved when time interpolation is used. However it should be noted that

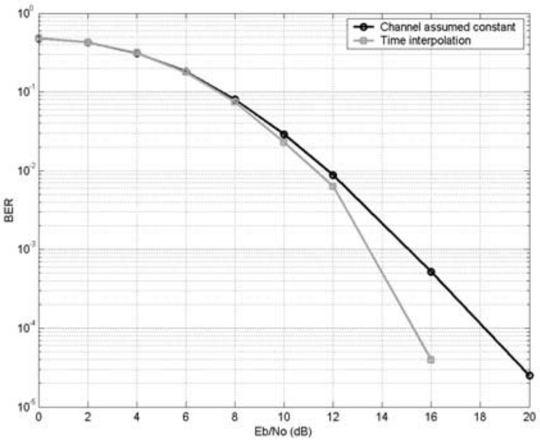

Figure 5: BER Performance for Channel 6, interpolated in time vs Assumed Constant.

when the channel is assumed to be constant, only one OFDM symbol will contain pilots and so the number of pilots is halved. The overall throughput will therefore be higher than in the interpolated case, resulting in a trade-off. Although the bit error rate will be higher if the channel is assumed to be constant, the peak data rate will also be higher. However, as the channel becomes less correlated (i.e. as mobile velocity increases), the assumption that the channel remains constant will become invalid and time interpolation will become necessary. Future work will further investigate this subject for different modulation schemes, packet sizes and velocities.

D. Adaptive Pilots

In order to adaptively change the number of pilots and their spacings, the transceiver needs a method of identifying its current operating environment in order to select an appropriate pilot pattern. An estimate of the maximum excess delay spread is required in order to space the pilots appropriately in frequency. An estimate of the mobile velocity is required to determine whether time interpolation is required or if the channel can be assumed to remain constant. A system capable of estimating the frequency selectivity of the channel and the temporal channel correlation would thus be capable of supporting an adaptive pilot scheme. Such a system would therefore be able to adapt dynamically to the operating conditions.

Delay spread estimation can be achieved by looking at the time domain profile of an oversampled OFDM symbol. The maximum excess delay can be determined as the last delay component that has a power level that is below a certain threshold relative to the highest power tap. Periodically (or at the request of the mobile terminal, e.g. if the packet error rate suddenly rises) the base station will send a packet with high pilot density (as proposed for environment 6). This will be the optimum sampling rate for environments 5 and 6, but oversampled for all other channels, so will therefore accurately sample all possible delay spreads. The maximum excess delay can then be estimated by taking the IFFT of the zero-padded pilots. Additionally, by looking at the correlation between the first and last row of pilots, the mobile velocity can be estimated. Further analysis of this implementation and its performance are the subject of further study.

VI. CONCLUSIONS

In this paper, pilot schemes for an OFDM system operating in the ETSI UTRA channels 1-6 have been proposed, and two interpolators compared. The FFT interpolator is found to have superior performance to the spline interpolator, using the minimum number of pilots in order to maximize data throughput. Boosted pilots have been used to mitigate the effects of noise and bring performance closer to that of the case with perfect channel knowledge. An adaptive pilot scheme has also been proposed. Future work will include an in-depth study of the needs for time interpolation and channel characteristic identification from the received pilots in order to implement an adaptive pilot scheme.

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