LINEAR MULTIUSER RECEIVERS FOR ASYNCHRONOUS MC-CDMA SYSTEMS

Tiziano Bianchi, Fabrizio Argenti, and Enrico Barsali

Dipartimento di Elettronica e Telecomunicazioni, University of Florence
Via S. Marta 3, 50139, Firenze, Italy
phone/fax: +39 055 4796485, email: {bianchi, argenti, barsali}@lenst.det.unifi.it

ABSTRACT

In this paper, we propose a linear multiuser receiver for asynchronous MC-CDMA systems. The proposed receiver consists of two stages, namely a bank of MRC receivers and a MMSE multiuser detector, and it relies both on channel and delay estimation. The performance of the receiver is greatly improved with respect to the simple MRC approach. Moreover, the additional complexity is moderate, so that the proposed approach is well suited for practical applications.

1. INTRODUCTION

The next generation of wireless communications must provide a larger capacity physical layer to satisfy the requirements of bandwidth consuming services such as data and video transmission. For this purpose, the combination of Orthogonal Frequency Division Multiplexing (OFDM) and Code Division Multiple Access (CDMA) seems one of the best solutions [1]. OFDM and CDMA can be combined according to two different schemes, MC-CDMA and MC-DS-CDMA, in which either a frequency-domain spreading or a time-domain spreading is implemented, respectively.

In the case of the transmission from one access point (AP) to several mobile terminals (MTs) over a frequency-selective channel, usually MC-CDMA shows better performance than both MC-DS-CDMA and DS-CDMA, since it is able to fully exploit the frequency diversity of the channel. However, when considering the reverse link, MC-CDMA requires more complicated receiver structures [2]. Multiuser detection (MUD) techniques can sensibly improve the performance of CDMA systems in the uplink. In particular, linear MUD [3] is well suited for practical applications due to its tractable complexity.

In this paper, we propose a reduced complexity linear multiuser receiver that is based on two stages. The first stage uses a bank of maximal-ratio combining (MRC) single user receivers synchronized with the user of interest that produces a vector of temporary decision variables. The approach is similar to the MRC receiver proposed in [4], even if our method considers an all digital MC-CDMA system with a cyclic prefix. The second stage refines the MRC decision variables by means of a linear minimum mean squared error (MMSE) multiuser detector. The main difference from the classical linear MMSE receiver proposed in [5] is that our approach requires the inversion of an $N_u \times N_u$ matrix, where N_u is the number of active users, whereas the receiver in [5] would require the inversion of a $2M \times 2M$ matrix, where M is the number of subcarriers, even for a single active user.

2. ASYNCHRONOUS MC-CDMA

The MC-CDMA modulated signal of a generic user indicated by the index ℓ can be expressed by the samples

$$x_\ell(iN+m) = \frac{1}{\sqrt{N}} \sum_{k=0}^{M-1} s_{\ell,k} b_\ell(i) e^{j2\pi\frac{km}{M}},\ 0 \le m < M \quad (1)$$

where $b_\ell(i)$ is the ith transmitted bit, $s_{\ell,k}$ are the chips of the spreading sequence associated with the ℓth user and M indicates the number of subcarriers. The transmitted signal is periodically extended by means of a cyclic prefix of L samples, i.e., $x_\ell(iN+m) = x_\ell(iN+M+m)$ for $-L \le m < 0$, resulting in a symbol length of $N = M+L$ samples. If we let $n = iN+m$, then the transmitted waveform is

$$x_\ell(t) = \sum_{n=-\infty}^{+\infty} p(t-nT-\tau_\ell) x_\ell(n) \quad (2)$$

where T is the system sampling period, $p(t)$ indicates the response of the pulse shaping filter and τ_ℓ is the delay of the ℓth user. The received waveform after matched filtering is given by

$$y(t) = \sum_{\ell \in \mathscr{U}} \sum_{k=-\infty}^{+\infty} \phi_\ell(t-kT-\tau_\ell) x_\ell(k) + w(t) \quad (3)$$

