Chapter 2

Multiuser Detection

Multiuser detection (MUD) is a broad field which includes all theory pertaining to the detection of multiple users whose received signals are not orthogonal to one another. This typically corresponds to (non-orthogonal) CDMA systems, since these systems have a large number of users whose signals overlap in time and frequency.

The typical practice in CDMA systems is to independently detect each user in parallel, using a matched filter which consists of the unique spreading code used by that user. The spreading sequences are designed to be uncorrelated so that the interference from all other users will appear as non-coherent interference, and can hence be treated as simple additive white noise. By using a sufficiently large spreading factor, usually accompanied with some coding gain, the desired user can be detected after despreading as the other users' signal strengths are reduced by the spreading factor, as described in Section 1.4.

This approach, while simple and robust, is dramatically suboptimal. All the interfering users do not have to be treated as random uncancellable noise, which is a very pessimistic approach. In fact, these interfering signals have about as much structure and information content as the desired signal. The field of multiuser detection attempts to exploit this structure to achieve a higher system capacity than is currently achieved with the conventional, matched-filter receiver.

This chapter is organized as follows. First, the optimum multiuser detector, discovered by Verdu in the early 1980s [83, 84], is introduced. While the discussion in this section focuses on a synchronous system (all users aligned in time), the discussion naturally extends to an asynchronous system, with the same important conclusions. A thorough treatment of optimum multiuser detection is available in [88]. Because the optimum receiver has prohibitive complexity, there has been intense research on suboptimal techniques which approach its performance. Linear MUD, which consists of a decorrelating or minimum mean square error (MMSE) receiver, is introduced in Section 2.2, with discussion based largely upon the excellent surveys in [44, 88, 25]. Non-linear techniques that use a variant of the decorrelating or MMSE detector in conjunction with feedback are then introduced. Finally, interference cancelling detectors that don't rely on a decorrelating detector at the front end, such as the one in this dissertation, are discussed and compared with the other forms of multiuser detectors.

2.1 Optimum Multiuser Detection

Until the pioneering work of Verdu at the University of Illinois [83], it was believed that the optimum detector for a given user, say user 1, was simply the matched filter described above. This misconception derived from the assumption that the receiver for user 1 would naturally use user 1's spreading code to despread the signal before proceeding onto detect the the bits for user 1, $b_1(t)$. It's not immediately obvious why the despread versions from other users' spreading codes would help with the detection of b_1, but in fact, they can help enormously.

The optimum multiuser detector derived by Verdu jointly maximizes the likelihood functions for K users by choosing the bits $\{b_1, b_2, \ldots, b_K\}$ that minimize the mean-square error (MSE) between the estimated received signal and the actual composite received signal $y(t)$. The composite received signal $y(t)$ is the sum of the received signals for all K users, plus noise, which for an additive noise channel is:

$$y(t) = \sum_{k=1}^{K} x_k(t) A_k(t) + n(t) \tag{2.1}$$

where $x_k(t)$ is the transmitted signal for user k, A_k is the received amplitude for user

k, and $n(t)$ is additive white Gaussian noise (AWGN) with noise power σ^2.

It's worth noting that the maximum likelihood criterion doesn't necessarily minimize the bit-error rate(BER), but typically gets very close for all practical purposes. For the simple case of two users, the maximum-likelihood criterion corresponds to:

$$\max_{(b_1,b_2)} \exp\left[\frac{-1}{2\sigma^2}\int_0^T [y(t) - A_1b_1c_1(t) - A_2b_2c_2(t)]^2\, dt\right] \tag{2.2}$$

where c_k is the spreading code for user k. If just the terms with b_1 and b_2 are considered, this becomes equivalent to maximizing

$$\Omega_2(b_1, b_2) = b_1A_1y_1 + b_2A_2y_2 - b_1b_2A_1A_2\rho \tag{2.3}$$

where

$$\begin{aligned} y_k &= \int_0^T y(t)c_k(t)dt && \text{and} \\ \rho &= \int_0^T c_1c_2(t)dt && \text{is the cross-correlation of } c_1 \text{ and } c_2 \end{aligned}$$

Deducing the best two bits to pick in order to maximize (2.3) is not overly complicated. However, when the situation is extended to K users, the analogous expression to maximize is

$$\Omega_K(\mathbf{b}) = 2\mathbf{b}^T\mathbf{A}\mathbf{y} - \mathbf{b}^T\mathbf{A}\mathbf{R}\mathbf{A}\mathbf{b}. \tag{2.4}$$

Here, $\mathbf{b}$ is a Kx1 vector, $\mathbf{A}$ is a diagonal KxK matrix of channel amplitudes, and $\mathbf{R}$ is a KxK cross-correlation matrix of the user's spreading sequences, i.e. $R_{ij} = E[c_i(t)c_j(t)]$.

Maximizing (2.4) for $\mathbf{b}$ is increasingly complicated as K increases, having complexity of $O(2^K)$ for a general cross-correlation matrix, if a search tree approach is adopted en lieu of an even more time-consuming exhaustive search. It has additionally been shown in [85] that discovering a less-complex method to find the optimum $\mathbf{b}$ is unlikely, as it would also solve a number of other thoroughly studied NP-hard combinatorics problems. The search tree approach could be implemented using the well-known Viterbi algorithm, preceded by K matched-filters, but would still have

$O(2^K)$ complexity.

