NEW FRAME SYNCHRONIZATION TECHNIQUE FOR OFDM/OFDMA AND MC-CDMA SYSTEMS

C.D. Lee and M. Darnell
Institute of Integrated Information Systems, School of Electronic & Electrical Engineering
University of Leeds, Leeds LS2 9JT, UK.

ABSTRACT

In the context of orthogonal frequency division multiplexing (OFDM), most papers define OFDM symbol synchronization as frame synchronization. In this paper, a frame is defined as a block of several OFDM symbols in the time dimension. The main contribution of this work is to propose a novel, low-complexity, frame synchronization method for multi-carrier systems that does not require any transmission overhead; this increases the channel capacity, power and bandwidth efficiency. Also, it enables a flexible multiple-access scheme to be implemented in OFDM, whereby each user can have different frame size. The proposed frame synchronization method is compared with a conventional method using a preamble. Power compensation and frame averaging techniques are proposed to improve the performance of the frame synchronizer. The performance of the proposed frame synchronizer is evaluated over a Rayleigh fading channel for orthogonal frequency division multiple-access (OFDMA) and multi-carrier code-division multiple-access (MC-CDMA) systems.

1. INTRODUCTION

Frame synchronization is an essential element in wireless digital communication systems. It determines the boundary between data frames so that the information can be recovered correctly from a stream of data. Most papers [1,2,3,4] define OFDM symbol synchronization as frame synchronization. In this paper, a frame is defined as a block of several OFDM symbols in time dimension. In the context of multi-user environment, frame synchronization in time dimension allows each user to have a more flexible structure. Conventional frame synchronization techniques typically require special symbols (preambles) to precede an OFDM frame [5,6]. These methods decrease the channel capacity, bandwidth and power efficiency due to the presence of frame synchronization overheads. Therefore, a new low complexity frame synchronization method for multi-carrier systems that does not require any transmission overhead is proposed here.

This paper is organised as follows: in Section 2 we describe the novel frame synchronization method for single user multi-carrier systems; in Section 3 we then extend the proposed method to a multi-user OFDM systems; in Section 4, frame averaging and power compensation methods are described to improve the performance of the frame synchronizer; in section 5, the performance of the proposed frame synchronization method is compared with the conventional frame synchronization method using a preamble for both OFDMA and MC-CDMA systems. Finally, we present the overall conclusions.

2. FRAME SYNCHRONIZATION

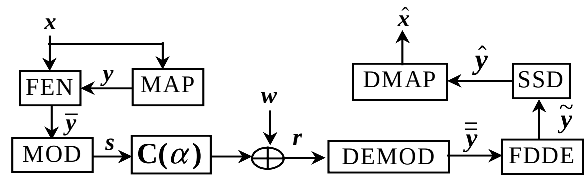

Fig 1. Model of a multi-carrier system over a Rayleigh fading channel.

Figure 1 shows a model of a multi-carrier system operating over a Rayleigh fading channel. Let $\boldsymbol{x}$ be an N random data symbol vector, i.e.

$$\boldsymbol{x} = [\, x_1 \quad x_2 \quad \dots \quad x_N \,]^{\mathrm{T}} \qquad (1)$$

$$D = \{1,\, 2, \dots, U\}, \quad x_n \in D \quad \text{where } n \in [1, N]$$

where $^{\mathrm{T}}$ denotes the transpose and D is the data alphabet with size U. Each data symbol is mapped to a signaling symbol, y_n, using the MAP operation. The mapping is such that each possible data symbol is associated with one particular value of a set of U distinct values

$$\boldsymbol{y} = [\, y_1 \quad y_2 \quad \dots \quad y_N \,]^{\mathrm{T}} \qquad (2)$$

$$y_n = A(x_n) \qquad (3)$$

$$\boldsymbol{A} = \{A(1)\,, A(2), \dots, A(U)\,\}, \; y_n \in \boldsymbol{A} \quad \textit{where} \;\; n \in [1, N\,]$$

