Fifth IEEE Workshop on Signal Processing Advances in Wireless Communications, Lisboa, Portugal, July 11-14, 2004

On the Frequency Domain Approach for Spread Spectrum Receivers: Towards a Convergence of DS-CDMA, MC-CDMA and OFDM

Cristiano Panazio
Conservatoire National des Arts et Métiers (CNAM)
292, rue Saint-Martin, 75142, Paris - France - Cedex 03
Email: cpanazio@cnam.fr

Maurice Bellanger
Conservatoire National des Arts et Métiers (CNAM)
292, rue Saint-Martin, 75142, Paris - France - Cedex 03
Email: bellang@cnam.fr

Abstract — **The RAKE receiver is suboptimal when noise is non white, as in wideband CDMA systems. Frequency domain processing provides an efficient way to eliminate narrowband noise or exploit colored noise and it can significantly outperform the RAKE receiver. Additionally, other functions can be carried out directly in frequency domain, such as despreading, synchronization that is crucial for performance and equalization, which can mitigate multiuser interference. In this paper we discuss the frequency domain processing for DS-CDMA and potential gains are assessed by simulation results. An additional and important feature is that the frequency domain receiver for DS-CDMA also provides a common platform for MC-CDMA and OFDM, paving the way for an universal receiver.**

I. Introduction

Spread spectrum receivers are generally implemented in the time domain: each block of received chips is correlated with the code to recover the spread data. The transmission channel is assumed flat and the major problem is the level of the noise, which is presupposed to be white and Gaussian, leading to a spreading gain equal to the length of the code.

The assessment of the performance of spread spectrum is not so simple and straightforward when the transmission channel and the noise cannot be assumed flat, as in wideband CDMA (Code Division Multiple Access) systems.

Non flat channel generates multiuser interference. Colored noise may arise from co-channel interference for example. Narrowband interference may be generated by means of intentional jamming, cross-modulation and intermodulation from adjacent narrowband system, harmonic distortion, interference of high clock computers and other electronic equipments.

An elegant approach to introduce the dependency of the system performance on the channel frequency response and also the noise spectrum, consists in analyzing the operations of the receiver in the frequency domain. Efficient implementations of some or all the functions of spread spectrum receivers have even been proposed [1]-[6]. They are based on a DFT (Discrete Fourier Transform) whose length L equals the length N of the spreading code and they exploit the fact that spreading, in fact, is a multicarrier modulation, with L carriers characterized by their amplitudes and their phases. The approach is computationally intensive, but a crucial advantage is that it provides an efficient way to eliminate narrowband interference and exploit colored noise. In addition, a global optimization of the receiver can be performed, including synchronization, equalization and optimal detection.

The purpose of the present paper is to discuss frequency domain despreading and assess the potential gains. The principle of the receiver is recalled in section 2 and its main functions are described. The impact of the noise spectrum on the performance is analyzed in section 3. Section 4 is dedicated to synchronization issues while section 5 deals with channel equalization. An important aspect of future cellular and wireless systems is raised in the conclusion, namely the compatibility of CDMA with the other major multicarrier technique, OFDM (Orthogonal Frequency Domain Multiplex). In the context of software defined radio, one can think of designing a frequency domain receiver capable of processing both types of signals.

II. The Frequency Domain Receiver

The spreading code of length N of a DS-CDMA (Direct Sequence) system can be described in the frequency domain as N carriers characterized by their amplitudes and phases. We may see this as the opposite of the generation of the time-domain signal of an MC-CDMA (Multi Carrier) system.

The block-diagram of the frequency domain receiver is shown in figure 1.

