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# Performance Evaluation of Channel Estimation Techniques for a Proposed '4G' MC-CDMA Based System in a Time Varying Channel

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**Abstract**—This paper investigates the performance of channel estimation techniques applied to a proposed Fourth Generation (4G) Multi Carrier – Code Division Multiple Access (MC-CDMA) system. Coherent detection requires a per-sub band estimation of the channel frequency response for each Coded Orthogonal Frequency Division Multiplexing (COFDM) symbol. This paper compares the performance of a number of Pilot Symbol Assisted Modulation (PSAM) methods for achieving such estimates. Performance results are characterised by bit-error-rate (BER), data throughput (DT) and mean-squared error (MSE) for ETSI UTRA specified channel environments. It is shown that in an indoor environment, FFT filtering provides superior data throughput performance, whereas in a high Doppler vehicular environment, a reduced complexity Wiener filter is able to offer the best performance.

**Keywords**—Channel Estimation; MC-CDMA; '4G'; Doppler; PSAM

## I. INTRODUCTION

Multi Carrier Code Division Multiple Access (MC-CDMA) is highly regarded as a possible candidate for implementation as the fourth generation (4G) Physical Layer (PHY). It has been recognised that future enhancements to cellular mobile technology should include the inherent ability to support ad-hoc self organizing networks, interwork with existing broadcast infrastructure and provide flexibility through the use of software radio technology [1]. Coded Orthogonal Frequency Division Multiplexing (COFDM) and MC-CDMA are able to operate successfully in a wideband channel through the exploitation of its frequency selective nature. Multipath effects have traditionally been seen to provide a potential obstacle to efficient transmission. The inability of modulation schemes to combat the effects of excess delay spread has been seen to produce a spreading of symbol energy into subsequent data symbols leading to the undesirable effect of Inter-Symbol Interference (ISI). However, in an OFDM modulation scheme, ISI is readily avoided by the insertion of a guard interval (GI) of duration longer than the excess delay spread of the channel. These characteristics have made COFDM highly popular; resulting in its adoption into many recent standards for Wireless Local Area Networks (WLANs) and Wireless

Metropolitan Area Networks (WMANs) as well as broadcasting standards [2], [3], [4], [5].

The effect of a time-varying channel is to insert a frequency offset as described by the power spectral density probability function to sub-carriers within an OFDM symbol. The effects of Doppler spread on OFDM and MC-CDMA is well understood. If not corrected, it has been shown to result in a performance penalty as InterCarrier Interference (ICI) is introduced into each OFDM symbol [6], [7].

Coherent detection in a mobile environment via PSAM necessitates the derivation of a per sub-band estimation of the channel frequency response for all instances in time. This is achieved either through the insertion of pilot symbols (PS) of known values at regular intervals in the time/frequency modulation grid according to the Nyquist criterion, or through the insertion of a training sequence (TS) comprising a known OFDM symbol as a prefix to a packet. At the receiver the symbols corresponding to the location of pilot symbols in the grid are utilised in conjunction with the known values and the channel frequency response is estimated at these points. In a practical system it is necessary to undertake interpolation in time as well as frequency in order to provide a channel estimate for all points in the time/frequency modulation grid. Interpolation can be performed through either 1-D or 2-D techniques; the former being possible through the use of filters such as cubic spline interpolation and FFT interpolation with the latter implemented through Wiener filtering.

Whilst these techniques have been studied in relation to COFDM, no previous study has been conducted for MC-CDMA. This paper is organised as follows: Section II details the MC-CDMA system under investigation, with the channel models explained in Section III. Section IV details the pilot insertion and interpolation techniques utilised, with the results and conclusions presented in Sections V and VI respectively.

