

# A Combined OFDM-CsDMA Approach to Cellular Mobile Communications

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**Abstract**— We present a combined orthogonal frequency-division multiplexing (OFDM) and code-division multiple-access cellular system. It is derived from the OFDM model by introducing an extra code-shift division multiple access layer. This mitigates intercell interference without affecting intracell orthogonality and such property can be maintained in multipath environments. The new scheme is suitable for both up and down links. It retains the low-receiver complexity property of the OFDM system.

**Index Terms**— Code-division multiple-access, land mobile radio cellular systems, mixed TDMA/FDMA/CDMA systems, personal communication networks.

## I. INTRODUCTION

THE CAPACITY of a code-division multiple-access (CDMA) system can be enhanced by suppressing multiple-access interference (MAI). Maximum-likelihood (ML) estimation technique can be used for this purpose, but the complexity involved is generally high [1]–[3].

In this paper we present a new CDMA scheme free from intracell MAI. Starting from an orthogonal frequency-division multiplexing (OFDM) model [4], we derive the proposed scheme by introducing an extra code-shift division multiple access (CsDMA) layer [5]. The new layer does not affect the normal transmission of the original system, but it provides a spreading effect to alleviate the intercell MAI problem. The orthogonality among same-cell users is maintained in a multipath environment. The receiver is realized by a simple quasi-coherent detection technique without the necessity of high-cost ML estimation.

When used for the up links, frame synchronization among same-cell users is assumed in the proposed scheme. However, the accuracy requirement is very flexible as frame synchronization error can be treated in essentially the same way as random delay.

## II. THE CYCLIC PREFIX TECHNIQUE

Let  $\mathbf{x} = \{x_n\}$  and  $\mathbf{y} = \{y_n\}$  be two discrete sequences and  $\langle n - n' \rangle = n - n'$  modulo  $N$ . Define sliding convolution  $\mathbf{z} = \mathbf{x} * \mathbf{y}$ :

$$z_n = \sum_{n'=-\infty}^{\infty} x_{n'} y_{n-n'} \quad (1a)$$

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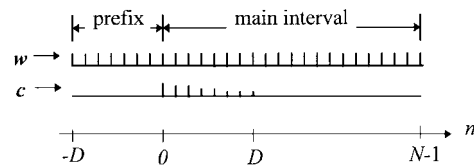


Fig. 1. The cyclic prefix transforms a sliding convolution into a circular one.

$N$ -point cyclic convolution  $\mathbf{z} = \mathbf{x} \otimes \mathbf{y}$ :

$$z_n = \sum_{n'=0}^{N-1} x_{n'} y_{\langle n-n' \rangle}, \quad 0 \leq n \leq N-1. \quad (1b)$$

The multipath effect in a digital system is usually modeled by a sliding convolution  $\mathbf{c} * \mathbf{w}$  where  $\mathbf{w}$  is the transmitted sequence and  $\mathbf{c}$  is a vector of the path reflection coefficients. Assume that  $\mathbf{c}$  has a limited nonzero span in  $(0, D)$ , i.e.,  $c_n = 0$  for  $n < 0$  and  $n > D$  (see Fig. 1). Given  $\mathbf{w} = \{w_n | n = 0, 1, \dots, N-1\}$ , the prefix of  $\mathbf{w}$  is its cyclic extension defined by  $w_n = w_{n+N}$ ,  $n \in [-D, -1]$ . Assuming  $D < N$ , the prefix technique transforms a sliding convolution into a circular one as

$$\begin{aligned} \sum_{n'=-\infty}^{\infty} c_{n'} w_{n-n'} &= \sum_{n'=0}^D c_{n'} w_{n-n'} \\ &= \sum_{n'=0}^D c_{n'} w_{\langle n-n' \rangle} \\ &= \sum_{n'=0}^{N-1} c_{n'} w_{\langle n-n' \rangle} \end{aligned} \quad (2)$$

or simply  $\mathbf{c} * \mathbf{w} = \mathbf{c} \otimes \mathbf{w}$  with the understanding that (2) is defined only in  $[0, N-1]$ . This relationship is the basis for OFDM [4] as well as for the new system introduced below.

## III. THE SYSTEM MODEL

### A. The OFDM System

Consider the system model in Fig. 2 where  $F$  and  $F^{-1}$  are a pair of discrete Fourier transformation (DFT) and inverse discrete Fourier transform (IDFT) operators. We first ignore the effect of sequence  $\mathbf{p}$  by setting  $\mathbf{p} = \delta = \{1, 0, \dots, 0\}$ . Then  $\mathbf{w} = \mathbf{v} \otimes \delta = \mathbf{v}$ ,  $\hat{\mathbf{v}} = \hat{\mathbf{w}} \otimes \delta = \hat{\mathbf{w}}$  and the system reduces to a common OFDM [4]. A prefix is padded to  $\mathbf{w}$  before transmitting. Let the underlying quadrature amplitude modulator (QAM) layer be described by the well-known model  $\hat{\mathbf{w}} = \mathbf{c} * \mathbf{w} + \eta$  [6], where  $\mathbf{c} = \{c_n\}$  and  $\eta = \{\eta_n\}$  represent the intersymbol interference and additive noise, respectively.