where A is the signaling alphabet with size U. Each y_n is allocated a subchannel. The vector $\boldsymbol{y}$ is encoded by the frame encoding block (FEN) only if it is the first symbol of a frame; otherwise, $\bar{\boldsymbol{y}} = \boldsymbol{y}$. Then, MOD modulates $\bar{\boldsymbol{y}}$ to produce an OFDM symbol vector $\boldsymbol{s}$. OFDM breaks down the transmission bandwidth into narrow subcarriers, which can be regarded as flat fading channels; here, they are modelled as Rayleigh fading. This is described by a diagonal matrix $\boldsymbol{C}(\alpha)$, with the fading coefficients, α, on the main diagonal. Also additive white Gaussian noise (AWGN), $\boldsymbol{w}$, is combined with the signal. Thus,

$$\boldsymbol{r} = \boldsymbol{C}(\alpha) \cdot \boldsymbol{s} + \boldsymbol{w} \qquad (4)$$

The receiver consists of a demodulation block, DEMOD, followed by a frame detection and decoding block, FDDE, a signaling symbol decision block, SSD, and a signaling symbol demapper, DMAP. In the receiver, perfect OFDM symbol and carrier recovery and perfect channel estimation are assumed. A linear equaliser is used to offset the effect of fading in the DEMOD.

2.1. Proposed Frame Synchronization Algorithm

The frame encoder only encodes the first OFDM symbol of every frame. The total number of subchannels, N, in vector $\boldsymbol{y}$ is divided into q groups of U subchannels for frame encoding.

$$\boldsymbol{y} = \begin{bmatrix} \boldsymbol{y}(1) & \boldsymbol{y}(2) & \dots & \boldsymbol{y}(\mathrm{q}) & \boldsymbol{y}_{\mathrm{R}} \end{bmatrix}^{\mathrm{T}} \quad (5)$$

where $\boldsymbol{y(n)}$ is a 1xU vector and $\boldsymbol{y_R}$ is a vector of size ($N - qU$) containing the remaining signaling symbols. Here, q is defined as the maximum group available for frame encoding and is given by the integer part of the division of N by U. Note that $N \geq U$ is required here. The vector $\boldsymbol{y_R}$ is not involved in the frame encoding process. Each vector $\boldsymbol{y(n)}$ in $\boldsymbol{y}$ is encoded as follows:

$$\bar{y}_1 \leftarrow y_{x_1} \quad (6)$$

$$\bar{y}_{x_1} \leftarrow 0 \quad (7)$$

$$\bar{y}_n \leftarrow y_n \quad (8)$$

where $n \in [2, U]$, $n \neq x_1$. The x_1 and $\bar{y}_1$ correspond to the first data symbol and the signaling symbol in the first subchannel in each vector $\bar{\boldsymbol{y}}(\mathbf{n})$ respectively. The first data symbol, x_1, specifies the i^{th} subchannel which will replace the first subchannel, $\bar{y}_1$. Then, the i^{th} subchannel is deleted and no signal energy will be transmitted in i^{th} subchannel. Note that no information is lost in this process because the information in i^{th} subchannel is conveyed via the first subchannel, and the information in the first subchannel is specified by the position of the deleted subchannel.

The frame detection and decoding block must first detect the start of the frame before it can recover the data from a frame-encoded OFDM symbol. Like the frame encoder, the received OFDM symbol is divided into q groups of U subchannels:

$$\bar{\bar{\boldsymbol{y}}} = \begin{bmatrix} \bar{\bar{\boldsymbol{y}}}(1) & \bar{\bar{\boldsymbol{y}}}(2) & \dots & \bar{\bar{\boldsymbol{y}}}(\mathrm{q}) & \bar{\bar{\boldsymbol{y}}}_{\boldsymbol{R}} \end{bmatrix}^{\mathrm{T}} \quad (9)$$