where $\mathscr{U}$ is the set of the active users, $\phi_\ell(t) = p^*(-t) * g_\ell(t) * p(t)$, $g_\ell(t)$ models the effects of both the antennas and the multipath channel relative to the ℓth user and $w(t)$ models the thermal noise. If we express the users' delay as $\tau_\ell = D_\ell T + \delta_\ell$ and we sample $y(t)$ with period T, then a full digital transmission model can be obtained as

$$y(n) \triangleq y(nT) = \sum_{\ell \in \mathscr{U}} \sum_{k=-\infty}^{+\infty} h_\ell(n-k-D_\ell) x_\ell(k) + w(n) \quad (4)$$

where $h_\ell(n) \triangleq \phi_\ell(nT-\delta_\ell)$ represents the equivalent discrete time channel impulse response of the MC-CDMA system relative to the ℓth user and $w(n) \triangleq w(nT)$. In particular, we assume that the length of $h_\ell(n)$ is less than L.

2.1 Block Representation

Let $\mathbf{x}_\ell(i) = [x_\ell(iN),\ \ldots,\ x_\ell(iN+N-1)]^T$ be the vector of transmitted samples relative to the ith bit of the ℓth user. It can be expressed in a compact form as (see Fig. 1)

$$\mathbf{x}_\ell(i) = \boldsymbol{\Xi} \mathbf{W}_M^H \mathbf{s}_\ell b_\ell(i) \quad (5)$$

where the vector $\mathbf{s}_\ell = [s_{\ell,0}, \ldots, s_{\ell,M-1}]^T$ represents the spreading sequence associated to the ℓth user, $\mathbf{W}_M$ is the

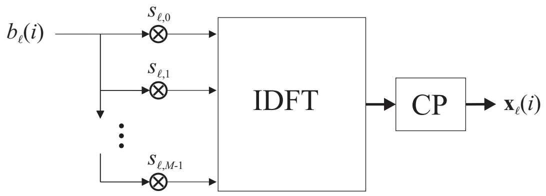

Figure 1: Block model of the ℓth user's MC-CDMA transmitter.

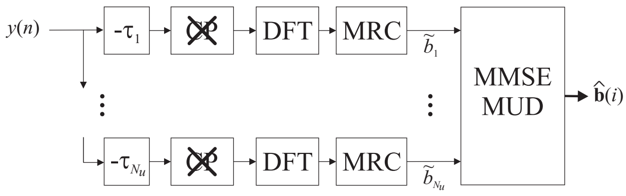

Figure 2: Block model of the MMSE-MUD receiver.

$M \times M$ DFT matrix and $\boldsymbol{\Xi}$ is a matrix that introduces the cyclic prefix. Let equation (4) be rewritten as

$$y(n) = \sum_{\ell \in \mathscr{U}} y_\ell(n - D_\ell) + w(n) \tag{6}$$

where we define $y_\ell(n) = \sum_{k=-\infty}^{+\infty} h_\ell(n-k)x_\ell(k)$ as the contribute of the ℓth user to the received signal. If we let $\mathbf{y}_\ell(i) = [y_\ell(iN), \ldots, y_\ell(iN+N-1)]^T$, then we can express the contribute of the ℓth user in matrix notation as

$$\mathbf{y}_\ell(i) = \mathbf{H}_\ell^{(0)}\mathbf{x}_\ell(i) + \mathbf{H}_\ell^{(1)}\mathbf{x}_\ell(i-1) \tag{7}$$

where $\mathbf{H}_\ell^{(0)}$ and $\mathbf{H}_\ell^{(1)}$ are defined as in [6]. Consider now the vector of received samples $\mathbf{y}(i) = [y(iN), \ldots, y(iN+N-1)]^T$. The vector $\mathbf{y}(i)$ is composed by the sum of the last samples of $\mathbf{y}_\ell(i-1)$ and the first samples of $\mathbf{y}_\ell(i)$. In matrix notation this can be expressed as

$$\mathbf{y}(i) = \sum_{\ell \in \mathscr{U}} \left[\boldsymbol{\Delta}_{-D_\ell}\mathbf{y}_\ell(i-1) + \boldsymbol{\Delta}_{D_\ell}\mathbf{y}_\ell(i)\right] + \mathbf{w}(i) \tag{8}$$

where

$$\boldsymbol{\Delta}_D = \begin{bmatrix} \mathbf{0}_{D\times(N-D)} & \mathbf{0}_D \\ \mathbf{I}_{N-D} & \mathbf{0}_{(N-D)\times D} \end{bmatrix} \tag{9}$$