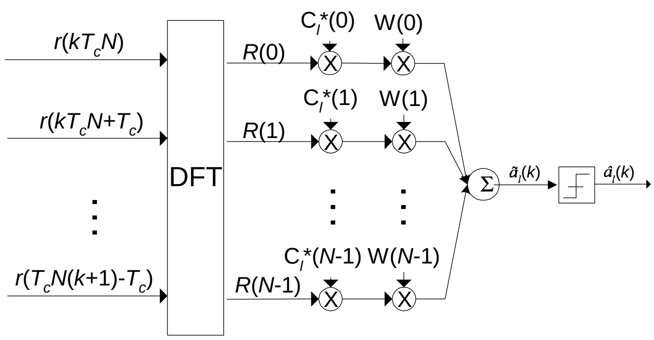

Figure 1: Frequency domain receiver schematics

The received signals are processed by blocks of the size of the spreading code N, obtained from the continuous time function that represents the received signal $r(t)$ given by:

$$r(t) = \sum_{l=1}^{L} \sum_{m=-\infty}^{+\infty} \left\{ a_l \left(\left\lfloor \frac{m}{N} \right\rfloor \right) c_l \left(mod(m,N) \right) h_l(t - mT_c) \right\} + n(t) \quad (1)$$

where l means the l-th user, the spreading sequence is represented by $c_l(k)$, the user's symbol is $a_l(k) \in \{+1, -1\}$, $n(t)$ is the noise and $h_l(t)$ is the channel, which is given by:

$$h_l(t) = \sum_{p=1}^{P} \gamma_{l,p}(t) \mathrm{r}_{cos}(t) * \delta(t - \tau_{l,p}) \quad (2)$$

where $r_{cos}(.)$ is the raised cosine function, $\delta(.)$ is the Dirac function, p means the p-th propagation path, $\tau_{l,p}$ and $\gamma_{l,p}(t)$ are the path delay and a complex time varying Rayleigh variable respectively. Since the despreading is obtained in time domain by the code matched filter, in frequency domain the despreading is done by multiplying the DFT outputs by the conjugate of the spreading code in frequency domain, namely:

$$C_l^*(i) = \sum_{n=0}^{N-1} c_l^*(n) e^{j\frac{2\pi n i}{N}} \quad (3)$$

The spread symbol is recovered by the following operation:

$$\tilde{a}(k) = \sum_{i=0}^{N-1} R(i) C_l^*(i) \quad (4)$$

The coefficient $W(i)$ is a complex gain that can be used to equalize the received signal and maximize the signal-to-noise ratio at the input of the decision device. For example, to implement the analogous of the RAKE receiver in frequency domain, we need the channel matched filter:

$$W_{RAKE}(i) = H^*(i) \quad (5)$$

where $H(i)$ is the N-point DFT of the channel impulse response. Such technique is used in [1].

It is worth noting that these operations in frequency would require a cyclic convolution of the channel with the transmitted signal, but this hypothesis does not hold since the traditional DS-CDMA system does not have a cyclic prefix (CP). This leads to a segmentation of the received delayed paths, as illustrated in 2, leading to intersymbol interference when trying to despread them and the lost of the energy of the samples outside the DFT window. The degradation is proportional to the delay of the path and its power. In order to illustrate such performance penalty, we have simulated a DS-CDMA system with a spreading factor equal to 64 over a channel $h(t) = 0.707 + 0.707\delta(t - mT_c)$ for various values of m. Then, we compared the performance of the frequency implementation of the RAKE with the conventional one. The result is presented in figure 3.

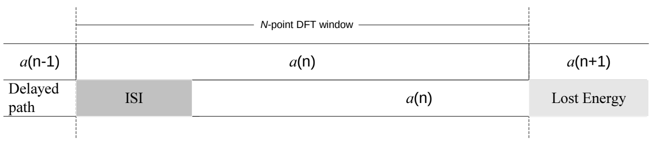

Figure 2: N-Point DFT window and symbol despreading.

However, such problem in frequency domain can be prevented by using a DFT of, at least, the size of the temporal channel-code matched filter, i.e., if the channel has M coefficients and the spreading factor is N, the DFT has at least $M + N - 1$ points. Assume that the channel is $h(z) = a(0) + a(1)z^{-1} + \ldots + a(M-1)z^{-M+1}$. The RAKE receiver for such channel can be in figure 4.