where $\bar{\bar{\boldsymbol{y}}}(\boldsymbol{n})$ is 1xU vector of the received signaling symbols, $\bar{\bar{y}}_n$ and $\bar{\bar{\boldsymbol{y}}}_{\boldsymbol{R}}$ is a vector of size ($N - qU$) containing the remaining received signaling symbols. Again, the vector $\bar{\bar{\boldsymbol{y}}}_{\boldsymbol{R}}$ is not involved in the frame detection or frame decoding processes. In each $\bar{\bar{\boldsymbol{y}}}(\boldsymbol{n})$ vector, a subchannel that has the minimum absolute magnitude among the subchannels within the group is selected. Then, the selected minimum absolute magnitude subchannels from all the groups are summed, i.e.

$$E = \frac{1}{q}\sum_{n=1}^{q} \min(abs(\bar{\bar{\boldsymbol{y}}}(\boldsymbol{n}))) \quad (10)$$

where $\boldsymbol{min(.)}$ is the minimum of a group of number n and $n \in [1,q]$ and $\boldsymbol{abs(.)}$ is the absolute value of the argument. E is then compared with a predefined threshold. This threshold can be chosen according to the required false alarm and miss detection rates, and the prevailing channel conditions:

$$E \underset{\mathrm{H_F}}{\overset{\mathrm{H_A}}{\gtrless}} \mathrm{T_F} \quad (11)$$

where $\mathrm{T_F}$ is the threshold for frame detection and $\mathrm{H_F}$ and $\mathrm{H_A}$ are the hypotheses indicating the frame is present or absent respectively. If all the elements in signaling alphabet set $\boldsymbol{A}$ have similar energy and the consequences of a false alarm and a miss detection are the same, then the threshold should be chosen as half the maximum absolute magnitude.

After the frame is detected, the subchannels in the frame encoded OFDM symbol have to be rearranged to recover the actual OFDM symbol. This is simply the reverse of the frame encoding procedure. For each $\bar{\bar{\boldsymbol{y}}}(\boldsymbol{n})$ vector, the position of the minimum absolute magnitude subchannel among the subchannels within the group is determined by

$$i = pos(\min(abs(\bar{\bar{\boldsymbol{y}}}(\boldsymbol{n})))) \quad (12)$$

where $n \in [1, q]$, and $\boldsymbol{pos(.)}$ is the position of the argument in a vector. Then, the signaling symbol in i^{th} subchannel is replaced by the signaling symbol in the first subchannel, and the signaling symbol for the first subchannel is the i^{th} element in signaling alphabet set, $\boldsymbol{A}$:

$$\tilde{y}_i \leftarrow \bar{\bar{y}}_1 \quad (13)$$

$$\tilde{y}_1 \leftarrow \mathrm{A(i)} \quad (14)$$

$$\tilde{y}_n \leftarrow \bar{\bar{y}}_n \quad (15)$$

where $n \in [2, U]$, $n \neq i$. This frame decoding procedure is implemented only when a frame is detected, otherwise, $\tilde{\boldsymbol{y}} = \bar{\bar{\boldsymbol{y}}}$.

The proposed method shows that the frame information can be embedded in the normal data stream without the need for a special preamble sequence. Consequently, frame synchronization can be achieved without transmission overheads. Furthermore, the method has low complexity and is simple to implement.

3. MULTIPLE ACCESS

The proposed frame synchronization scheme can be extended to a multi-user situation. This is done by encoding the first symbol in each frame separately for each user and independently of other users; Each user will have their own frame encoding, detection and decoding block which is independent of other users. The frame encoding, detection and decoding techniques for each user are the same as those described above for the case of a single user. Consequently, a multiple-access scheme can be applied to OFDM system. This is illustrated in Figure 2, where each user can have a different frame size and different frame start times. If the frame synchronization technique is applied to all q groups of U subchannels, then the frame size is constrained to be any multiple of N symbols. However, if it is applied say to the upper half of the q groups independently of the lower half of