In addition to the complexity issue, the alert reader may have also noticed that this detector requires knowledge of the amplitudes of all K users after transmission through the channel, as well as the noise level σ^2, and the spreading signatures and timing of all K users. In typical cellular systems, the latter information is available, but *a priori* knowledge of all the user amplitudes is not. While the optimal detector provides a very large increase in capacity over the conventional matched-filter detector, these difficult issues require the search for a suboptimal multiuser detector that hopefully can achieve a large capacity gain, with lower complexity and less explicit information about the received signals. This has motivated over a decade of intense research on multiuser detection.

2.2 Linear Multiuser Detection

Linear multiuser detectors are an important class of suboptimal techniques that are additionally used in the front-end of many of the feedback-based non-linear multiuser detectors discussed in the next section. The goal of linear MUD [44, 54, 56] is to attain as much of the capacity increase from optimum MUD as possible, with a feasible and low-complexity implementation based on well-understood linear filters. From the last section, the three principle problems associated with optimum MUD are:

1. The decision algorithm complexity grows exponentially with K
2. A large amount of accurate channel and user information is required
3. K matched filters were required, where K is the number of users

These three issues will be revisited throughout this section, to see how linear MUD can relax these requirements.

2.2.1 Linear MUD: How it works

A linear multiuser detector is simply a filter that is designed to attenuate multiple-access interference (MAI) according to a specific criterion. In discrete-time, these

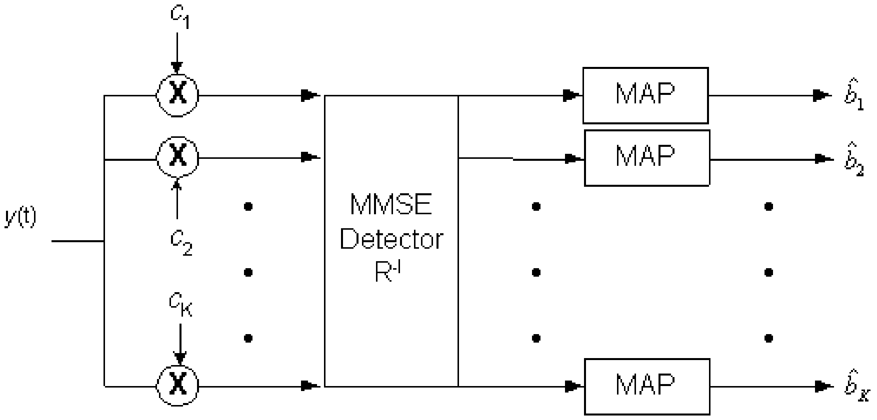

Figure 2.1: Linear Multiuser Detector Block Diagram

have a low-complexity and familiar implementation in the form of a finite impulse response (FIR) filter, also referred to as a tapped-delay line (TDL). There are two important types of linear multiuser detectors, and they are known as the decorrelating detector, and the minimum mean square error (MMSE) detector [56]. They are highly analogous to the zero-forcing and MMSE equalizers used to combat inter-symbol interference in a single-user channel [64].

The decorrelating detector attempts to completely eliminate the MAI for all users. The MMSE detector instead tries to minimize the square of the residual noise plus interference. Hence, the decorrelating detector is simply a special case of the MMSE detector, where the noise is zero. The decorrelating detector often results in unacceptable noise enhancement. Furthermore, it is undefined for the situation where there are more users simultaneously using the channel than spreading chips per information bit, since it is impossible to drive the interference to zero in this situation. For these reasons, attention will now be restricted to the more general and practical MMSE detector, with comparisons to the decorrelating detector.

The MMSE detector is depicted in Fig. 2.1. For each user, $y(t)$ is despread using a matched-filter for that user, which corresponds to a suitably synchronized version of the spreading code for user k. This is identical to conventional CDMA, and causes the signal of interest to become a strong narrowband signal, while the other users' signals remain as low-power wideband interference. After the matched-filter bank is applied, the resulting signals are passed into the MMSE detector.

The MMSE detector is the inverse of correlation matrix $\mathbf{R}$ between all the users, which is defined as:

$$\mathbf{R} = E[\mathbf{r}\mathbf{r}^T] = \sum_{k=1}^{K} A_k^2 \mathbf{c}_k \mathbf{c}_k^T + \sigma_n^2 \mathbf{I} \tag{2.5}$$

where $\mathbf{r}$ is a vector of samples of $y(t)$ over the current symbol to be detected, A_k is the received magnitude of the $k^t h$ user, $\mathbf{c}_k$ is the vector of spreading chips over the current symbol for user k, and σ_n^2 is the noise variance. This is a slightly simplified expression for $\mathbf{R}$ that conveys the important concepts of a linear multiuser detector, but doesn't take into account the number of samples, and the fact that $\mathbf{R}$ is in fact a block diagonal matrix. For a more lengthy and precise formulation, refer to [44] or [88].

The important aspects of linear MUD can be seen from (2.5) and Fig. 2.1. The first and third issues which render optimum MUD impractical have been addressed, namely the requirement for K matched-filter banks, and the complicated decision algorithm with exponentially increasing complexity in K.

2.2.2 Linear MUD Performance

In this section, the theoretical performance of the linear MUD techniques is compared with the optimal and conventional scenarios. While practical considerations may alter some of the conclusions about the merits of the various techniques, it is a good basis for discussion. The plots used for this discussion, Fig 2.2 and Fig 2.3, were provided by S. Verdu, and first appeared in [89].

