行政院國家科學委員會專題研究計畫　成果報告

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計畫主持人：蘇育德

計畫參與人員：陳勝志、陳彥志、余俊宏、黃俊傑

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行政院國家科學委員會補助專題研究計畫成果報告

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※ 前瞻性B3G無線接取技術(I) ※
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計畫編號：NSC 91-2219-E-009 -023
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計畫主持人： 蘇育德 教授
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行政院國家科學委員會專題研究計畫成果報告

前瞻性 B3G 無線接取技術:同步與通道估計技術(I)

Advanced Technologies for B3G Radio Access:

Synchronization and channel estimation algorithms(I)

計畫編號: NSC 91-2219-E-009 -023

執行期限：91 年 8 月 1 日至 92 年 7 月 31 日

主持人：蘇育德教授　交通大學電信工程系

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一、中文摘要

(Orthogonal Frequency Division Multiplexing, OFDM) 是一種可以有效抵抗選擇性衰退的方法，另一方面，分碼多重擷取（CDMA）則提供較傳統多工更多的容量。因此，此計畫目的在於結合 OFDM 與 CDMA 的優點來提供更好的抗多重路徑與抗衰褪的多用戶高速傳輸。

我們針對 OFDM-CDMA 系統推導出最佳同步及非同步接收機之架構並完成了模型式最小平方逼近（Model-based Least-square Fitting, MB-LSF）二維通道估測器. 我們也探討了通道估測器的參數設定會為信號錯誤率(BER)帶來如何的影響，以及影響單一使用者信號的偵測。

關鍵詞：OFDM、CDMA、MB-LSF、通道估測、多重路徑衰退。

二、計畫緣由與目的

Multi-carrier systems have been extensively studied in the last decade. The successful launching of the European digital broadcasting standard based on multi-carrier technique, the direct audio broadcast (DAB) system [1], has further accelerated the development and application of various multi-carrier systems.

Orthogonal Frequency Division Muiltiplexing (OFDM) is an effective multi-carrier waveform for combating frequency-selective fading. On the other hand, the code division multiple access (CDMA) technique has attracted a great deal of interest for its potential to offer system capacity larger than those achieved by other conventional multiple access techniques. Therefore, it is conceived that OFDM combined with CDMA (OFDM-CDMA) can provide enhanced anti-multipath fading capability while accommodating a large number of active system users.

In 1993, a radio access scheme that combines the multi-carrier and spread spectrum techniques known as multi-carrier spread spectrum (MC-SS), was proposed by Yee [2]. Kaiser [3] later suggested a similar scheme called OFDM-CDMA which is now also referred to as the MC-CDMA scheme. In this project, we will derive optimal synchronous frequency-domain spread OFDM-CDMA receivers and evaluate their performance.

Optimal detection of a wideband signal like that generated by a OFDM-CDMA transmitter calls for fast and accurate channel estimation so that data demodulation can be accomplished. Many channel estimation proposals have been reported and evaluated. A survey of the existing estimators concludes that the model-based least-square fitting (MB-LSF) algorithm [4], [5] can serve our application well. Since the 2-D block selecting of MB-LSF is critical to its performance, we will study how the system performance is affected by the 2-D block selection and obtain the optimal system parameters. The MB-LSF algorithm does not need the matrix inversion operation and channel statistics like the channel correlation matrix and the noise power level. Moreover, MB-LSF is independent of the block length used while for the conventional LMMSE method larger block size means larger matrix size and more cumbersome matrix inversion. We assume that the orthogonal Walsh codes are used by the system as the spreading codes.