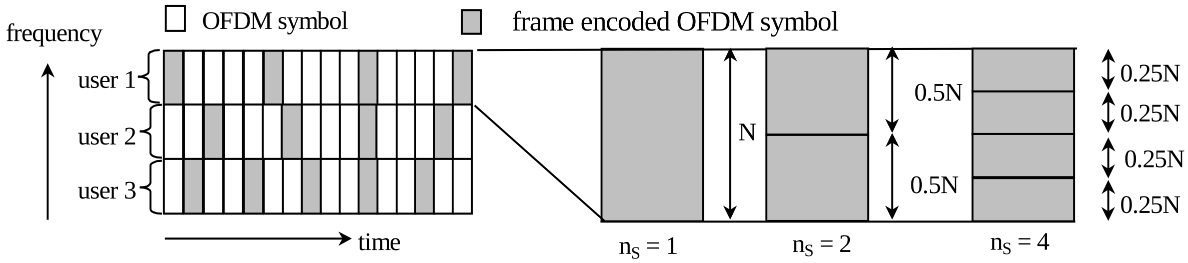

Fig2. Illustration of orthogonal frequency division multiple access (OFDMA) scheme ($q = 4$).

the q groups, then the frame size can be any multiple of 0.5N. If the upper half and lower half are further split into 2 subgroups, the frame size can be any multiple of 0.25N.

Nevertheless, this can be done only if the division of N by the number of subgroups, n_S , yields an integer. Note that, as n_S increases, the number of subchannels that can be used for frame detection in each subgroup, N/n_S, decreases. Hence, the flexibility in frame size is inversely dependent on the robustness of the frame synchronization. The minimum possible frame size, U, is achieved when $n_S = q$, where U is the signaling symbol alphabet size. Furthermore, the frame size can be varied during data transmission without reallocating the subchannels for each user, and still maintaining the same bandwidth efficiency.

This scheme provides a more flexible system than the system where the frame allocation for each user is done in the frequency dimension only over a single OFDM symbol. The frame size for such scheme cannot be increased without increasing the available bandwidth if all the subchannels are occupied; also, it may not be possible to reduce the frame size without reducing the bandwidth efficiency.

Since there are similarities between OFDMA and MC-CDMA systems, the proposed frame synchronization techniques also been applied to MC-CDMA systems. In this paper, a recently developed rotated Hadamard spreading transform matrix [7] is used. The proposed frame synchronization technique applied is still the same.

4. PROPOSED IMPROVEMENTS

Two methods are proposed to further improve the performance of the frame synchronizer. The first is to increase the energy of all the subchannels, except for the deleted subchannel, for frame-encoded OFDM symbols in order to compensate the energy loss due to the subchannel deletion. Note that the power efficiency is still the same because the output power will be the same as for non-frame encoded OFDM symbols. The second improvement is to use an averaging filter to average the frame boundary estimates. However, this requires the frame size to be predefined before data transmission, and then fixed thoughout data transmission. The proposed averaging method evolves from the averaging method developed for modulation-derived symbol synchronizers (MDS) [8]. It is modified here to achieve frame synchronization, instead of the original symbol synchronization; the frame averaging model is shown in Figure 3. The length of the synchronization buffer is similar to the frame size. The FDDE sends an impulse to the synchronization buffer when it detects the presence of a frame; otherwise, it remains idle during every other symbol period. The output of the averaging filter, $p(n)$, is related to the input, $g(n)$, given by (16),

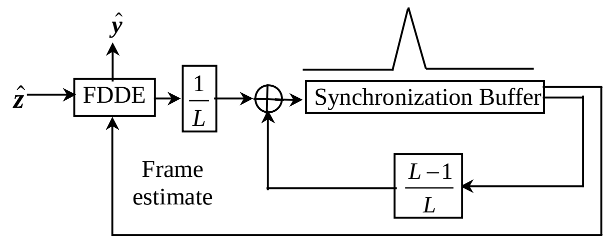

Fig3. Frame estimate averaging filter.