First, in Fig. 2.2, the CDMA Shannon capacities are considered as a function of the system loading. The system loading is quantified as K/N, or the number of users divided by the system spreading factor. Some of the important attributes of the techniques can be seen from this figure. First, performance is bounded by the "single user bound", or as labelled on the plot "No Spreading". The orthogonal capacity increases linearly right up to $K/N = 1$, at which point no more orthogonal codes are available. The optimal multiuser detector for non-orthogonal spreading increases gradually and approaches the single-user bound as K/N becomes large.

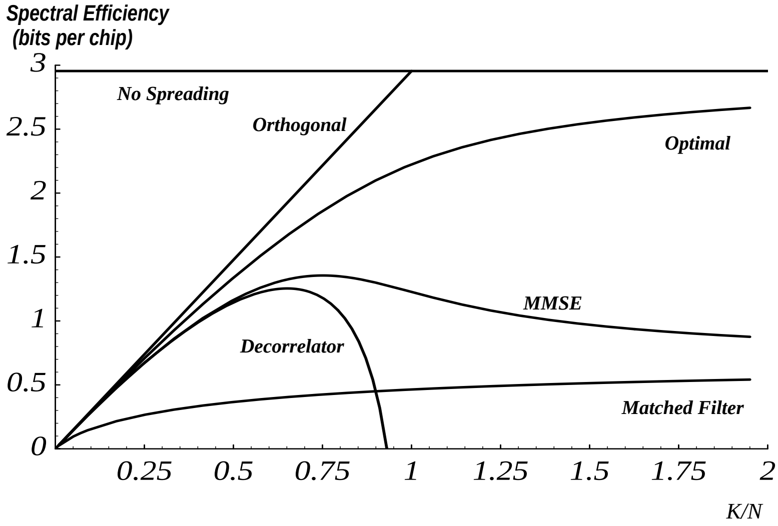

Figure 2.2: Spectral Efficiency vs. System Loading at $E_b/N_0 = 10$ dB [89]

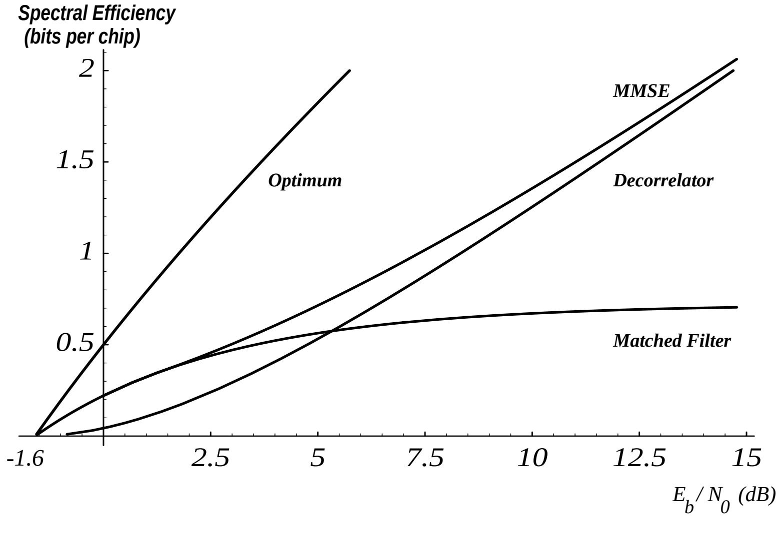

Figure 2.3: Large K Spectral Efficiencies with Optimum K/N [89]

The two linear MUD cases show interesting characteristics that are predictable from the derivations of the techniques. The decorrelating detector tries to completely remove multiple-access interference, and is undefined for $K/N > 1$. As can be seen, the performance starts to degrade sharply at about 75% loading, due to the noise enhancement that results from trying to invert the MAI of so many users. The MMSE linear multiuser detector follows similar contours to the decorrelating detector, but has a far smoother degradation in performance since it balances MAI mitigation with noise enhancement. Nevertheless, as the loading increases, its capacity also decreases asymptotically to zero. These two cases contrast to the matched filter, which shows reasonable robustness to noise and increased loading, but is suboptimal by about an order of magnitude.

Fig 2.3 shows the Shannon capacity as the E_b/N_0 increases, for large K/N. As expected, the optimum performance is far superior. The MMSE and decorrelator both have performance that increases about linearly with E_b/N_0, with the decorrelator approaching the MMSE as the noise (and hence noise enhancement) becomes small. The matched filter is superior to the decorrelating detector as low signal-to-noise ratios, but is rapidly surpassed as the system becomes MAI-limited, rather than noise-limited.

2.2.3 Linear MUD Implementation Issues

Returning our attention to the description of the linear multiuser detector in (2.5), this filter does not appear straightforward to implement, nor does it eliminate the second problem of the optimum multiuser detector – the requirement for accurate channel and user information. As can be seen in (2.5), the inversion of a KxK matrix $\mathbf{R}$ is required. As K grows large, this becomes a very complex operation. In addition, knowledge of the channels and spreading codes are required for all users, along with a noise estimate. While the spreading codes are typically known at the base station and required for all multiuser detectors, accurate channel and noise estimates may be impractical to attain.

The first problem of a KxK matrix inversion can be solved with an adaptive implementation for selecting the FIR taps [86, 40] which approximate $\mathbf{R}$, but this typically requires the spreading codes to repeat for each symbol in order for the changes in $\mathbf{R}$ from symbol to symbol to be small. Short spreading codes, however, have a number of undesirable properties with regards to their autocorrelation function, and hence multipath suppression.