The paths synchronization, phase correction and gain ponderation is achieved by the channel matched filter. The code correlation can be made with an code matched filter, i.e., $c^*(1/z^*) = c(0) + c(1)z^1 + \ldots + c(N-1)z^{N-1}$. Therefore, we can represent the RAKE receiver as a correlator given by the filter $h^*(1/z^*)c^*(1/z^*)$ that should be sampled at each N chip to obtain the received symbol. This correlator has $M + N - 1$ coefficients and can be implemented in frequency domain by an DFT of the same size, without performance loss.

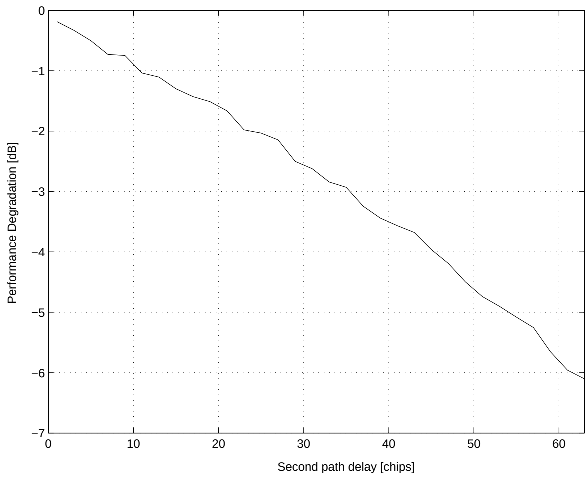

Figure 3: Performance degradation of the frequency domain RAKE.

III. Noise Influence in Performance

While the spreading-despreading process of the CDMA concept provides intrinsic robustness against narrowband interference and colored noise [7], the RAKE receiver is unable to exploit these characteristics. Many receivers were proposed to fill this performance gap. Among the proposed linear receivers, the LMMSE (Linear Minimum Mean Square Error) chip-level equalizer provides a good solution for CDMA systems that uses long codes, i.e., when the spreading sequence periodicity spans for more than a symbol period. The rationale behind the LMMSE chip-level equalizer is that in downlink all users codes pass through the same channel and thus, with the equalization at chip-level, we can restitute the orthogonality of the spreading codes and eliminate multiuser interference. Such LMMSE chip-level equalizer can also take into account the problem of narrowband interference and colored noise. The code-channel matched filter for colored noise or narrowband interference, which has a power spectral density S_n, is given by:

$$W_{MF}(i) = \frac{H^*(i)}{S_n(i)} \quad (6)$$

Note that, without the compensation for the noise, the matched filter for the colored noise or narrowband interference is exactly the RAKE receiver.

The LMMSE criterion in time domain is given by:

$$J_{LMMSE} = E\left\{ \left| s(k) - \mathbf{w}^H \mathbf{r}(k) \right|^2 \right\} \quad (7)$$

where $s(k)$ is the desired user spread signal and $(.)^H$ denotes conjugate and transpose. The dual in frequency-domain is given by:

$$J_{LMMSE} = \mathrm{E}\left\{ \left| \mathbf{C}_l(i) a\left(k\right) - W^H(i) R(i) \right|^2 \right\} \quad (8)$$