## II. MC-CDMA SYSTEM ARCHITECTURE

Each modulated OFDM symbol consists of a summation of sub-carriers each of which is BPSK modulated to give a transmitted signal  $S$  where the elements of  $S \in [1, -1]$ . Orthogonal modulation (achieved using an Inverse Fast Fourier

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Transform (IFFT)) results in a sub-carrier spacing  $\Delta f$  equal to the inverse of the useful data symbol period  $T_u$ . An MC-CDMA signal consisting of  $N$  active sub-carriers is considered, where  $N$  is defined by the product of the spreading code of length  $SF$  and the number of coded bits per OFDM symbol,  $P$ . In a multiple user system, the data stream for each of the  $k$  users is summed prior to application of the IFFT. The addition of a cyclic prefix (or guard interval) of duration  $T_{GI}$  to the useful symbol of duration  $T_U$  is implemented in order to prevent ISI. The MC-CDMA modem considered in this paper is illustrated in Fig. 1 with numerical simulation parameters defined in Table 1.

The BPSK modulated symbols are derived from the input data via a combination of a  $1/2$ -rate convolutional Forward Error Correcting (FEC) code with random block interleaving over the entire packet in order to exploit the frequency diversity. Channel State Information (CSI) is additionally exploited in the soft decision Viterbi decoder to calculate the metric and Minimum Mean-Squared Error Combining (MMSEC) is implemented for equalisation. Perfect symbol synchronisation and zero phase noise in the receiver are assumed.

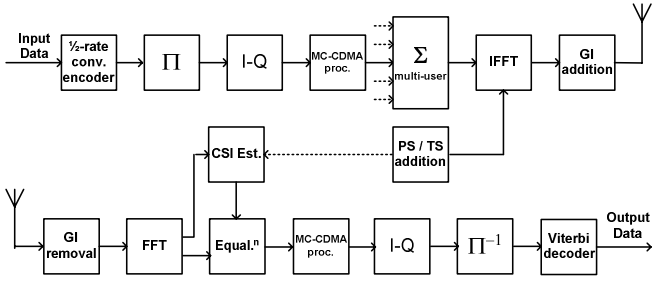


Figure 1. Downlink MC-CDMA System Model Architecture.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Bandwidth $B$	4.096MHz
Total Sub-Carriers $N$	512
Sub-Carrier Spacing $\Delta f$	8kHz
Sampling Period $T$	244ns
Operating Frequency $f$	5.2GHz
Spreading Factor $SF$	32
Channel Coding	$1/2$ -rate convolutional code $K = 7, \{133, 171\}_{\text{octal}}$
Useful Symbol Duration $T_u$	125μs
Guard Interval Duration $T_{gi}$	2.69μs
Total Symbol Duration $T_{symbol}$	127.69μs

### III. CHANNEL MODEL

In order to provide a realistic channel operating scenario, models based on those proposed by European Telecommunication Standards Institute (ETSI) for the UMTS Terrestrial Radio Access (UTRA) study [8] were considered. These models specify tapped delay line profiles representative of a range of operating environments and provide a statistical

approach to channel modelling based on the Wide Sense Stationary Uncorrelated Scattering (WSSUS) model. In this simulation a total of 16 arriving rays of uniform azimuth distribution with phase assumed to take random independent and identically distributed (iid) uniform variables in the period  $[0, 2\pi]$  are simulated. The channel impulse response (CIR)  $h$ , over a multipath channel comprising  $L$  paths is given as follows, where  $\tau$ ,  $t$  and  $\tau_l$  represent the delay domain, time domain and propagation delay for the  $l^{\text{th}}$  path respectively.  $\delta(\cdot)$  is the Dirac delta function,  $\alpha$  the tap amplitude and  $\Phi$  the tap phase.

$$h_v(\tau, t) = \sum_{l=0}^{L-1} \alpha_l(t) e^{-j\phi_l(t)} \delta(\tau - \tau_l) \quad (1)$$

The maximum Doppler frequency is given by (2), where  $c$  ( $\text{ms}^{-1}$ ) is the velocity of light and  $v$  ( $\text{ms}^{-1}$ ) the relative velocity between transmitter and receiver.

$$f_{D_{\max}} = \frac{vf}{c} \quad (2)$$

The channel model parameters as defined are displayed in Table II which are defined for indoor to outdoor and vehicular environments which are liable to experience maximum relative velocities of 3km/h and 120km/h corresponding to  $\sim 14\text{Hz}$  and  $\sim 578\text{Hz}$  for channel models A and B respectively.