The second problem of channel knowledge can be solved with a so-called *blind* adaptive algorithm for attaining the desired filter taps of $\mathbf{R}$ [55, 43, 96]. The term "blind" means that training sequences to estimate each user's channel are not required. While cleverly avoiding the capacity-reducing requirement for training, blind algorithms are typically quite noisy and slow to converge.

2.3 Non-linear Multiuser Detection

While a linear multiuser detector is easier to analyze, and lends itself easily to existing adaptive algorithms, the linearity constraint can restrict performance. In this section, a number of non-linear techniques are briefly described. They all have in common that feedback is used to reduce MAI for future attempts at detection. There is naturally some overlap with the techniques of the next section, as interference cancellation techniques are also non-linear and use previously made decisions to reduce the multiple-access interference. The techniques discussed in this section are differentiated from the successive and parallel interference cancellation techniques of the next section in that the non-linear techniques described here use a variant of the decorrelating detector to suppress interference prior to decoding.

Decision-Feedback (DF) multiuser detectors have been developed for both synchronous [26, 78] and asynchronous [1, 27, 101] applications. They are analogous to the decision-feedback equalizers developed for inter-symbol interference suppression [64], where decisions made for stronger users are used to cancel interference for later users. The feedforward filter is the Cholesky factorization of the correlation matrix $\mathbf{R}$, which yields a lower triangular matrix. The problems with this technique are similar to that of the linear multiuser detectors: accurate channel estimates are required, and a matrix inversion must be performed. If the channel estimates are accurate, the DF detector outperforms the linear detectors, with the later users approaching the single-user bound. However, the earlier users don't see an increase in performance (unlike in SIC), and integration of error-correction with this design is not straightforward. Due to its complexity and questionable robustness, it is doubtful that DF MUD can be applied to a realistic wireless channel.

Turbo MUD is a fairly recent type of nonlinear multiuser detection based on the best known technique for decoding concatenated error correcting codes [19, 23]. Decoding in turbo MUD is accomplished via an iterative process in which soft-decisions are passed back and forth between two soft-input soft-output (SISO) channel decoders, with interleaving. The early versions of turbo MUD [6, 58] showed impressive capacity approaching the optimum detector, but at the cost of exponential complexity. Later work has reduced the complexity significantly [97], while also combatting other-cell interference [98, 67]. The problems with turbo MUD are that it still requires a complex implementation with significant latency, and there are a number of unproven issues with regards to its robustness in a multipath fading channel. Nevertheless, this could be an interesting technique in the years to come.

2.4 Interference Cancellation

Interference cancellation as defined in this dissertation is different from the previous approaches to multiuser detection discussed in this chapter in that it attempts to remove multiple-access interference *after* decoding, without any other multiuser technique used in the actual forward decoding process. While the previously discussed nonlinear systems often involve a technique that could be (and often is in the literature) referred to as "interference cancellation", this is the distinction that will be used in this dissertation. The distinction is important because it relaxes a number of requirements of the filtering approaches to multiuser detection, such as accurate a priori channel estimation, and is typically much closer in design to the existing and proven CDMA receivers.

The interference cancellation approach can be divided into parallel (PIC) and successive (SIC) techniques at suppressing MAI. The PIC receiver [24, 100, 104] simultaneously processes all K users, cancelling their interference after they have all been decoded independently. The parallel techniques typically require more than one iteration per user since the first iteration generates very noisy estimates for all K users, with subsequent iterations becoming increasingly more accurate. The successive technique requires at least K iterations, but each iteration is much less complex than in PIC, being performed for only one user. The successive technique could also be applied over an integer multiple of K iterations in order to further increase performance, but this will increase latency with diminishing returns, so usually isn't considered.

Parallel interference cancellation is often also called multistage cancellation [79], and can also use a decorrelating front end [80], although this is not required. It has the advantages over SIC that it is typically lower-latency, more robust to bit errors in a given user, and attains its peak performance under the conventional CDMA requirement of equal received powers. However, under the assumption of unequal powers as in a Rayleigh fading channel, SIC has superior performance [63, 25]. If the received power levels for SIC are optimized, the capacity advantage for SIC becomes much larger.

After the results on power control and estimation error robustness that will be developed in this dissertation, the only important advantage that PIC enjoys over SIC is latency. However, this advantage is paid for at the expense of approximately K times more hardware, and reduced capacity. Further, the latency advantage becomes less important as processor speed increases. On the other hand, spectral efficiency is constantly increasing in value, as explained in Section 1.3. For these reasons, we focus on developing a functioning system design for SIC in this dissertation.

The important system design difficulties for SIC were enumerated in Section 1.6. In the next chapter, a preliminary system design for SIC is presented and optimal power control in the presence of imperfect interference cancellation is developed.

Bibliography

[1] M. Abdulrahman, A. Sheikh, and D. Falconer, "Decision Feedback Equalization for CDMA in Indoor Wireless Communications", *IEEE Journal on Selected Areas in Communications*, Vol. 12, pp. 698-706, May 1994.

[2] N. Abramson, "Multiple Access in Wireless Digital Networks", *Proceedings of the IEEE*, Vol. 82, No. 9, pp. 1360-1370, Sept. 1994.

[3] A. Agrawal, J. Andrews, J. Cioffi, T. Meng, "Power Control for Successive Interference Cancellation with Imperfect Cancellation", *IEEE International Conference on Communications*, New York, April 2002.