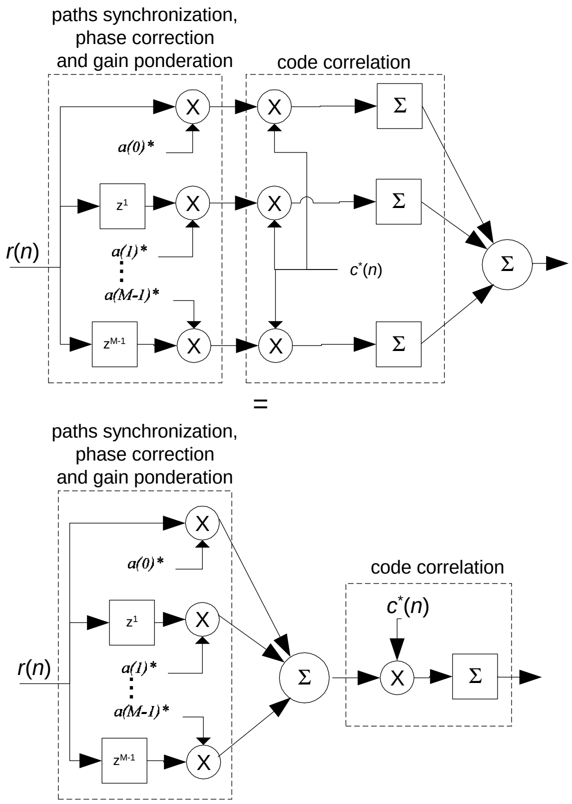

Figure 4: Scheme of RAKE receiver.

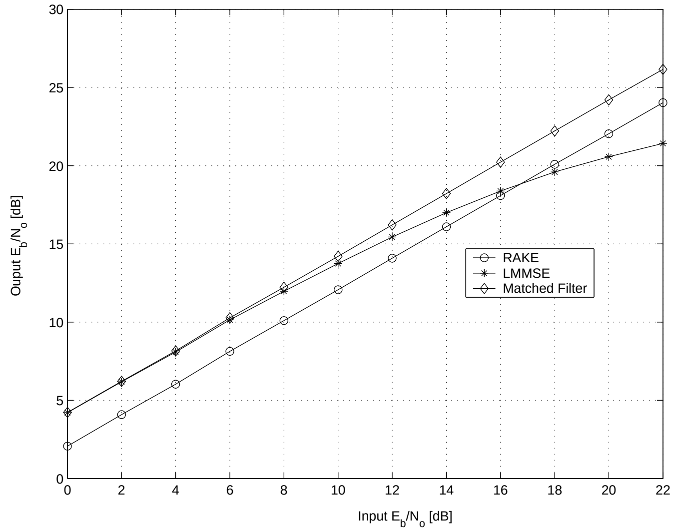

Figure 5: Colored Gaussian noise generated with a white Gaussian noise filtered with $n(z) = 0.857 + 0.5145z^{-1}$.

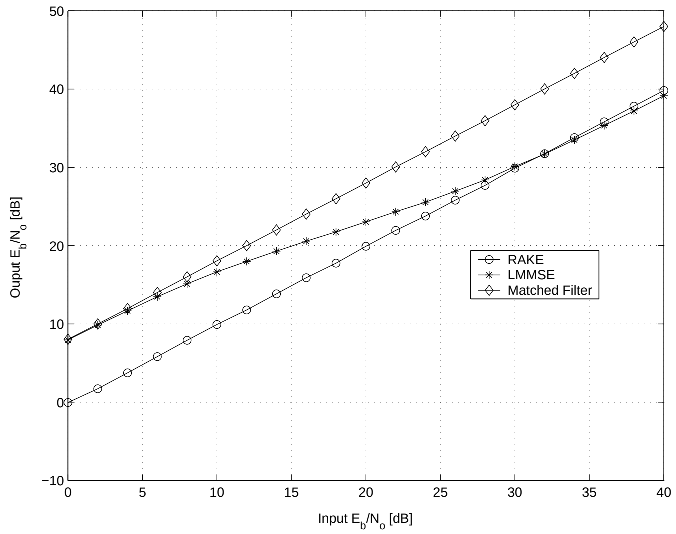

Figure 6: Narrowband Gaussian interference generated with a filter whose zeros are $0.8e^{\pm j0.469\pi}$ and $0.8e^{\pm j0.547\pi}$ and the poles are $0.99e^{\pm j0.469\pi}$ and $0.99e^{\pm j0.547\pi}$.

The solution for this cost function, assuming that all users transmit with the same power is :

$$W_{LMMSE}(i) = \frac{\sigma_a^2 H(i)}{\sigma_a^2 N_u \left|H(i)\right|^2 + \sigma_n^2 S_n(i)} = \frac{H(i)}{N_u \left|H(i)\right|^2 + \frac{S_n(i)}{SNR}} \qquad (9)$$

where N_u is the number of active users.