TABLE II. UTRA CHANNEL MODELS

Model	Description	RMS Delay Spread (ns)	Excess Delay (ns)	Maximum Doppler Frequency $f_{D_{\max}}$ (Hz)
A	Indoor/Outdoor	65	488	14.44
B	Vehicular	370	2686	577.8

### IV. PSAM CHANNEL ESTIMATION

#### A. Pilot Insertion

Channel estimation using Pilot Symbol Assisted Modulation (PSAM) techniques [9] require the insertion of pilots in both the time and frequency domains. In order to avoid aliasing channel estimation must be conducted by sampling at or above the Nyquist frequency. This requirement determines the minimum separation of the scattered pilot symbols that must be deployed in order to avoid aliasing. Over-sampling may be carried out to improve the channel estimation accuracy. The Nyquist spacing for frequency and time are given in (3), where  $s_f$  and  $s_t$  are the pilot spacing for frequency and time respectively,  $\tau_{\max}$  the maximum excess delay spread and  $f_{D_{\max}}$  the maximum Doppler spread to be experienced.

$$s_t \leq \frac{1}{\Delta f \tau_{\max}} \quad (3)$$

$$s_f \leq \frac{1}{2f_{D_{\max}} T_{\text{symbol}}} \quad (4)$$

Given the multiple user access scenario considered, it cannot be assumed that all concurrently supported users will

experience the same channel environment with all its associated delay and Doppler parameters. Hence it is necessary to use the same pilot patterns for both channel models. Due to efficiency requirements for the implementation of FFT interpolation the pilot spacing must be a power of 2 and is chosen to be less than or equal to the optimum value calculated to satisfy the Nyquist criterion. Oversampling in time and frequency would inherently improve the channel estimate and BER performance at the cost of reduced throughput. Clearly, an optimum pilot pattern can be derived to give the highest data throughput capability. In channel model A, the OFDM symbols are highly correlated in time and therefore can be considered to be subjected to the same channel frequency response. However as we cannot assume that the system will be deployed in the same channel for all users simultaneously, we have assumed a worst case scenario in terms of pilot location. As a result the calculated values are  $s_f = 16$  and  $s_t = 2$ . The packets are uncorrelated between one another, with a packet consisting of 3 OFDM symbols allowing for the transmission of 544 data bits.

A training sequence approach leads to the requirement to insert an OFDM symbol containing known pilot symbols on all sub-carriers. This will surpass the need for frequency domain interpolation but is not able to respond to the time variant nature of the channel. The effective insertion of a large number of pilot symbols, though able to provide an enhanced frequency estimate over the scattered pilot approach, is liable to have an effect on the transmission efficiency; leading to reduced data throughput (DT). Data throughput is approximated by:

$$DT = (1 - PER) \times NDR \quad (5)$$

where  $PER$  and  $NDR$  is the Packet Error Rate and Nominal Data Rate respectively.

### B. Interpolation

1) *1-D Techniques*: Cubic spline interpolation requires the fitting of a Bezier curve to the extracted pilot symbols. This technique offers the least complex solution but it is liable to perform badly in simulations for a number of reasons. The estimated channel frequency response contains white noise components which results in an infinite time response, i.e. noise components are present in the time delay profile whereas in practice the excess delay is strictly bandlimited. These extra sample are known not to exist in practice.

FFT interpolation operates by performing bandlimiting in the time domain in order to remove noise components exceeding the duration of the excess delay as shown in Fig. 2. This technique requires conversion of the pilot symbols to the time domain by taking an IFFT. Windowing is subsequently performed whereby all the components exceeding a power threshold corresponding to the excess delay of the channel are preserved, and the components exceeding the excess delay are reduced to zero. This power delay profile is the converted back to the frequency domain through implementation of the FFT prior to frequency domain equalisation. This technique, while offering a good performance through noise limitation, requires the use of an IFFT/FFT transform pair adding significantly to

the computational requirements of the estimator. This technique has been implemented both through a scattered pilot approach where 32 pilot symbols are utilised for channel estimation, as well as by using a training sequence approach (TS FFT).