三、結果與討論

Part I：System and Channel Models

A. The transmitter block

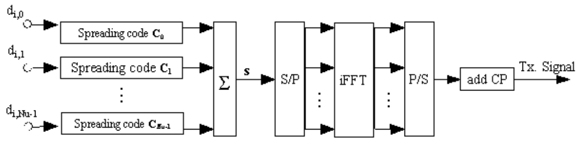

Fig. 1. A transmitter of a synchronous OFDM-CDMA system

A model of a synchronous OFDM-CDMA system transmitter is plotted in Fig. 1. Similar to the notation used in Fig. 1, $\{d_{i,0}, d_{i,1}, ..., d_{i,N_u-1}\}$ are the ith data symbol that is spread by the signature code $\{c_0, c_1, ..., c_{N_u-1}\}$. Let $s_{i,j}$ be the signal vector representing the *i*th data symbol of the *j*th user after spreading, we have

$$s_{i,j}[n] = d_{i,j} \cdot c_j[n], \qquad n = 0, 1, \ldots, N-1 \quad (1)$$

$$\mathbf{s}_{i,j} = [\ s_{i,j}[0] \quad s_{i,j}[1] \quad \ldots \quad s_{i,j}[N-1]\ ]^T$$
$$\mathbf{c}_j = [\ c_j[0] \quad c_j[1] \quad \ldots \quad c_j[N-1]\ ]^T,$$

where N is the FFT block size. The received discrete-time noiseless sample stream that consists of all users' signals after serial-to-parallel conversion and inverse DFT can be expressed as

$$a_i[k] = \frac{1}{N} \cdot \sum_{n=0}^{N-1} \sum_{j=0}^{N_u-1} s_{i,j}[n] \cdot e^{j2\pi nk/N}, \qquad (2)$$

$$x[k] = \sum_{i=-\infty}^{\infty} a_i[(k-N_G)_N] \qquad (3)$$
$$k = 0, 1, \ldots, N+N_G-1,$$

where $k = 0,1,2,\ldots, N-1$. Note that a circular prefix of is added to each OFDM frame (block)

$$x(t) = \sum_{k=-\infty}^{\infty} x[k] p(r - kT_c) \qquad (4)$$

$$p(t) = \begin{cases} 1, & 0 \le t < T_c \\ 0, & \text{else} \end{cases}$$

B. A multi-path channel mode

We sample the continuous-time impulse response *h(t)* at a rate of T_c, then we have

$$h[n] = h(nT_c) \qquad (5)$$

Thus, the channel impulse response after sampling is modeled as

$$h[k] = \sum_{l=0}^{L-1} \alpha_l[k] \cdot \zeta\left[k - \frac{\tau_l}{T_c}\right] \qquad (6)$$

where L is the total number of the multipath, τ_l is the l lth path delay. $\alpha_l[k]$ is the complex attenuation coefficient and is generated by Jake's model [6].

As signals transmit through multi-path channel, the received signal is written as

$$r[k] = h[k] \otimes x[k] + w[k] \qquad (7)$$

where $w[k]$ is a white noise sequence.

C. A candidate receiver structure

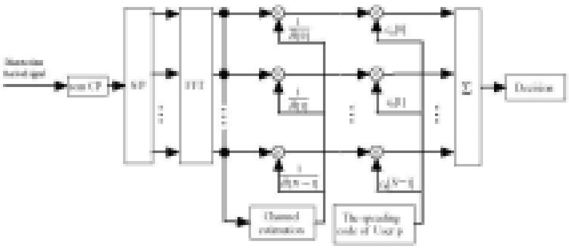

Fig. 2. A receiver structure for synchronous OFDM/CDMA signals

Fig. 2. shows the receiver structure of a single user. After initial timing and frequency synchronization, we remove the circular prefix of each OFDM frame and then perform the discrete Fourier transform (DFT).

As the DFT operator is a transform from time domain to frequency domain, we write frequency channel response as

$$H[n] = \sum_{k=0}^{N-1} h[k] \cdot e^{-j2\pi nk/N} \qquad (8)$$

which can also be expressed in vector form

$$H = [H[0] \ \ H[1] \ \Lambda \ H[n-1]] \qquad (9)$$

When $N_G \ge L$, we can safely assume that the received samples are free of inter-symbol interference (ISI) after removing the circular prefix. Therefore, we rewrite the DFT output samples as [3]

$$\mathrm{R}_i = \mathrm{H}_i \sum_{j=0}^{N_u-1} s_{i,j} + \mathrm{W}_i \qquad (10)$$

where

$$\mathbf{R}_i = [\ R_i[0] \quad R_i[1] \quad \ldots \quad R_i[N-1]\ ]^T$$
$$\mathbf{s}_{i,j} = [\ s_{i,j}[0] \quad s_{i,j}[1] \quad \ldots \quad s_{i,j}[N-1]\ ]^T,$$
$$\mathbf{W}_i = [\ W_i[0] \quad W_i[1] \quad \ldots \quad W_i[N-1]\ ]^T,$$
$$W_i[n] = \sum_{k=0}^{N-1} w[k] \cdot e^{-j2\pi nk/N}.$$