This equalization technique generally needs many coefficients since the delay spread usually covers many chips. Therefore, the frequency domain implementation is well-suited for minimizing the computational cost burden.

Comparing the LMMSE solution to the matched filter solution, we can see that the LMMSE solution tends to the matched filter when we have small values of SNR, i.e., when the second term of the denominator of the LMMSE solution predominates over the first one. For higher values of SNR, the LMMSE solution tends to the zero forcing solution and may cause noise enhancement.

In order to illustrate the performance gains for some non-white noise conditions, we simulate a DS-CDMA system with a 64 length Walsh-Hadamard orthogonalization code concatenated with a complex random scrambling code and $h(z) = 0.727 - 0.582z^{-1} + 0.364z^{-3}$. The frequency receiver was implemented with a 64-point FFT.

For the colored noise case in figure 5, the gain is approximately 2.2 dB and for the narrowband interference in figure 6, the gain is much more pronounced and is around 8 dB.

IV. Symbol and Chip Synchronization

Synchronization is a crucial aspect of communication systems. In a frequency domain receiver implementation, the position of the DFT window must be determined, i.e., we must determine what is the timing of the CDMA spread symbol. After accomplishing this task, we must pass to chip synchronization in order to refine some misadjustment of the symbol synchronization phase and/or compensate variations of time propagation or sample frequency offsets.

One way of achieving symbol synchronization is to use the correlation properties of the code. We can take the inverse transform of $R(k)C_l^*(k)$ and search for the maximum value that represents the path with largest energy.

The estimation of chip synchronization error can be executed directly in frequency domain, for example, using a technique described in [2]. Such a technique needs only the knowledge of the desired user spread code and provides performance similar to the Müller and Mueller Detector [8]. For small values of roll-off (e.g., 0.22) it is similar to the performance of the traditional Early-Late Gate timing error detector [8], which is commonly used in CDMA.

It is worth noting that narrowband interferers can be detected and eliminated in order to improve synchronization performance.

V. Multiuser Interference Mitigation

It is well known that a frequency selective channel destroys the orthogonality between the user codes. To solve this problem many techniques have been developed [9]. The optimal receiver is far too complex for practical implementation, a suboptimal technique must be used. In this paper we focus on linear chip-level equalization techniques based on MMSE criterion.

We may think of two different MMSE criterion. One has the capacity to decorrelate the users by working in the code space, taking into account the noise and users powers. It is called MMMSE linear multiuser detection in [11] and we will denote LMMSE detector (LMMSED). Its cost function is given by:

$$J_{LMMSED} = E\left\{|a - \mathbf{w}^H\mathbf{r}|^2\right\} \quad (10)$$

where a is the desired user transmitted symbol, $\mathbf{w}$ is a Q column vector, where Q is the equalizer length and $\mathbf{r}$ is a Q column vector that contains the received samples. It works by calculating the cross-correlation among the users and it uses this information to eliminate multiuser interference. It is worth noting that the frequency domain equalizer is analogous to (10), where the only difference is that the vector $\mathbf{r}$ is replaced by the output of the Q-point DFT or larger.

It is important to observe that the equalizer size Q can be of the size of the spreading code convoluted with the channel for short codes downlink systems, when all users are synchronized and intersymbol interference is negligible. For the uplink system, this receiver is resistent to the near-far problem. However, with asynchronous users, an infinite number is needed to attain optimality. A suboptimal solution for (10) can be achieved if we use a truncated window and if we have the knowledge of all the channels and spreading codes of the active users. The same is valid for long codes system, even synchronous one. It is noteworthy that better performance can be achieved for asynchronous chip and symbol CDMA system by means of fractionally spaced equalizers [12].