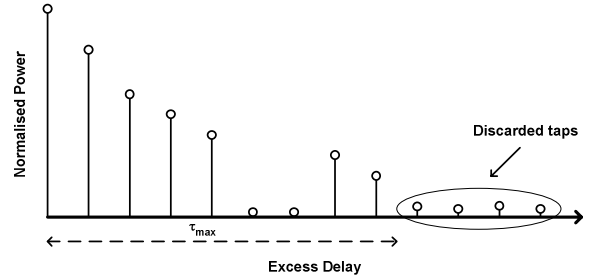


Figure 2. FFT interpolation performed in the time domain.

2) *2-D Techniques*: A Wiener Filter is able to provide per-sub-band channel estimates based on information derived from all pilot symbols [10], [11]. Here, we propose to implement a reduced complexity filter which uses the four nearest pilot symbols to interpolate each sample. The MMSE estimate of each point is given as [12]:

$$\hat{h} = R_{h\hat{p}} \left( R_{pp} + \frac{1}{SNR} I \right)^{-1} \hat{p} \quad (6)$$

where  $R_{h\hat{p}}$  is the cross-covariance matrix between  $h$  and the known channel samples  $\hat{p}$ ,  $R_{pp}$  is the auto-covariance matrix of the known channel samples, and  $SNR$  the assumed signal-to-noise ratio which cannot realistically be calculated *a priori*. The cross-covariance and auto-covariance matrices are calculated from the correlation functions in time and frequency.

$$E\{h_{k,l}, \hat{p}^*_{k',l'}\} = \frac{J_0(2\pi f_{Dmax} T_{symbol}(l-l'))}{1 + j2\pi\tau_{rms}(k-k')\Delta f} \quad (7)$$

where  $J_0$  is the zeroth order Bessel function of the first kind and  $l$  and  $k$  are the indices of the channel sample in time and frequency respectively.

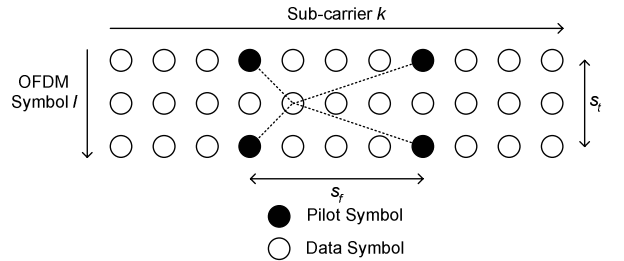


Figure 3. Per Sub-band Channel Estimation for Wiener Filtering.

The SNR given in (6) is assumed to be 10dB which offers a reasonable performance for the  $E_b/N_0$  under consideration. A full Wiener filter is accepted as offering the best performance in terms of mean-squared error but its high computational complexity tends to restrict its implementation in low cost applications.

## V. RESULTS

The BER performance of 1-D and 2-D techniques simulated for channel model A is shown in Fig. 4. It is clear that FFT interpolation employing a training sequence (TS FFT) approach performs the best due to its ability to accurately calculate the time delay profile. This is done by windowing to the excess delay of the channel (practical limitations may require the assumption a certain threshold level). However, the requirement for an additional FFT and IFFT to support this method and the consequent increase in complexity should not be overlooked [13]. FFT interpolation using a scattered pilot approach results in almost an identical performance to TS FFT as the channel is relatively ‘flat’ in nature and hence characteristic diversity fades are not present. The time variation of the channel over the packet is relatively small and consequently TS FFT interpolation provides accurate CSI for all OFDM symbols. Spline interpolation performs the worst due to the high delay harmonics inadvertently introduced leading to excess noise components which reduce the performance.