[4] A. Agrawal, J. Andrews, J. Cioffi, and T. Meng, "Iterative Power Control with Successive Interference Cancellation for DS-CDMA Systems", submitted to *IEEE Transactions on Vehicular Technology*, Jan. 2002.

[5] M.S. Akther, J. Asenstorger, P.D. Alexander, and M.C. Reed, "Performance of Multi-Carrier CDMA with Iterative Detection", *IEEE Interational Conference on Universal Personal Communications*, pp. 131-5, October 1998.

[6] P.D. Alexander, M.C. Reed, J.A. Asentorfer, and C.B. Schlegel, "Iterative Multiuser Interference Reduction: Turbo CDMA", *IEEE Transactions on Communication*, Vol. 47, pp. 1008-1014, July 1999.

[7] J. Andrews and T. Meng, "Amplitude and Phase Estimation Considerations for Asynchronous CDMA with Successive Interference Cancellation", *IEEE Vehicular Technology Conference*, pp. 1211-15, Boston, MA, Sept. 2000.

[8] J. Andrews and T. Meng, “Transmit Power and Other-Cell Interference Reduction via Successive Interference Cancellation with Imperfect Channel Estimation”, *IEEE International Conference on Communications (ICC)*, pp. 1940-44, June 2001.

[9] J. Andrews and T. Meng, “Optimum Power Control for Successive Interference Cancellation with Imperfect Channel Estimation”, to appear, *IEEE Transactions on Wireless Communications*, 2002.

[10] J. Andrews and T. Meng, “Multiple Access Interference Cancellation in Fading Multipath Channels: Progress and Limitations”, *IEEE Vehicular Technology Conference*, pp. 1804-8, May, 2001.

[11] J. Andrews and T.H. Meng, “Performance of MC-CDMA with Successive Interference Cancellation in a Multipath Fading Channel”, submitted to *IEEE Transactions on Communications*, March 2002.

[12] J. Andrews and T.H. Meng, “Performance of MC-CDMA with Imperfect Successive Interference Cancellation in a Multipath Fading Channel”, to appear, *IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA)*, Sept. 2002.

[13] J. Andrews, A. Agrawal, T. Meng and J. Cioffi, “A Simple Iterative Power Control Scheme for Successive Interference Cancellation”, to appear, *IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA)*, Sept. 2002.

[14] S. Ariyavisitakul and L.F. Chang, “Signal and Interference Statistics of a CDMA System with Feedback Power Control”, *IEEE Transactions on Communications*, Vol. 41, No.11, pp. 1626-1634, Nov. 1993.

[15] A. Bahai and B. Saltzburg, *Multicarrier Digital Communications: Theory and Applications of OFDM*, Kluwer Academic Publishers, New York, 1999.

[16] A. S. Bahai and G. Fettweis, “Results on Multi-carrier CDMA Receiver Design”, *IEEE International Conference on Communications*, pp. 915-18, 1995.

[17] N. Bambos, S. Chen, G. Pottie, “Radio Link Admission Algorithms for Wireless Networks with Power Control and Active Link Quality Protection”, *Proceedings, Globecom*, Vol. 1, pp. 97-104, April 1995.

[18] N. Bambos, S. Chen, G. Pottie, “Channel Access Algorithms with Active Link Protection for Wireless Communication Networks with Power Control”, *IEEE-ACM Transactions on Networking*, Vol. 8, No. 5, Oct 2000.

[19] C. Berrou, A. Glavieux, and P. Thitimajshima, “Near Shannon Limit Error-Correction Coding and Decoding: Turbo Codes”, *IEEE International Conference on Communications*, Vol. 44, pp. 1064-70, 1993.

[20] E. Biglieri, G. Caire, and G. Taricco, “CDMA System Design Through Asymptotic Analysis”, *IEEE Transactions on Communications*, Vol. 48, No. 11, pp. 1882-96, Nov. 2000.

[21] R. Bracewell, *The Fourier Transform and its Applications*, 3rd ed. New York, McGraw-Hill, 1999.

[22] B. Charney, “Europe Protests Pricey 3G Auctions”, *CNET News*, March 26, 2001.

[23] K. M. Chugg, A. Anastasopoulos, and X. Chen, *Iterative Detection: Adaptivity, Complexity Reduction, and Applications*, Kluwer Academic Press, 2001.

[24] D. Divsalar, M.K. Simon, and D. Raphaeli, “Improved Parallel Interference Cancellation for CDMA,” *IEEE Transactions on Communications*, Vol. 46, No. 2, pp. 258-68, Feb. 1998.

[25] A. Duel-Hallen, J. Holtzman, and Z. Zvonar, “Multiuser Detection for CDMA Systems”, *IEEE Personal Communications Magazine*, pp. 46-58, April 1995.

[26] A. Duel-Hallen, “Decorrelating Decision-Feedback Multiuser Detector for Synchronous CDMA”, *IEEE Transactions on Communications*, Vol. 41, pp. 285-90, Feb. 1993.

[27] A. Duel-Hallen, “A Family of Multiuser Decision-Feedback Deteectors for Asynchronous Code-Division Multiple-Access Channels”, *IEEE Transactions on Communications*, Vol. 43, pp. 421-34, Feb/Mar/Apr. 1995.

[28] L. Fang and L.B. Milstein, “Performance of Successive Interference Cancellation in Convolutionally Coded Multicarrier DS/CDMA Systems”, *IEEE Transactions on Communications*, Vol. 49, pp. 2062-7, Dec. 2001.