Assuming the estimated channel is given by

$$\tilde{\mathrm{H}}_i = [\tilde{H}_i[0] \ \tilde{H}_i[1] \ \Lambda \ \tilde{H}_i[\mathrm{N-1}]]^T \qquad (11)$$

we can use $\tilde{\mathrm{H}}_i$ to equalize (Zero-Forcing) the received signal.

$$\hat{R}_i[n] = \frac{1}{\tilde{H}_i[n]} \cdot R_i[n] = u_i[n] \cdot \sum_{j=0}^{N_u-1} s_{i,j}[n] + \hat{W}_i[n] \qquad (12)$$

Next, we despread the above signal by the desired user's signature code. Assuming user *0* is the desired user, $\hat{d}_{i,0}$ of the desired user is given by

$$\hat{d}_{i,0} = \sum_{n=0}^{N-1} \left(u_i[n] \cdot s_{i,0}[n] + u_i[n] \cdot \sum_{j=1}^{N_u-1} s_{i,0}[n] + \hat{W}_i[n] \right) \cdot c_0[n]$$
$$= d_{i,0} \cdot \varepsilon_i + \rho_{MAI_i} + \rho w_i \qquad (13)$$

where

$$\varepsilon_i = \sum_{n=0}^{N-1} u_i[n] c_0[n] c_0[n],$$

$$\rho_{MAI_i} = \sum_{j=1}^{N_u-1} d_{i,j} \sum_{n=0}^{N-1} u_i[n] c_j[n] c_0[n],$$

$$\rho w_i = \sum_{n=0}^{N-1} \hat{W}_i[n] \cdot c_0[n]$$

Noted that if perfect channel estimate is available i.e, $\tilde{H}_i[n] = H_i[n], n = 0,1,\ldots\ldots,N-1$, then $u_i[n] = 1 \ \forall n$, and the multiple access interference ρ_{MAI_i} disappears. Hence it is important that we obtain a good channel estimator.

In the following section, we present a novel channel estimation estimator to serve such a design purpose.

Part II: Model-Based LS-Fitting Channel Estimate

The model-based least-square-fitting estimation method proposed in [4], [5] is employed as our OFDM-CDMA channel estimator. To begin with, let us assume that all users adopt the same pilot symbol distribution.

$$\begin{aligned} \mathrm{R}_i &= \mathrm{H}_i \sum_{j=0}^{N_u-1} \left(\frac{1}{N_u} \cdot \mathrm{P}_i \right) + \mathrm{W}_i \\ &= \mathrm{H}_i \mathrm{N}_u \left(\frac{1}{N_u} \cdot \mathrm{P}_i \right) + \mathrm{W}_i \\ &= \mathrm{H}_i \cdot \mathrm{P}_i + \mathrm{W}_i \end{aligned} \tag{14}$$

where P_i is the vector of the transmitted pilot symbols and

$$\mathrm{P}_i = [P_i[0] \ P_i[1] \Lambda \ P_i[N-1] \ ]^T$$

We now rewrite the received samples at the pilot locations as

$$R_i[n] = H_i[n] \cdot P_i[n] + W_i[n] \tag{15}$$

$$\hat{H}_i[n] = \frac{R_i[n]}{P_i[n]} = H_i[n] + \frac{W_i[n]}{P_i[n]} \tag{16}$$

Since the discrete channel response $H_i[n]$ can be view as a sampled version of two dimensional continuous complex fading process. We consider 2-D blocks for making use the time- and frequency-correlation between channel responses.