$\boldsymbol{\Delta}_{-D} = \boldsymbol{\Delta}_{N-D}^T$ and $\mathbf{w}(i)$ is defined as $\mathbf{y}(i)$.

3. LINEAR RECEIVER APPROACH

As can be seen in (8), if the receiver considers a vector of N samples from the output of the matched filter this will contain only a partial information relative to two adjacent bits for each user. In order to collect sufficient information to detect at least one bit for each user, the receiver should consider a number of samples equal to $N + D_{max}$, where D_{max} indicates the maximum delay (in samples) between two users. However, in this case a linear receiver approach would require the inversion of an $(N+D_{max}) \times (N+D_{max})$ matrix irrespective of the number of active users, leading to an highly expensive implementation.

This increased receiver complexity can be avoided by resorting to a suboptimal approach. The rationale of the proposed approach is that for each active user the receiver considers a set of N samples that are synchronized with the user of interest. Consider the generic ℓth user. When detecting the ith bit of the ℓth user, the proposed receiver considers the vector $\mathbf{y}^{(\ell)}(i) = [y(iN+D_\ell), \ldots, y(iN+N-1+D_\ell)]^T$. If we suppose that the users' indexes are ordered according to their delays, then we can express the above vector as

$$\begin{aligned}\mathbf{y}^{(\ell)}(i) =& \mathbf{y}_\ell(i) + \sum_{u<\ell}\left[\boldsymbol{\Delta}_{-D_u^{(\ell)}}\mathbf{y}_u(i) + \boldsymbol{\Delta}_{D_u^{(\ell)}}\mathbf{y}_u(i+1)\right] \\ &+ \sum_{u>\ell}\left[\boldsymbol{\Delta}_{-D_u^{(\ell)}}\mathbf{y}_u(i-1) + \boldsymbol{\Delta}_{D_u^{(\ell)}}\mathbf{y}_u(i)\right] + \mathbf{w}^{(\ell)}(i)\end{aligned} \tag{10}$$

where we define the delays relative to the ℓth user either as $D_u^{(\ell)} \triangleq D_u - D_\ell$ if $D_u > D_\ell$ or $D_u^{(\ell)} \triangleq D_u - D_\ell + N$ if $D_u < D_\ell$ and $\mathbf{w}^{(\ell)}(i)$ is defined in a similar way as $\mathbf{y}^{(\ell)}(i)$.

From (10) it is evident that the vector $\mathbf{y}^{(\ell)}(i)$ contains the ith OFDM symbol from ℓth user plus some interference term due to the other asynchronous users. Hence, we can demodulate the ith bit of the ℓth user by means of a classical OFDM approach, i.e., by removing the cyclic prefix and taking the DFT of the output. In matrix notation, this can be expressed by considering the vector $\mathbf{z}^{(\ell)}(i) = \mathbf{W}_M\boldsymbol{\Theta}\mathbf{y}^{(\ell)}(i)$, where $\boldsymbol{\Theta}$ indicates cyclic prefix removing. The dependence of $\mathbf{z}^{(\ell)}$ from the transmitted bits can be expressed by rewriting it as in equation (11) at the top of the next page where $\boldsymbol{\Lambda}_\ell = \mathbf{W}_M\boldsymbol{\Theta}\mathbf{H}_\ell^{(0)}\boldsymbol{\Xi}\mathbf{W}_M^H$ is a diagonal matrix whose entries are the ℓth user's channel frequency response and we define

$$\boldsymbol{\Omega}_{\ell,\pm D}^{(n)} \triangleq \mathbf{W}_M\boldsymbol{\Theta}\boldsymbol{\Delta}_{\pm D}\mathbf{H}_\ell^{(n)}\boldsymbol{\Xi}\mathbf{W}_M^H. \tag{12}$$