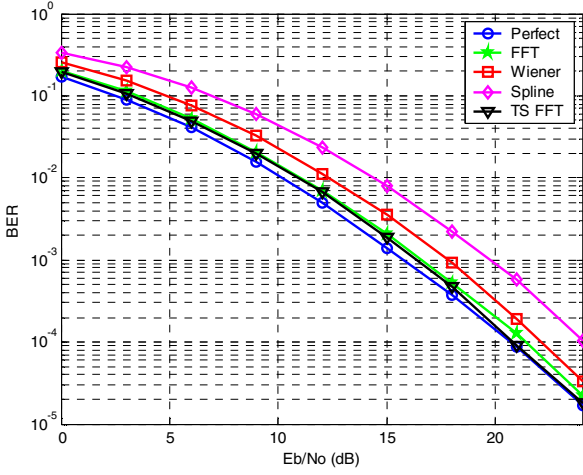


Figure 4. BER performance for channel model A at 3km/h showing the superior performance of TS FFT and scattered pilots FFT. Spline interpolation performs poorly due to the additional high frequency components which exist.

Fig. 5 shows the BER performance in channel model B (with frequency diversity than channel model A, leading to a 6dB improvement assuming perfect CSI). This model, characterised by a Doppler spread of 577.8Hz, has an effect on the ability of the estimator to track the channel over the packet. The reduced complexity Wiener filter slightly outperforms the FFT interpolator at high  $E_b/N_0$  values due to its ability to exploit information taken at different instances in time. FFT interpolation in frequency utilised by necessity with linear interpolation in time is the only practicable method where only two pilots are considered. The performance of TS FFT interpolation results in an error floor of  $3.3e-4$  due to its inherent failure to track the channel over time as the Doppler has a greater effect.

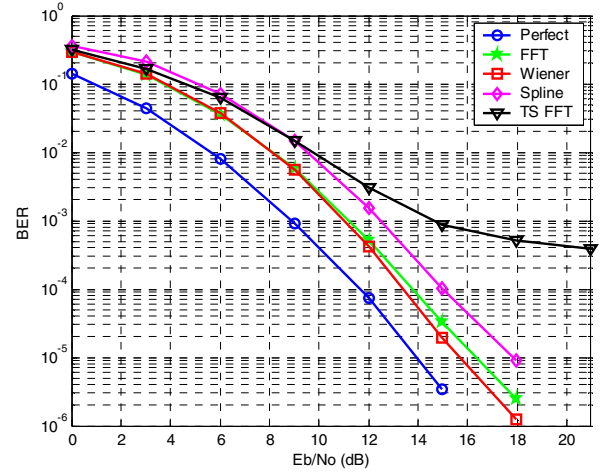


Figure 5. BER performance for channel model A at 3km/h showing the superior performance of TS FFT and scattered pilots FFT. Spline interpolation performs poorly due to the additional high frequency components which exist

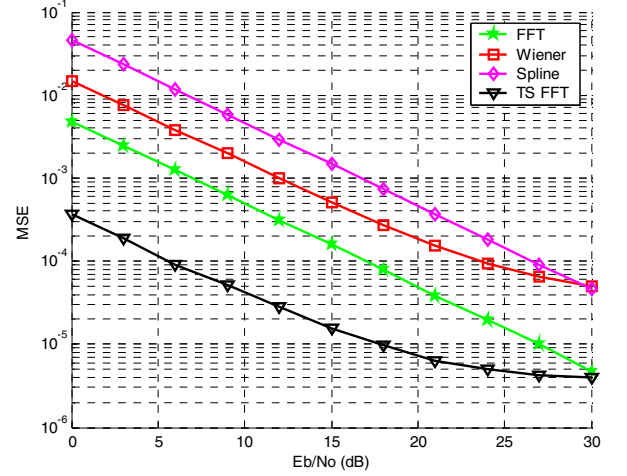


Figure 6. MSE performance of interpolation techniques in model A.

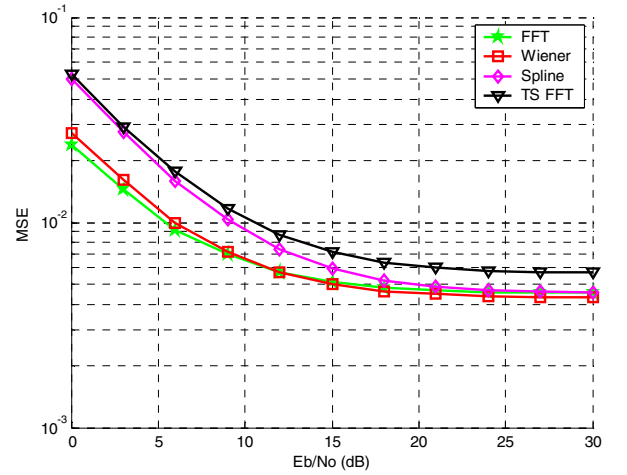


Figure 7. MSE performance of interpolation techniques in model B.