The selected 2D-block contains L_t. L_n channel responses in the time-frequency domain. The MB-LSE estimator models the true channel response (CR) $H_i[n]$ within this block by a quadrature surface. As Fig. 3, we insert a pilot in every r_t OFDM-symbols, then there will be L_t. L_n pilot symbols in the selected block, where $L_t = \frac{L_i}{r_t} + 1$.

The true sampled fading process $H_i[n]$ within the region is modeled as a quadrature surface. For example,

$$\begin{aligned} F(i,n,\mathbf{c}) &= c_0 n^2 + c_1 n i + c_2 i^2 + c_3 n + c_4 i + c_5, \\ & 0 \le i < L_t \\ & aL_n \le n < (a+1)L_n \quad a = 0,1,\ldots,q-1 \end{aligned} \tag{17}$$

where the coefficient vector= $c = (\mathrm{c}_0, \mathrm{c}_1, \Lambda\ )^T$ and $q \cdot L_n = N$, for some positive integer q. The relationship between $F(I,n,c)$ and true channel response $H_i[n]$ is

$$F(i,n,\mathbf{c}) = \mathbf{H_i[n]} + \mathbf{g(i,n)} \tag{18}$$

where $g(i,n)$ represents the modeling error. By choosing the surface to fit the tentative estimates in a block, ***c*** is chosen such that the squared modeling error

$$\begin{aligned} & \min_{\mathbf{c}} \sum_{(i,n)\in\mathcal{P}} \left| \frac{R_i[n]}{P_i[n]} - F(i,n,\mathbf{c}) \right|^2 \\ &= \min_{\mathbf{c}} \sum_{(i,n)\in\mathcal{P}} \left| \hat{H}_i[n] - F(i,n,\mathbf{c}) \right|^2 \end{aligned} \tag{19}$$

is minimized. The set ρ denotes the set of all pilots symbols in the selected 2-D block.

$$\mathcal{P} = \left\{ (i,n) \;\middle|\; \begin{array}{c} i = 0, r_t, 2r_t, \ldots, (L_t - 1)r_t \\ n = 0, 1, 2, \ldots, (L_n - 1) \end{array} \right\} \tag{20}$$

For simplification, we estimate the real part of ***c*** and imagine part of ***c*** respectively. After ***c*** is determined, the estimated CR $\tilde{H}_i[n]$ is obtained by

$$\begin{aligned} \Re\left\{ \hat{H}_i[n] \right\} &= F(i,n,\Re\{\mathbf{c}\}) \\ \Im\left\{ \hat{H}_i[n] \right\} &= F(i,n,\Im\{\mathbf{c}\}) \end{aligned} \tag{21}$$

Since

$$\begin{aligned} L_i \cdot N &= L_i \cdot (qL_n) \\ &= q(L_i \cdot L_n), \end{aligned} \tag{22}$$

we can divide a block with L_iN CR's into q2-D blocks to perform channel estimator independently. Depending on the choice of L_n, L_n will be adjusted according to the variation of the true channel response. In low SNR, large L_n can suppress the additive noise impact, while larger L_n induces channel modeling error in high SNR [4], [5]. This fact will become evident later when we present our simulation results.

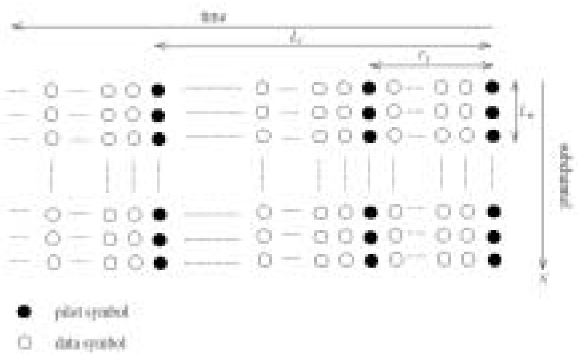

Fig. 3. A pilot symbol distribution in the time-frequency plan.