In particular, if the cyclic prefix is well designed it can be shown that $\boldsymbol{\Omega}_{u,-D_u^{(\ell)}}^{(1)} = \mathbf{0}$, eliminating the dependence from $b_u(i-2)$ as well as from $b_u(i-1)$ when $u < \ell$. Relying on (11), several linear and nonlinear techniques can be applied in order to detect the desired bit. In this paper, first we will analyze a simple MRC receiver, then we will investigate a MMSE-MUD strategy that refines the decision variables obtained from the MRC.

3.1 MRC Receiver

The decision variable of the MRC receiver can be expressed as $\tilde{b}_\ell(i) = \mathbf{s}_\ell^H\boldsymbol{\Lambda}_\ell^H\mathbf{z}^{(\ell)}(i)$. In order to gain some insight about the MRC receiver, the decision variable can be expressed in a more meaningful form as

$$\begin{aligned}\tilde{b}_\ell(i) =& \gamma_\ell b_\ell(i) + \sum_{u<\ell}\left[\gamma_{\ell,u}^{(-D_u^{(\ell)})}b_u(i) + \gamma_{\ell,u}^{(D_u^{(\ell)})}b_u(i+1)\right] \\ &+ \sum_{u>\ell}\left[\gamma_{\ell,u}^{(D_u^{(\ell)})}b_u(i) + \gamma_{\ell,u}^{(-D_u^{(\ell)})}b_u(i-1)\right] + e_\ell(i)\end{aligned} \tag{13}$$

$$
\begin{aligned}
\mathbf{z}^{(\ell)}(i) =& \mathbf{\Lambda}_\ell \mathbf{s}_\ell b_\ell(i) + \sum_{u<\ell} \left[\mathbf{\Omega}^{(0)}_{u,-D_u^{(\ell)}} \mathbf{s}_u b_u(i) + \mathbf{\Omega}^{(1)}_{u,-D_u^{(\ell)}} \mathbf{s}_u b_u(i-1) + \mathbf{\Omega}^{(0)}_{u,D_u^{(\ell)}} \mathbf{s}_u b_u(i+1) + \mathbf{\Omega}^{(1)}_{u,D_u^{(\ell)}} \mathbf{s}_u b_u(i) \right] \\
&+ \sum_{u>\ell} \left[\mathbf{\Omega}^{(0)}_{u,-D_u^{(\ell)}} \mathbf{s}_u b_u(i-1) + \mathbf{\Omega}^{(1)}_{u,-D_u^{(\ell)}} \mathbf{s}_u b_u(i-2) + \mathbf{\Omega}^{(0)}_{u,D_u^{(\ell)}} \mathbf{s}_u b_u(i) + \mathbf{\Omega}^{(1)}_{u,D_u^{(\ell)}} \mathbf{s}_u b_u(i-1) \right] + \mathbf{W}_M \mathbf{\Theta} \mathbf{w}^{(\ell)}(i)
\end{aligned} \tag{11}
$$

where we define

$$\gamma_\ell \triangleq \mathbf{s}_\ell^H \mathbf{\Lambda}_\ell^H \mathbf{\Lambda}_\ell \mathbf{s}_\ell \tag{14}$$

$$\gamma_{\ell,u}^{(-D_u^{(\ell)})} \triangleq \mathbf{s}_\ell^H \mathbf{\Lambda}_\ell^H \left(\mathbf{\Omega}^{(0)}_{u,-D_u^{(\ell)}} + \mathbf{\Omega}^{(1)}_{u,D_u^{(\ell)}} \right) \mathbf{s}_u \tag{15}$$

$$\gamma_{\ell,u}^{(D_u^{(\ell)})} \triangleq \mathbf{s}_\ell^H \mathbf{\Lambda}_\ell^H \mathbf{\Omega}^{(0)}_{u,D_u^{(\ell)}} \mathbf{s}_u \tag{16}$$

$$e_\ell(i) \triangleq \mathbf{s}_\ell^H \mathbf{\Lambda}_\ell^H \mathbf{W}_M \mathbf{\Theta} \mathbf{w}^{(\ell)}(i). \tag{17}$$