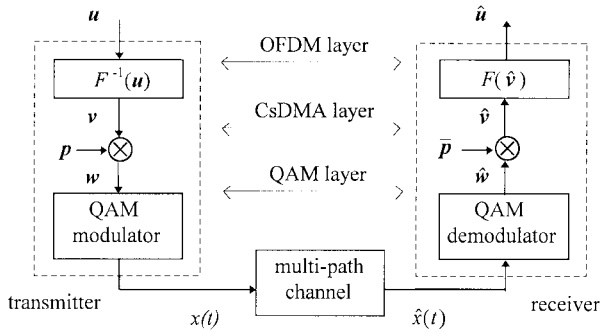


Fig. 2. Overview of the proposed OFDM-CsDMA system. The QAM layer is based on the well-known quadrature amplitude modulation principle [6].

Provided that the prefix length is longer than the maximum-delay dispersion, from (2)

$$\hat{w} = \mathbf{c} \otimes \mathbf{w} + \eta \quad (3)$$

or

$$\hat{v} = \mathbf{c} \otimes \mathbf{v} + \eta \quad (4)$$

when  $\mathbf{w} = \mathbf{v}$  and  $\hat{v} = \hat{w}$ . Applying DFT to  $\hat{v}$  in (4), we have the end-to-end relationship

$$\mathbf{u} = F(\hat{v}) = \{C_k u_k + \zeta_k\} \quad (5)$$

where  $\{C_k\} = F(\mathbf{c})$  and  $\{\zeta_k\} = F(\eta)$ . Equation (5) implies that the orthogonality among the OFDM frequency carriers is maintained in a multipath environment [4].

### B. The OFDM-CsDMA System and Orthogonality Among Same-Cell Users

We now derive the proposed system by relaxing the constraint on  $\mathbf{p}$  as

$$\mathbf{p} \otimes \bar{\mathbf{p}} = \delta \quad (6)$$

where  $\bar{\mathbf{p}}$  is the conjugate of  $\mathbf{p}$ . Now  $\mathbf{w} = \mathbf{v} \otimes \mathbf{p}$  in Fig. 2. Based on (1b)

$$\mathbf{w} = \mathbf{v} \otimes \mathbf{p} = \sum_{n'=0}^{N-1} v_{n'} \mathbf{p}^{(n')} \quad (7)$$

with  $\mathbf{p}^{(n')}$  the cyclic shift of  $\mathbf{p}$  toward right by  $n'$  positions. Equation (7) can be regarded as spreading  $v_{n'}$  by  $\mathbf{p}^{(n')}$ , which is equivalent to the CsDMA principle in [5] and, hence, the name for the middle layer.

Suppose that a cyclic prefix is padded to  $\mathbf{w}$  and so that (3) still holds. Substituting the relationships  $\mathbf{w} = \mathbf{v} \otimes \mathbf{p}$ ,  $\hat{v} = \hat{w} \otimes \bar{\mathbf{p}}$  and  $\mathbf{p} \otimes \bar{\mathbf{p}} = \delta$  into (3), we have

$$\hat{v} = \mathbf{c} \otimes \mathbf{v} + \eta' \quad (8)$$

with  $\eta' = \eta \otimes \bar{\mathbf{p}}$ . The similarity between (4) and (8) indicates that the upper layer transfer function of the wanted signal is not affected by the CsDMA layer. In particular, the orthogonality relationship implied by (5) still holds.

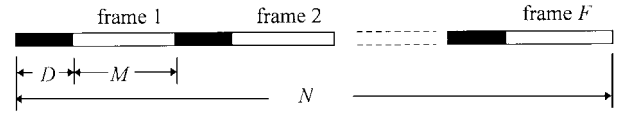


Fig. 3. A general signal structure of  $\mathbf{v}$ . The dark signals represent prefixes.

Fig. 3 is a more general structure for  $\mathbf{v}$ . Assume that the input  $\mathbf{u}$  is partitioned into sequential frames. The IDFT of each frame of  $\mathbf{u}$  is referred to as an OFDM frame. In Fig. 3,  $F$  OFDM frames together with their prefixes are multiplexed in  $\mathbf{v}$ , which are convoluted with  $\mathbf{p}$  together. An extra prefix is padded to the resultant  $\mathbf{w}$ . In this way, it can be verified that (5) is again valid. Let the OFDM frame length be  $M$ . Each frame contains  $M$  orthogonal carriers distinguished by their discrete frequencies [4]. A total of  $F \times M$  orthogonal carriers can be established within  $\mathbf{v}$  in this way and they can carry  $F \times M$  complex symbols.