The other technique applies to the downlink, where all active users pass through the same propagation channel. It consists in recovering the orthogonality by equalizing the received signal which is often referred to chip-level equalization. It works with short or long codes systems. It has the same performance of the linear MMSE detector for full load or one active user systems, but it has lower performance for other load conditions. We have called such technique of chip-level LMMSE and the criterion in the time domain is presented in eq. (7) and, in the frequency domain by eq. (8).

Many articles (e.g., [3][4][5]) have treated the problem of frequency domain equalization for DS-CDMA systems. However, the majority of them make use of cyclic prefix, which is unrealistic, since, currently, there is no DS-CDMA system with cyclic prefix.

In this work, we do not assume cyclic prefix and, to illustrate, the mitigation of multiuser interference is demonstrated in the following example. We assume a downlink DS-CDMA system with a 64 Walsh-Hadamard as orthogonalization code with a random complex scrambling sequence, no cyclic prefix and full load. We use the 4 path profile specified in 3GPP standard [10], with relative delay 0, T_c, $2T_c$, $3T_c$ and $4T_c$ with the respective average power 0 dB, -3 dB, -6 dB and -9 dB. We assumed perfect knowledge of the channel. For the $2N$-point DFT we made a 15 pre-lap of the previous symbol.

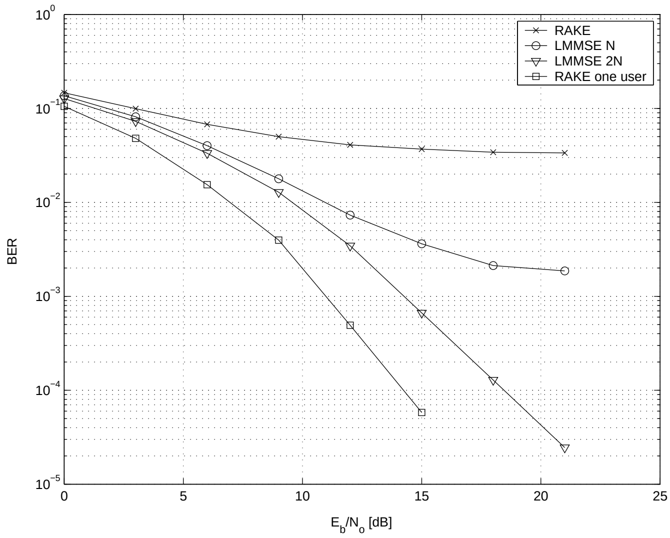

Figure 7: Equalization Performance

In this simulation, the RAKE implemented with N-point DFT matches the performance of the RAKE with $2N$-point DFT for both load cases, since the channel does not have a considerable delay spread. It is worth noting that in this case the performance of the frequency RAKE implementation perfectly matches the performance of temporal RAKE. With respect to the equalization technique, the performance changes dramatically with the size of the DFT. It is seen in figure **??** that the N-point DFT implementation has an error floor, while the $2N$-point DFT implementation does not present such problem for the simulated E_b/N_o range.

It is worth noting that for CP systems, it suffices a DFT of the size of the code spreading factor. Since the CP turns the propagation channel into a circular channel, it can be perfectly inverted by the DFT, except if the channel delay exceeds the CP size.

An adaptive solution for the LMMSE can be easily achieved. From (9), the denominator is the power spectral density, which can be directly estimated from the output of the DFT. Such procedure avoids the problem of knowing the number of active users and the estimation of the power of the noise. The channel can be estimated recursively using a pilot channel or a training sequence of the desired user by mean of a LMS (Least Mean Square) or a normalized LMS or even a RLS (Recursive Least Squares) algorithm.

VI. Discussion, Conclusion and Perspectives

A terminal that can support multimode access technologies provides a more comfortable usage and it can minimize cost structure of deployed systems.

In order to implement such terminal, we propose to adopt an universal receiver for DS-CDMA, MC-CDMA, OFDM and even single carrier transmission based on frequency domain processing that can fulfill these requirements and can provide an efficient receiver implementation paving the way for an universal receiver.