[29] G.J. Foschini, Z. Miljanic, “A Simple Distributed Autonomous Power Control Algorithm and its Convergence”, *IEEE Transactions on Vehicular Technology*, Vol. 42, No. 4, pp. 641-46, Nov. 1993

[30] P. Frenger, P. Orten, and T. Ottosson, “Code-Spread CDMA with Interference Cancellation”, *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 12, pp. 2090-95, Dec. 1999.

[31] P. Frenger, P. Orten, and T. Ottosson, “Code-Spread CDMA Using Maximum Free Distance Low-Rate Convolutional Codes”, *IEEE Transactions on Communications*, Vol. 48, No. 1, pp. 135-44, Jan. 2000.

[32] GSM World News, http://www.gsmworld.com/, official GSM website.

[33] K.S. Gilhousen et al, “On the capacity of a cellular CDMA system,” *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 2, pp. 303-12, May 1991.

[34] A. J. Goldsmith, L.J. Greenstein, and G. J. Foschini, “Error Statistics of Real-Time Power Measurements in Cellular Channels with Multipath and Shadowing”, *IEEE Transactions on Vehicular Technology*, Vol. 43, No. 3, pp. 439-46, Aug. 1994.

[35] M. Grebb, “Wireless Spectrum for Dummies”, *Business 2.0*, December 2000.

[36] X. Gui and T. S. Ng, "Performance of Asynchronous Orthogonal Multicarrier System in a Frequency Selective Fading Channel", *IEEE Transactions on Communications*, Vol. 47, No. 7, July 1999, pp. 1084-91.

[37] S. Hara and R. Prasad, "Overview of Multicarrier CDMA", *IEEE Communications Magazine*, pp. 126-33, Dec. 1997.

[38] S. Hara and R. Prasad, "Design and Performance of Multicarrier CDMA System in Frequency-Selective Rayleigh Fading Channels", *IEEE Transactions on Vehicular Technology*, Vol. 48, No. 5, Sept. 1999, pp. 1584-95.

[39] P. Hatrack and J.M. Holtzman, "Reduction of Other-Cell Interference with Integrated Interference Cancellation/Power Control", *IEEE Vehicular Technology Conference*, Vol. 3, pp.1842-46, 1997.

[40] S. Haykin, *Adaptive Filter Theory*, 3rd ed., Prentice Hall, 1996.

[41] J.D. Herdtner, E.K.P. Chong, "Analysis of a Class of Distributed Asynchronous Power Control Algorithms for Cellular Wireless Systems", *IEEE Journal on Selected Areas in Communications*, Vol. 18, No. 3, March 2000

[42] H. Holma, J. Laakso, "Uplink Admission Control and Soft Capacity with MUD in CDMA", *IEEE Vehicular Technology Conference*, Vol. 1, pp. 431-435, 1999.

[43] M. Honig, U. Madhow, and S. Verdu, "Blind Adaptive Multiuser Detection", *IEEE Transactions on Information Theory*, Vol. 41, No. 4, pp. 944-60, July 1995.

[44] M.L. Honig and H.V. Poor, "Adaptive Interference Suppression," *Wireless Communications: Signal Processing Perspectives*, Chap. 2, Prentice-Hall, New Jersey, 1998.

[45] R.A. Horn, C.R. Johnson, *Matrix Analysis*, Cambridge University Press, 1999

[46] C.Y. Huang, R.D. Yates, "Call Admission in Power Controlled CDMA Systems", *IEEE Vehicular Technology Conference*, Vol.3, pp. 1665-9, April 1996.

[47] A. Hui and K. Letaief, "Successive Interference Cancellation for Multiuser Asynchronous DS/CDMA Detectors in Multipath Fading Links", *IEEE Transactions on Communications*, Vol. 46, No. 3, pp. 384-91, March 1998.

[48] P. Jung, P.W. Baier, and A. Steil, "Advantages of CDMA and Spread Spectrum Techniques over FDMA and TDMA in Cellular Mobile Radio Applications", *IEEE Transactions on Vehicular Technology*, Vol. 42, No. 3, pp. 357-64, Aug. 1993.

[49] M.J. Juntti, "Multiuser detector performance comparisons in multirate CDMA systems", *IEEE Vehicular Technology Conference*, Vol. 1, pp 31-35, May 1998

[50] S. Kaiser and J. Hagenauer, "Mulit-Carrier CDMA with Iterative Decoding and Soft-Interference Cancellation", *IEEE Global Telecommunications Conference*, Vol. 1, pp. 6-10, Nov. 1997.

[51] F. Kleer, S. Hara, and R. Prasad, "Detection Strategies and Cancellation Schemes in a MC-CDMA System", Chap. 7 in *CDMA Techniques for Third Generation Mobile Systems*, Kluwer Academic Publishers, 1999.

[52] N. Kong and L. B. Milstein, "Error Probability of Multicell CDMA Over Frequency Selective Fading Channels with Power Control Error", *IEEE Transactions on Communications*, Vol. 47, No. 4, pp. 608-17, April 1999.

[53] J. Kuri, P. Mermelstein, "Call Admission on the Upink of a CDMA System based on Total Received Power", *Proceedings, IEEE International Conference on Communications*, Vol. 3, pp. 1431-6, June 1999.

[54] R. Lupas and S. Verdu, "Linear Multiuser Detectors for Synchronous Code-Division Multiple-Access Channels", *IEEE Transactions on Information Theory*, Vol. 35, No. 1, pp. 123-36, Jan. 1989.