The MSE performance for channel model A is shown in Fig. 6 and shows the superior performance of TS FFT. At high  $E_b/N_0$  its performance is seen to converge with that of FFT interpolation. Fig. 7 shows the results from channel model B where scattered pilot FFT filtering has the best performance in terms of MSE, followed closely by Wiener filtering. TS FFT suffers the worst performance in this case.

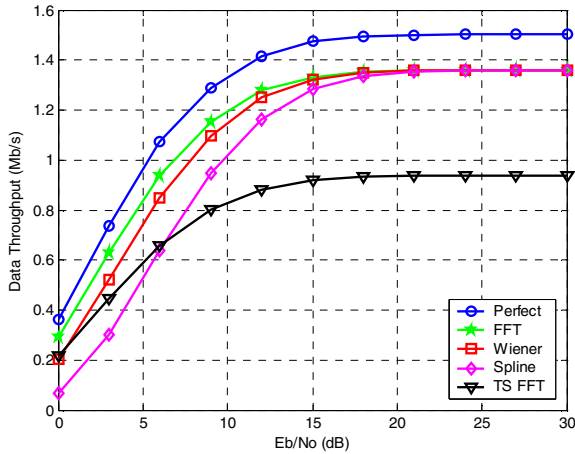


Figure 8. Data Throughput in channel model A

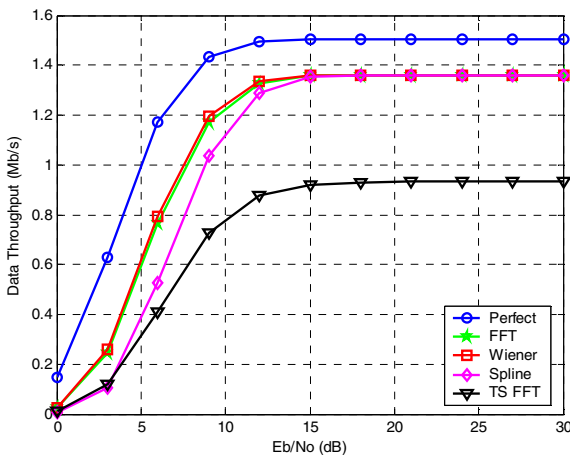


Figure 9. Data Throughput in channel model B

Data throughput results for channel models A and B are shown in Fig. 8 and Fig. 9 respectively. Scattered pilot FFT interpolation provides superior throughput over the other techniques in channel model A and at low  $E_b/N_0$  compares well with perfect CSI. Wiener filtering provides a similar performance to scattered pilot FFT interpolation and would be highly favourable considering the complexity disadvantages of FFT interpolation. Model B shows a marginal performance improvement for Wiener filtering over FFT interpolation. Spline interpolation offers the lowest data throughput of the scattered pilot symbol approaches for both channel models. In contrast, FFT noise reduction derived from a sent training sequence gives a poor throughput performance for channel model A despite the comparable BER performance with the

FFT interpolation, due to the loss of sub-carriers available through channel estimation requirements. Its performance in channel model B is likewise poor though at low  $E_b/N_0$  offers increased throughput only over Spline interpolation.

## VI. CONCLUSIONS

This paper has investigated the performance of channel estimation techniques for a proposed 4G system. It is evident that a scattered pilot FFT filtering approach performs well in both low diversity low Doppler channel as well as high diversity high Doppler channels. FFT filtering derived through training sequence implementation performs the best in a low Doppler environment but is unable to track the channel in high Doppler scenarios. In both channel models, data throughput is inhibited through high pilot density requirements. A reduced complexity Wiener filter is able to offer the best data throughput performance in a vehicular channel.

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