In (13), it is shown that the decision variable is proportional to the desired bit plus an interference term that depends on data transmitted by the other active users, their channel status and their relative delays. We suppose that these quantities are all known to the receiver, so that a strategy that reduces the impact of this interference can be derived.

3.2 MMSE-MUD Receiver

Linear Multiuser Detectors are proved to achieve good performance in uplink CDMA communication while retaining the receiver complexity reasonably low. Let us consider the vector $\mathbf{b}(i) = [b_1(i), \ldots, b_{N_u}(i)]^T$ containing the ith bit of all active users, as well as the vector $\tilde{\mathbf{b}}(i) = [\tilde{b}_1(i), \ldots, \tilde{b}_{N_u}(i)]^T$ containing the output of the MRC receivers. In particular, we suppose that the AP processes the received signal through a bank of N_u MRC receivers each synchronized with a different user, as shown in Fig. 2. The output of this bank of MRC receivers can be expressed as

$$\tilde{\mathbf{b}}(i) = \mathbf{\Gamma} \mathbf{b}(i) + \mathbf{\Gamma}_B \mathbf{b}(i-1) + \mathbf{\Gamma}_F \mathbf{b}(i+1) + \mathbf{e}(i) \tag{18}$$

where we define

$$[\mathbf{\Gamma}]_{\ell,u} \triangleq \begin{cases} \gamma_{\ell,u}^{(-D_u^{(\ell)})} & u<\ell \\ \gamma_\ell & u=\ell \\ \gamma_{\ell,u}^{(D_u^{(\ell)})} & u>\ell \end{cases} \tag{19}$$

$$[\mathbf{\Gamma}_B]_{\ell,u} \triangleq \begin{cases} \gamma_{\ell,u}^{(-D_u^{(\ell)})} & u>\ell \\ 0 & \text{elsewhere} \end{cases} \tag{20}$$

$$[\mathbf{\Gamma}_F]_{\ell,u} \triangleq \begin{cases} \gamma_{\ell,u}^{(D_u^{(\ell)})} & u<\ell \\ 0 & \text{elsewhere} \end{cases} \tag{21}$$

whereas $\mathbf{e}(i) = [e_1(i), \ldots, e_{N_u}(i)]^T$. Relying on (18), the MMSE-MUD receiver can be expressed as

$$\hat{\mathbf{b}}(i) = \mathbf{\Gamma}^H \left(\mathbf{\Gamma}\mathbf{\Gamma}^H + \mathbf{\Gamma}_B \mathbf{\Gamma}_B^H + \mathbf{\Gamma}_F \mathbf{\Gamma}_F^H + \frac{1}{\sigma_b^2} \mathbf{R}_{\mathbf{ee}} \right)^{-1} \tilde{\mathbf{b}}(i) \tag{22}$$

where σ_b^2 indicates the power of the transmitted bits and $\mathbf{R}_{\mathbf{ee}} = E\{\mathbf{e}\mathbf{e}^H\}$. The receiver in (22) requires the inversion of an $N_u \times N_u$ matrix, thus resulting in a feasible implementation.

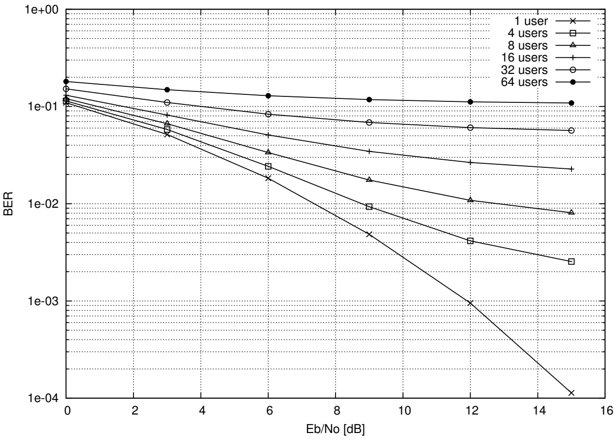

Figure 3: Bit error rate of MRC receiver with different numbers of active users.