[55] U. Madhow, "Blind Adaptive Interference Suppression for Direct-Sequence CDMA", *Proceedings of the IEEE*, Vol. 86, No. 10, Oct. 1998.

[56] U. Madhow and M.L. Honig, “MMSE Interference Suppression for Direct-Sequence Spread-Spectrum CDMA”, *IEEE Transactions on Communications*, Vol. 42, No. 12, pp. 3178-88, Dec. 1994.

[57] A.C. McCormick, P.M. Grant, and J.S. Thompson, “A Novel Interference Cancellation Receiver for Uplink Multi-Carrier CDMA”, *IEEE International Symposium on Spread Spectrum Techniques and Applications*, pp. 155-8, September 2000.

[58] M. Moher, “An Iterative Multiuser Decoder for Near-Capacity Communications”, *IEEE Transactions on Communications*, Vol. 46, pp. 870-80, July 1999.

[59] S. Moshavi, “Multi-user Detection for DS-CDMA Communications”, *IEEE Communications Magazine*, Vol. 34 No. 10, pp. 124-36, Oct. 1996.

[60] R. Muller and J. Huber, “Capacity of Cellular CDMA Systems Applying Interference Cancellation and Channel Coding”, *IEEE Global Telecommunications Conference*, pp. 179-184, Nov. 1997

[61] R. Muller and S. Verdu, “Design and Analysis of Low-Complexity Interference Mitigation on Vector Channels”, *IEEE Journal on Selected Areas in Communications*, Vol. 19, No. 8, Aug. 2001.

[62] P. Patel and J. Holtzman, “Analysis of a simple successive cancellation scheme in a DS/CDMA system”, *IEEE Journal on Selected Areas in Communications*, Vol. 12, No. 5, pp. 796-807, June 1994.

[63] P. Patel and J. Holtzman, “Performance Comparison of a DS/CDMA System Using a Successive Interference Cancellation (IC) Scheme and a Parallel IC Scheme Under Fading”, *IEEE International Conference on Communications*, pp. 510-15, May 1994.

[64] J. G. Proakis, *Digital Communications*, McGraw-Hill, New York, 1989.

[65] M. Pursley, “Performance Evaluation for Phase-Coded Spread-Spectrum Multiple-Access Communication - Part I: System Analysis”, *IEEE Transactions on Communications*, Vol. 25, No. 8, pp. 795-99, Aug. 1977.

[66] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice-Hall, NJ, 1996.

[67] D. Reynolds and X. Wang, “Turbo Multiuser Detection with Unknown Interferers”, *IEEE Transactions on Communications*, Vol. 50, No. 4, pp. 616-22, Apr. 2002.

[68] A. Salmasi and K. Gilhousen, “On the System Design Aspects of Code Division Multiple Access (CDMA) Applied to Digital Cellular and Personal Communications Networks”, *IEEE Vehicular Technology Conference*, pp. 57-62, May 1991.

[69] S. Sarkar, T. Chen, G. Leung, L. Blessent, and E. Tiedemann, “cdma2000 Reverse Link: Design and System Performance”, *IEEE Vehicular Technology Conference*, Sept. 2000.

[70] E. Seneta, *Non-negative Matrices and Markov Chains*, 2^{nd} edition, Springer Verlag, 1981.

[71] Siu Man Shum, Roger S. Cheng, “Power Control for Multirate CDMA Systems with Interference Cancellation”, *IEEE Global Telecommunications Conference*, Vol. 2, pp. 895-900, 2000.

[72] J.I. Smith, “A Computer Generated Multipath Fading Simulation for Mobile Radio”, *IEEE Transactions on Vehicular Technology*, Vol. 24, No. 3, pp. 39-40, Aug. 1975.

[73] E. Sourour and M. Nakagawa, “Two Stage Co-Channel Interference Cancellation in Orthogonal Multi-Carrier CDMA in a Frequency Selective Fading Channel”, *IEEE Personal, Indoor, and Mobile Radio Communications Conference*, pp. 189-93, 1994.

[74] E. A. Sourour and M. Makagawa, “Performance of Orthogonal Multicarrier CDMA in a Multipath Fading Channel”, *IEEE Transactions on Communications*, Vol. 44, No. 3, pp. 356-67, March 1996.

[75] G. L. Stuber, *Principles of Mobile Communication*, Addison-Wesley, Reading, MA, 1995.

[76] C.W. Sung, W.S. Wong, “A Distributed Fixed-Step Power Control Algorithm with Quantization and Active Link Quality Protection”, *IEEE Transactions On Vehicular Technology*, Vol. 48, No. 2, March 1999

[77] R.D.J. Van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*, Artech House, 2000.

[78] M. Varanasi, “Decision Feedback Multiuser Detection: a Systematic Approach”, *IEEE Transactions on Information Theory*, Vol. 45, No.1, pp. 219-40, Jan. 1999.

[79] M. Varanasi and B. Aazhang, “Multistage detection in asynchronous code-division multiple access communications”, *IEEE Transaction on Communications*, Vol. 38, pp. 509-19, Apr. 1990.

[80] M. Varanasi and B. Aazhang, “Near-Optimum Detection in Synchronous Code-Division Multiple Access Systems”, *IEEE Transactions on Communications*, Vol. 39, pp. 725-36, May 1991.