$$p(n) = \sum_{n=(j-1)v}^{jv-1} \left[\frac{1}{L} g(n) + \sum_{i=1}^{\infty} \left(\frac{L-1}{L} \right)^{i} \left(\frac{1}{L} \right) g(n-iv) \right] \quad (16)$$

where L is the memory length of the frame synchronizer, v is the frame size and j indicates the j^{th} frame. The present frame estimate is summed with progressively lower weighted previous frame estimates, in this case an exponentially weighted memory. The frame synchronizer searches for the peak in the synchronization buffer every frame period, and the position of the peak gives the estimate of the start of a frame.

5. PERFORMANCE ANALYSIS

The simulation was set up according to Figure 1 for both OFDMA and MC-CDMA systems. 8 users were simulated where each user having 13 subchannels ($N = 13$); each BPSK ($U = 2$) subchannel undergoes Rayleigh flat fading. The frame size is chosen as 78 BPSK symbols. In the simulation, perfect channel estimation, carrier and symbol timing recovery are assumed. For the proposed frame synchronization, 6 groups of U subchannels were used for frame coding and $n_s = 1$. The threshold for frame detection was 0.5 of the maximum absolute amplitude. A conventional frame synchronization method [5] was used for comparison; the synchronization pattern chosen was 13 bit Barker sequence. The threshold was chosen to be 0.9 to minimize false alarms due to random data (i.e. random data that resembles the Barker sequence) at high E_b/N_o. Figure 4 shows the probability of bit error (P_b); note that the P_b here does not take framing error into account. Figure 5 shows the frame error rate (FER) per symbol; this is obtained by summing the probability of miss detection and the probability of false alarm. FER per frame can be obtained by multiplying the FER by the frame size. The notations for the results are as follows: 'of' = OFDMA; 'cd' = MC-CDMA; 'B' = Barker sequence; 'F1' = the proposed frame synchronization; 'F2' = the proposed frame synchronization with power compensation and frame averaging

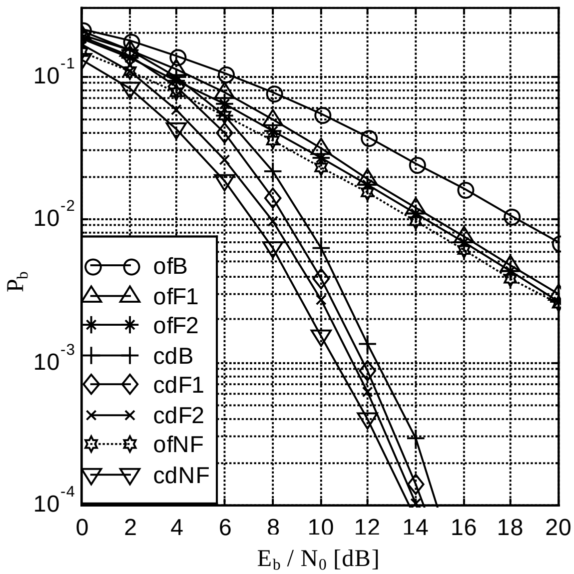

Fig 4. Probability of bit error for OFDMA and MC-CDMA

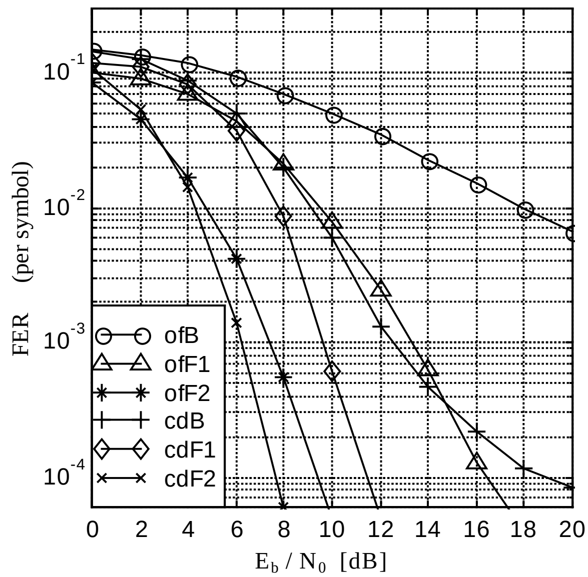

Fig5. The FER for OFDMA and MC-CDMA.