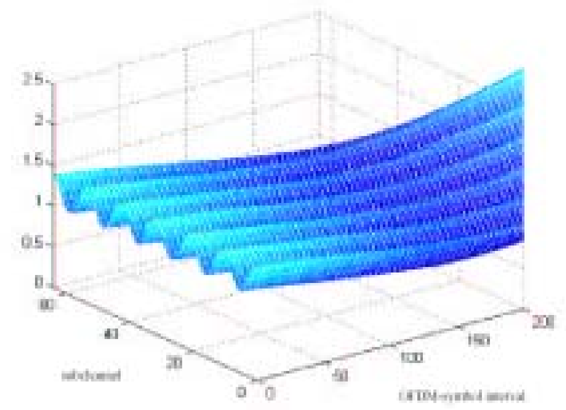

Fig. 4. Frequency domain channel response; Doppler spread 200 Hz over a 200 OFDM symbol interval.

Part III：Numerical Results

The numerical examples given below assume a synchronous OFDM-CDMA system with a bandwidth of 20 MHz and 64 subchannels--the same as the processing gain. We use the family of Walsh codes as our signature codes. Different Doppler spread of fading channel is investigated, but we assume perfect synchronization of carrier frequency. For example, Doppler spread of the fading channel as the carrier frequency 5GHz at mobile speed of 50km/hr is 200Hz. The channel is setup as Table I.

Tap	Delay	Frac. Power
0	$0 \cdot T_c$	0.8
1	$6 \cdot T_c$	0.2

TABLE I
PAPAMETERS OF A TWO-TAP STATIC CHANNEL MODEL

The numerical performance of synchronous OFDM-CDMA systems employing an MB-LSF channel estimator will demonstrate that non-perfect channel estimation results in MAI even if synchronous orthogonal Walsh codes are used. As mentioned before, we model a 2D channel response block by a quadratic surface. The ensuing numerical examples assume that L_i=68 and L_n=1,8 or 64. Since 20MHz is a large bandwidth which is the standard of IEEE 802.11a, the channel response in frequency domain will vary seriously due to selective fading. We have to choose proper L_i and L_n such that the model, Eq (18), suffices for accurately representing the true channel responses.

Fig. 4. plots typical channel response for a Doppler spread of 200 hz over a 64 sub-carrier and 200 OFDM-symbol interval. Fig. 5. shows the system performance with perfect channel knowledge. Since we use the orthogonal code (Walsh code) as the spreading code, there is no MAI when perfect CSI is available. Fig. 6. plots the system with QAM modulation and $L_n = 1$. Figs. 7., 8., and 9. plot the system performance when L_n = 1, 8, 64, respectively. As the channel estimator with a larger L_n tends to yield smaller noise-induced error but larger modeling error. Thus at low SNRs where the bit error rate (BER) is primarily caused by noise, larger L_n brings about better BER performance while at high SNRs BER is mainly due to the modeling error, a reverse trend is noticed. We conclude that the choice of L_n is a tradeoff between modeling error and the noise-induced error.

As we can see from Figs. 11, 12, and 13, the performance is not sensitive to the Doppler spread within the range of interest. This is predictable since the channel coherent time, which is roughly the reciprocal of the Doppler spread is small with respect to L_i OFDM symbol intervals.

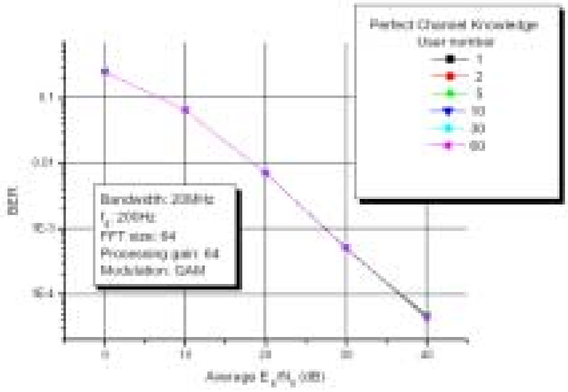

Fig. 5. Performance of synchronous OFDM-CDMA systems with QAM modulation and perfect CSI.