Consider to share these  $F \times M$  carriers among users in a cell for the up-link. Assume that same cell users are approximately synchronized with certain tolerance for frame synchronization error that has essentially the same effect as multipath delay. Provided that the combined effect of frame synchronization error and multipath delay is covered by the prefix length, the orthogonality among all the users can be maintained. This distinguishes the proposed system from a common CDMA.

### C. Intercell MAI Mitigation

We assign a set of different  $\mathbf{p}$  sequences, referred to as master codes, to the neighboring cells. Suppose that the master codes are properly designed to be approximately random to each other. For intercell MAI, the convolution involving  $\bar{\mathbf{p}}$  at the receiver is applied to the signal generated from different master codes. The distortion is mitigated by the randomness among master codes. The effect can also be seen as to evenly distribute the intercell MAI among all the users, which avoids the worst case interference between OFDM carriers of the same discrete frequency. This property will be demonstrated by the simulation results later.

### D. Transceiver Complexity

So far as transceiver is concerned, the main difference between OFDM and OFDM-CsDMA is the convolutions involving  $\mathbf{p}$  and  $\bar{\mathbf{p}}$ . These operations incur very modest costs if  $\mathbf{p}$  is carefully chosen. For example, let  $\mathbf{s}$  be a length- $N$   $m$ -sequence,  $\mathbf{e}$  an all-1 sequence,  $\alpha = 1/\sqrt{N+1}$  and  $\beta = (1 \pm \sqrt{N+1})/N$ . Then  $\mathbf{p} = \alpha(\mathbf{s} + \beta\mathbf{e})$  satisfies (6) [7]. Now  $\mathbf{v} \otimes \mathbf{p} = \alpha(\mathbf{v} \otimes \mathbf{s} + \beta\mathbf{v} \otimes \mathbf{e})$ . Since  $\mathbf{v} \otimes \mathbf{e}$  is trivial, we will concentrate on  $\mathbf{v} \otimes \mathbf{s}$ , which can be rewritten in a matrix form as

$$\mathbf{v} \otimes \mathbf{s} = [v_0 \quad \cdots \quad v_{N-1}] \begin{bmatrix} s_0 & s_1 & \cdots & s_{N-1} \\ s_{N-1} & s_0 & \ddots & \\ \vdots & \vdots & \ddots & s_1 \\ s_1 & \cdots & s_{N-1} & s_0 \end{bmatrix} = \mathbf{v}\mathbf{S} \quad (9)$$

Augment  $\mathbf{S}$  by one zero row and one zero column to give

$$\mathbf{S}' = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{S} \end{pmatrix}. \quad (10)$$

Then  $[\mathbf{0}, \mathbf{v} \otimes \mathbf{s}] = [\mathbf{0}, \mathbf{v}]\mathbf{S}'$ . The columns of  $\mathbf{S}'$  form the codeword set of a length  $N' = N + 1$  augmented  $m$ -sequence, which is equivalent to a Hadamard code up to an interleaving. There exist permutation matrices  $\mathbf{A}$  and  $\mathbf{B}$  such that  $\mathbf{S}' = \mathbf{A}\mathbf{H}\mathbf{B}$ , where  $\mathbf{H}$  is a Hadamard matrix. Hence

$$[\mathbf{0}, \mathbf{v} \otimes \mathbf{s}] = [\mathbf{0}, \mathbf{v}]\mathbf{A}\mathbf{H}\mathbf{B}. \quad (11)$$

Equation (11) can be implemented very efficiently by a fast Hadamard transform (FHT), costing  $N' \log_2 N'$  additions, and two interleavers. For detailed discussion, see [5].

#### IV. SIMULATION STUDY

##### A. System Model

The underlying propagation is based on COST-207 (typical urbane) models [8] with maximum-delay spread = 5  $\mu$ s, maximum-frame alignment error = 5  $\mu$ s, chip duration = 0.9977  $\mu$ s, bandwidth = 1.002 MHz, and carrier frequency = 1 GHz. The prefix length is  $D = 11$ . Rectangular pulse shaping and simple mixing-integration demodulator are used for the QAM layer.

Input information bits are encoded by a rate 1/2, constraint length 9 convolutional code (IS-95 rate-1/2 code) with 192 bits in a frame, producing a length 400 binary sequence (including 16 tailing bits), from which a length-200 complex sequence is formed in a quaternary phase-shift keying manner. It is convolutionally interleaved to generate the input vector  $\mathbf{u}$  in Fig. 2.