($L = 2$); 'NF' = no frame synchronization.

The conventional frame synchronization with a 13 bit Barker sequence has the worst performance for both OFDMA and MC-CDMA systems because some of the energy potentially available for data is used for the preamble. The proposed power compensation and frame averaging techniques give a small improvement in term of P_b. For the OFDMA system, the proposed frame synchronization with power compensation and frame averaging ($L = 2$) shows negligible performance loss as compared with the case of no frame synchronization. The performance loss is only approximately 1 dB for the MC-CDMA system. The conventional frame synchronizer with a 13 bit Barker sequence has the worst FER. This is because it is affected by the false alarms induced by the random data, whereas the proposed frame synchronization does not have this problem. The power compensation and the frame averaging technique improve the performance of the frame synchronizer significantly in term of FER for both systems.

6. SUMMARY

A novel frame synchronization technique that does not require any transmission overhead is proposed for multi-carrier systems. Since it allows each user to have a more flexible frame size; it can be implemented efficiently for multiple-access schemes. The proposed method was compared with a conventional method that uses a 13 bit Barker sequence as the synchronization pattern for the preamble. The proposed method has a better performance because all the available power can be allocated to the data and the false alarms are not caused by random data that resemble the synchronization pattern. The proposed power compensation and frame averaging techniques improve the performance of the frame synchronizer. Also, the proposed frame synchronization with power compensation and frame averaging ($L = 2$) has negligible implementation loss for OFDMA system and approximately 1 dB implementation loss for MC-CDMA system as compared with the no frame synchronization case.

7. REFERENCE

[1] J. H. Gunther, H. Liu, A. L. Swindlehurst, "A New Approach for Symbol Frame Synchronization and Carrier Frequency Estimation in OFDM Communication," Proc. of IEEE ASSP, vol. 5, pp. 2725-2728, 1999.

[2] M. H. Hsieh, C. H. Wei, "A Low-Complexity Frame Synchronization and Frequency Offset Compensation Scheme for OFDM Systems over Fading Channels," IEEE Trans. VT, vol. 48, pp. 1596-1609, 1999.

[3] M. Speth, F. Classen, H. Meyr, “Frame Synchronization of OFDM Systems in Frequency Selective Fading Channels,” Proc. of 47th IEEE VTC, vol.3, pp. 1807 -1811 1997.

[4] D. S. Han, Y. J. Kim, H. K. Lee, “On the Synchronization of MC-CDMA System for Indoor Wireless Communications,” Proc. of 50th IEEE VTC, vol.2, pp. 693 – 697, 1999.

[5] T. Keller, L. Hanzo, "Orthogonal Frequency Division Multiplex Synchronisation Technique for Wireless Local Area Networks,” Proc. of 7th IEEE PIMRC, vol. 3, pp. 963-967, 1996.

[6] Y. L. Huang, C. R. Sheu, C. C. Huang, "Joint Synchronization in Eureka 147 DAB System Based on Abrupt Phase Change Detection," IEEE Journal SAC, vol. SAC-17, pp. 1770-1780, 1999.

[7] A. Bury, J. Egle, J. Lindner, “Diversity Comparison of Spreading Transforms for Multi-Carrier Spread Spectrum Transmission Methods”, Proc. Conf. of an European Wireless 2000, Sept. 12-14, 2000.

[8] C. D. Lee, S.Brunt, M. Darnell, “Comparison of Various Types of Modulation-Derived Synchronisers under Low Sampling Rate Conditions”, 5th International Symposium on Communication Theory and Applications, Ambleside,1999.