[81] V. V. Veeravalli and A. Mantravadi, “The Coding-Spreading Tradeoff in CDMA Systems”, *IEEE Journal On Selected Areas in Communications*, Vol. 20, No. 2, pp. 396-408, Feb. 2002.

[82] S. Vembu and A.J. Viterbi, “Two different philosophies in CDMA - a comparison,” *IEEE Vehicular Technology Conference*, Vol. 2, pp. 869-73, May 1996.

[83] S. Verdu, *Optimum Multiuser Signal Detection*, Ph.D. Thesis, University of Illinois at Urbana-Champaign, Aug. 1984.

[84] S. Verdu, "Minimum probability of error for asynchronous Gaussian multiple-access channels," *IEEE Transactions on Information Theory*, Vol. 32, pp. 85-96, Jan. 1986.

[85] S. Verdu, "Computational Complexity of Optimum Multiuser Detection", *Algorithmica*, 4:303-312, 1989.

[86] S. Verdu, "Adaptive Multiuser Detection", *International Symposium on Spread Spectrum Techniques and Applications*, pp. 43-50, July 1994.

[87] S. Verdu, "Demodulation in the Presence of Multiuser Interference: Progress and Misconceptions", in *Intelligent Methods in Signal Processing and Communications*, D. Docampo, A. Figueras-Vidal, Eds., pp. 15-44, Birkhauser, Boston: 1997.

[88] S. Verdu, *Multiuser Detection*, Cambridge Press, 1998.

[89] S. Verdu and S. Shamai, "Spectral Efficiency of CDMA with Random Spreading", *IEEE Transactions on Information Theory*, Vol. 45, No. 2, pp. 622-40, March 1999.

[90] A.J. Viterbi, "Spread Spectrum Communications - Myths and Realities", *IEEE Communications Magazine*, pp. 11-18, May. 1979.

[91] A.J. Viterbi, "Very low rate convolutional codes for maximum theoretical performance of spread-spectrum multiple-access channels", *IEEE Journal on Selected Areas in Communications*, Vol. 8, pp. 641-9, May 1990.

[92] A.J. Viterbi, "The Orthogonal-Random Waveform Dichotomy for Digital Mobile Personal Communications", *IEEE Personal Communications Magazine*, pp. 18-24, First Quarter 1994.

[93] A. J. Viterbi, *CDMA - Principles of Spread Spectrum Communication*, Addison Wesley, 1995.

[94] A.J. Viterbi, A.M. Viterbi, E. Zehavi, "Other-Cell Interference in Cellular Power-Controlled CDMA", *IEEE Transactions on Communications*, Vol. 42, No. 2/3/4, Feb-Apr, 1994.

[95] A.M. Viterbi, A.J. Viterbi, "Erlang Capacity of a Power Controlled CDMA System", *IEEE Journal On Selected Areas in Communications*, Vol. 11, No. 6, August 1993.

[96] X. Wang and H. V. Poor, "Blind Multiuser Detection: A Subspace Approach", *IEEE Transactions on Information Theory*, Vol. 4, No. 2, pp. 677-90, March 1998.

[97] X. Wang and H. V. Poor, "Iterative (Turbo) Soft Interference Cancellation and Decoding for Coded CDMA", *IEEE Transactions on Communications*, Vol. 47, No. 7, pp. 1046-61, July 1999.

[98] X. Wang and A. Host-Madsen, "Group-blind Multiuser Detection for Uplink CDMA", *IEEE Journal On Selected Areas in Communications*, Vol. 17, pp. 1971-84, Nov. 1999.

[99] D. Warrier and U. Madhow, "On the capacity of cellular CDMA with successive decoding and controlled power disparities," *IEEE Vehicular Technology Conference*, Vol. 3, pp. 1873-7, May 1998.

[100] J. Weng, G. Xue, T. Le-Ngoc, S. Tahar, "Multistage Interference Cancellation with Diversity Reception for Asynchronous QPSK DS/CDMA Systems over Multipath Fading Channels", *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 12, pp. 2162-80, Dec. 1999.

[101] Z. Xie, R. Short, and C. Rushforth, "A Family of Suboptimum Detectors for Coherence Multiuser Communications", *IEEE Journal on Selected Areas in Communications*, Vol. 8, No. 4, pp. 683-90, May 1990.

[102] R. D. Yates, "A Framework for Uplink Power Control in Cellular Radio Systems", *IEEE Journal on Selected Areas in Communications*, Vol. 13, No. 7, Sept. 1995.

[103] N. Yee, J.-P. Linnartz, and G. Fettweis, “Multi-carrier CDMA in indoor wireless radio networks,” in *IEEE Interational Conference on Universal Personal Communications*, pp. 109-113, Sept. 1993.

[104] Y. C. Yoon, R. Kohno, and H. Imai, “A Spread-Spectrum Multiaccess System with Cochannel Interference Cancellation for Multipath Fading Channels”, *IEEE Journal On Selected Areas in Communications*, Vol. 11, No. 7, pp. 1067-75, Sept. 1993.

[105] L. Zhao, J.W. Mark, and Y.C. Yoon, “Coding-Spreading Tradeoff Analysis for DS-CDMA Systems”, *IEEE Vehicular Technology Conference*, pp. 404-8, Oct. 2001.

[106] EIA/TIA/IS-95 mobile station-base station compatibility standard for dual-mode wideband spread spectrum cellular system, July 1993.

[107] 3GPP TS 25.214 v3.5.0 (2000-12). Physical Layer Procedures (FDD) (Release 1999)