The master codes  $\{\mathbf{p}\}$  are constructed from length 511  $m$ -sequences (different cells using different  $m$ -sequences). The parameters for  $\mathbf{v}$  (see Fig. 3) are  $N = 511$ ,  $D = 11$ ,  $F = 11$ , and  $M = 32$ . One OFDM frame is used to estimate phase reference, which avoids the complicated pilot scheme. The remaining ten frames are used to carry information. We observed that the performance can be improved by setting the power level of the reference frame to about 5 dB above the information frames, which are used in all of the results presented below. The information symbols, prefixes and reference frame occupy a total of 473 positions in  $\mathbf{v}$ , leaving 38 positions unused. Within one frame of  $\mathbf{v}$ , every user is assigned with one fixed carrier, distinguished by a unique discrete OFDM frequency, in all 11 OFDM frames. This carrier changes for every frame of  $\mathbf{v}$  to average out the fading effect in a frequency-hopping manner. Leaving one carrier as reference, the remaining ten carriers carry a total of 20 coded bits. With a gating factor of 1/2, we obtain user rate  $R = 9.6$  kbps.

##### B. Results

Using dual antenna diversity and equal gain combining, BER =  $10^{-3}$  can be achieved at  $E_b/N_0 \approx 7$  dB. Leaving a 1-dB implementation margin, we set required  $E_b/N_0 = 8$  dB. Substitute this into the formula of [9] and consider the

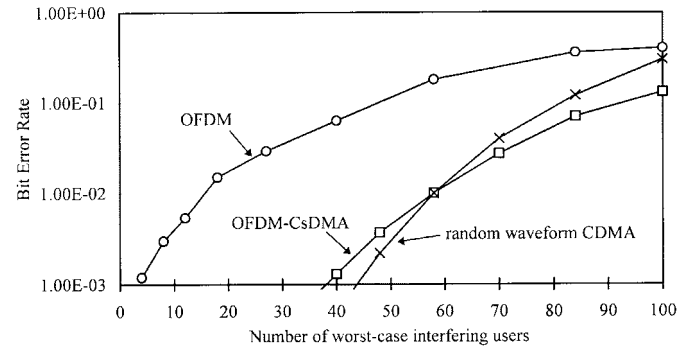


Fig. 4. Simulated up-link performance comparison with worst-case interference. Every interfering signal has the same mean arrival power as the wanted signal. The comparable random waveform CDMA employs spreading ratio  $\approx 105$ , a rate 1/3, constraint length 9 convolutional code, dual receiving antenna and a four-finger Rake receiver. The OFDM system is obtained by setting  $\mathbf{p} = \delta$  and keeping everything else unchanged.

elimination of the intracell MAI, the proposed system can achieve an uplink capacity of 54 user/cell. This is compared with about 24 user/cell for a random waveform CDMA system with similar spreading ratio of about 105 [9].

We observed that the system is not sensitive to vehicle speed up to about 400 km/h. Similar to the standard OFDM, the signal envelope of the proposed scheme is not constant. When peak-to-mean power ratio is clipped to 3 and 0 dB, respectively, the corresponding performance losses are about 0.2 and 0.8 dB at BER =  $10^{-3}$ .

A distinguished feature of CDMA is its robustness against worst case intercell MAI. This is demonstrated for the proposed scheme in Fig. 4 (vehicle speed = 50 km/h). Perfect power control is used. Every user is allocated to the cell that results in minimum-transmission power. Consequently, the maximum-arrival power level (averaged over fast fading) of an interfering signal cannot exceed that of the wanted signal. Let the service quality be BER <  $10^{-3}$  and  $N_{\text{worst}}$  be the maximum number of worst case interferers that can be tolerated. It is seen that the values of  $N_{\text{worst}}$  are, respectively, 3 for OFDM, 38 for OFDM-CsDMA, and 44 for a comparable random waveform CDMA. Recall that  $N_{\text{worst}}$  for a random waveform CDMA includes all the same-cell users. As a fair comparison, a fully loaded random waveform CDMA system with 24 users/cell can tolerate only about 20 worst-case other-cell interferers, which is considerably lower than OFDM-CsDMA. This clearly demonstrates the advantage of the proposed scheme.

#### V. DISCUSSIONS AND CONCLUSIONS

Eliminating intracell MAI may potentially lead to 2.8 times of CDMA capacity increase [9] relative to a random waveform CDMA. The example in Section IV achieves a capacity increase of about 2.2 times. The difference is due to the overheads (prefix and reference) involved. The proposed scheme is most suitable for applications with relatively low-delay dispersion, such as indoor systems. The low-receiver complexity of the proposed scheme makes it suitable to handle relatively high-data rates typically required in such applications.

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