4. SIMULATION RESULTS

The performance of the proposed receiver has been verified by simulating the uplink of an MC-CDMA system with the Monte Carlo method. The information bits are BPSK modulated and multiplied by 64-chip long Walsh-Hadamard spreading sequences. The multicarrier modulation uses 64 subcarriers. We use a cyclic prefix of 16 samples, so that the symbol length is $N = 80$ samples. The system sampling period is $T = 50$ ns, resulting in a 20 MHz bandwidth. The carrier frequency is 5 GHz. The users are supposed to transmit with random delays that are modeled as independent random variables with uniform distribution in the interval $[0, NT)$.

Each user transmits over an independent Rayleigh fading channel modeled according to the specifications of channel A in [7]. The maximum speed of the mobile terminals is 3 m/s, corresponding to a coherence time of about 20 ms which is large compared with the symbol duration.

We have simulated two different systems. The first one, referred to as MRC, employs a bank of MRC receivers synchronized with the user of interest. The second one, referred to as MMSE-MUD, refines the decision variables of the MRC receiver using the MMSE approach in (22). The proposed systems have been simulated considering different system loads, ranging from a single active user to 64 active users, i.e., the maximum allowable system load. In the case of a partially loaded system, the results have been averaged taking into account different subsets of spreading sequences.

The performance of the MRC system is shown in Fig. 3. As can be seen, even for small system loads the bit error rate (BER) suffers from a severe degradation. In particular, it is evident the error floor caused by the interference among the users. The performance of the MMSE-MUD system, shown in Fig. 4, appears to be sensibly improved. The MMSE-

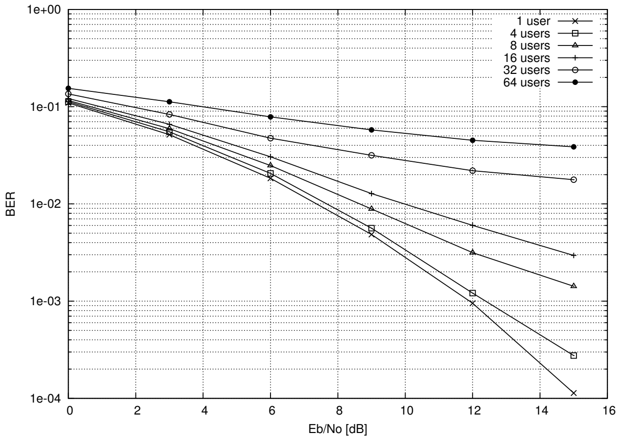

Figure 4: Bit error rate of MMSE-MUD receiver with different numbers of active users.

MUD receiver achieves the same BER performance of the MRC receiver with a system load up to four times that of the MRC system, as can be seen by comparing the curve referring to 4 users in Fig. 3 with the curve referring to 16 users in Fig. 4.

5. CONCLUSIONS

We have proposed a linear multiuser receiver for the uplink of an MC-CDMA system where the active users are completely asynchronous. The proposed receiver consists of two stages, namely a bank of MRC single user receivers synchronized with the user of interest and an MMSE multiuser detector, and it relies on the estimation of both channel status and users' delay. The performance of the proposed receiver appear to be significantly improved with respect to the simple MRC approach. Moreover, the additional complexity is sustainable and allow the proposed approach to be used in practical implementations.