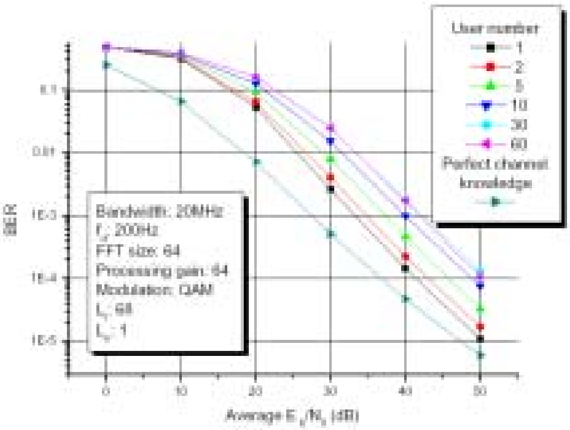

Fig. 6. Performance of synchronous OFDM-CDMA systems with QAM and L_n = 1.

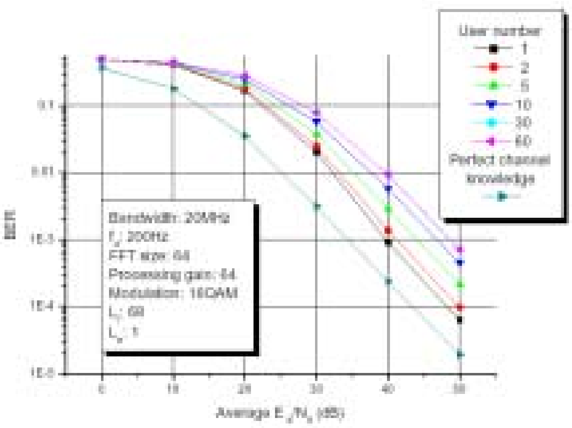

Fig. 7. Performance of synchronous OFDM-CDMA systems with 16QAM and L_n=1.

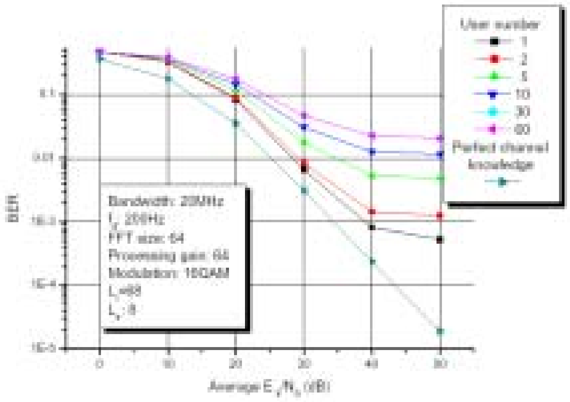

Fig. 8. Performance of synchronous OFDM-CDMA systems with 16QAM and $L_n = 8$.

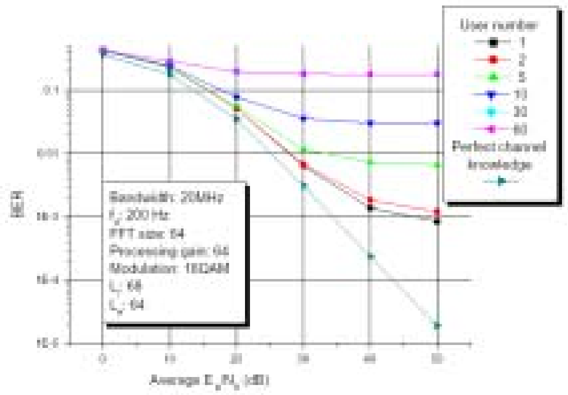

Fig. 9. Performance of synchronous OFDM-CDMA systems with 16QAM and $L_n = 64$.

四、計畫成果自評

本計畫已如期完成了針對 OFDM-CDMA 系統完成了最佳同步及非同步接收機之架構之推導，發展了一種以迴歸模式為基礎的最小平方逼近（Model-based Least-square Fitting, MB-LSF）二維通道估測器，並探討通道估測器的參數設定如何影響信號錯誤率(BER)。配合其他子計畫的成果，我們相信，在 B3G 空中介面的研究，我們已經奠定了相當廣泛且良好的基礎。

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