One may ask why use DS-CDMA for future systems instead of MC-CDMA. The answer is that DS-CDMA provides a constant envelope for one user while MC-CDMA has large peak to average ratio for the envelope even for one user. Another reason is that the addition of CP complicates considerably the synchronization process and results in redundancy that may not be even exploited. Also, it is worth noting that MC-CDMA provides the same performance of long code DS-CDMA with CP and a LMMSE equalizer [4].

The frequency domain receiver can offer significant gain with respect to conventional time domain receivers. We have shown that we can exploit the noise characteristics and gain as much as 8 dB in comparison with the RAKE receiver. This result shows that the use of a RAKE receiver as the standard receiver for wideband CDMA may not be the best choice. Moreover, such frequency receiver can efficiently implement an equalizer to counteract multiuser access interference and near-far problems.

The adaptation of the frequency equalizer can be done directly in the frequency domain by means of an LMS or RLS algorithms. The convergence rate of the iterative solutions will be analyzed in future works. Another aspect that should be analyzed is the size of pre-lap and post-lap for DFTs larger than the spreading factor.

For future works, a fractionally frequency implementation will also be analyzed for DS-CDMA system. Such filter can implement a matched pulse transmission filter and timing synchronization by interpolation in frequency domain, which can greatly reduce computational cost when compared to temporal implementation. It can also provide better equalization.

Acknowledgments

We would like to express our appreciation to CAPES/COFECUB for supporting this work.

References

[1] S. Y. Wang and C. C. Huang, "On the architecture and performance of an FFT-based spread-spectrum downlink RAKE receiver," *IEEE Transactions on Vehicular Technology*, vol. 50, no. 1, pp. 234–243, January 2001.

[2] C. Panazio and M. Bellanger, "Synchronisation de Symbole et de Chip dans le Domaine Fréquentiel pour les Systèmes DS-CDMA et MC-CDMA," in *GRETSI*, Paris, France, September 2003.

[3] L. Brühl and B. Rembold, "Unified Spatio-Temporal Frequency Domain Equalization for Multi- and Single-Carrier CDMA Systems," in *56th IEEE Vehicular Technology Conference VTC'02/Fall*, Vancouver, Canada, September 2002.

[4] F. Adachi, T. Sao, and T. Itagaki, "Performance of multicode ds-cdma using frequency domain equalisation in frequency selective fading channel," *IEE Electronics Letters*, vol. 39, no. 2, pp. 239–241, January 2003.

[5] I. Martoyo and F. K. Jondral, "Frequency Domain Equalization for the Downlink of CDMA Mobile Radio Systems," in *IEEE International Symposium on Advances in Wireless Communications ISWC2002*, Victoria, Canada, September 2002.

[6] R. Machauer, M. Iurascu and F. Jondral,"FFT speed multiuser detection for high rate data mode in UTRA-FDD," in *IEEE Vehicular Technology Conference, VTC 2001 Fall*, Altantic City, US, October 2001.

[7] A. Viterbi, "Spread spectrum communications: Mythes and realities," *IEEE Communications Magazine, 50th Anniversary Issue*, pp. 39–41, May 2002.

[8] U. Mengali and A. N. D'Andrea, *Synchronization Techniques for Digital Receivers*, 1st ed. New York and London : Plenun Press, 1997.

[9] D. Koulakiotis and A. H. Aghvami, "Data detection techniques for DS/CDMA mobile systems: a review," *IEEE Personal Communications*, vol. 7, no. 3, pp. 24–34, June 2000.

[10] *BS Radio transmission and Reception (FDD).* 3GPP TS 25.104, V5.4.0, 2002-09.

[11] S. Verdú, *Multiuser Detection*, 1st ed. Cambridge University Press, 1998.

[12] U. Madhow and M. L. Honig, "MMSE Interference Suppresion for Direct-Sequence Spread Spectrum CDMA," *IEEE Transaction on Communications*, vol. 42, no. 12, pp. 3178–3188, December 1994.