A. DERIVATION OF $\mathbf{R}_{\mathbf{ee}}$

The generic element of the covariance matrix $\mathbf{R}_{\mathbf{ee}}$ is given by

$$[\mathbf{R}_{\mathbf{ee}}]_{u,v} = E\{e_u(i)e_v(i)^H\} \tag{23}$$

where we have $e_u(i) = \mathbf{s}_u^H \mathbf{\Lambda}_u^H \mathbf{W}_M \mathbf{\Theta} \mathbf{w}^{(u)}(i)$. Therefore, we can rewrite equation (23) as

$$[\mathbf{R}_{\mathbf{ee}}]_{u,v} = \mathbf{s}_u^H \mathbf{\Lambda}_u^H \mathbf{W}_M E\{\mathbf{n}_u \mathbf{n}_v^H\} \mathbf{W}_M^H \mathbf{\Lambda}_v \mathbf{s}_v \tag{24}$$

where $\mathbf{n}_u = \mathbf{\Theta}\mathbf{w}^{(u)}(i)$ and we drop the index i from the noise process since we assume it stationary.

The problem of deriving the (u,v)th element of $\mathbf{R}_{\mathbf{ee}}$ reduces then to the derivation of the covariance matrix $E\{\mathbf{n}_u\mathbf{n}_v^H\}$. If $u = v$ the two noise vector coincide and we have $E\{\mathbf{n}_u\mathbf{n}_v^H\} = \sigma_w^2 \mathbf{I}_M$. If $u \neq v$, since $\mathbf{R}_{\mathbf{ee}}$ is Hermitian we can restrict our derivation to the case $u < v$ and then take the complex conjugate in the case of $u > v$. By considering that the vectors $\mathbf{n}_u$ and $\mathbf{n}_v$ represent the sampling of the same noise process in different time intervals, we can deduce that

$$E\{\mathbf{n}_u\mathbf{n}_v^H\} = \sigma_w^2 \mathbf{\Delta}_{D_v - D_u} \tag{25}$$

where $\mathbf{\Delta}_D$ is defined as in (9). Hence, the covariance matrix of $\mathbf{e}(i)$ is given by

$$[\mathbf{R}_{\mathbf{ee}}]_{u,v} = \begin{cases} \sigma_w^2 \mathbf{s}_u^H \mathbf{\Lambda}_u^H \mathbf{W}_M \mathbf{\Delta}_{D_v - D_u} \mathbf{W}_M^H \mathbf{\Lambda}_v \mathbf{s}_v & u < v \\ \sigma_w^2 \mathbf{s}_u^H \mathbf{\Lambda}_u^2 \mathbf{s}_u & u = v \\ [\mathbf{R}_{\mathbf{ee}}]_{v,u}^* & u > v. \end{cases} \tag{26}$$

REFERENCES

[1] S. Hara and R. Prasad, "Overview of multicarrier CDMA," *IEEE Commun. Mag.*, vol. 35, no. 12, pp. 126–133, Dec. 1997.

[2] S. Hara and R. Prasad, "Design and performance of multicarrier CDMA system in frequency-selective rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 48, no. 5, pp. 1584–1595, Sept. 1999.

[3] R. Lupas and S. Verdú, "Linear multiuser detectors for synchronous code-division multiple-access channels," *IEEE Trans. Inform. Theory*, vol. 35, no. 1, pp. 123–136, Jan. 1989.

[4] X. Gui and T. S. Ng, "Performance of asynchronous orthogonal multicarrier CDMA system in frequency selective fading channel," *IEEE Trans. Commun.*, vol. 47, no. 7, pp. 1084–1091, July 1999.

[5] P. Zong, K. Wang, and Y. Bar-Ness, "Partial sampling MMSE interference suppression in asynchronous multicarrier CDMA system," *IEEE J. Select. Areas Commun.*, vol. 19, no. 8, pp. 1605–1613, Aug. 2001.

[6] Z. Wang and G. B. Giannakis, "Wireless multicarrier communications: where Fourier meets Shannon," *IEEE Signal Processing Mag.*, vol. 47, no. 3, pp. 29–48, May 2000.

[7] J. Medbo and P. Schramm, "Channel models for HIPERLAN/2 in different indoor scenarios," Tech. Rep. 3ERI085B, ETSI BRAN, Mar. 1998.