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Invention Disclosure

Login Date 9/17/01 GTRC ID: 2542

1 Title of Invention: Efficient Training and Synchronization Sequence Structures for MIMO OFDM

2 Short Title: Sequence structure design for MIMO OFDM Systems.

3 Inventors *(Please include all inventors; Use additional sheets as necessary)*

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4 Did this invention result from sponsored research? *If so, please give details.*

Sponsor: Yamacraw G.I.T. Project Number: E-21-105;21021
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Yes X No ____ If YES, list name of Center GCATT

5 Has the invention been disclosed in an abstract, paper, talk, project report or thesis?

YES ____ NO X Disclosure Date: ________

Type of Disclosure Conference Paper

6 Is a publication or other disclosure planned within 6 months? YES: X NO: ____
Disclosure Date: Presentation due ~~10/18/2~~ 9/18/01 Type of disclosure: Conference Paper

7 **Brief description of the invention (attach more detailed description):**
This invention presents training sequence structures which also serve as synchronization sequence structures for MIMO OFDM systems. We present a technique by which the transmission matrix for each subcarrier is made unitary, hence satisfying the MMSE criterion for the coarse channel estimates. A search is carried out for structure with the lowest peak to average power ratios. For systems employing 2,4, and 8 transmit antennas, optimal sequence structures are obtained.

8 **Does the description provided above enable one skilled in this area of technology to make and use the invention?** YES: X NO: ____
If not, please explain.

9 **Have you disclosed the best mode known to you at this time of carrying out your invention?**
YES: X NO: ____ If not, please explain:

10 **Date of conception:** 8/26/01

11 **Has the invention been reduced to actual practice (i.e., have products, apparatus or compositions, etc. actually been made and tested?)** YES: X NO: 5/26/01
If YES, date of reduction to practice: Being implemented in a software radio set up

12 **Does the invention appear to pass the following tests for patentability:**
Novelty: Yes Non-Obviousness: Yes Usefulness: Yes

13 **Has a patent or literature search been undertaken?** YES: ____ NO: X

14 **Are related patents or other publications known to you?** YES: ____ NO: X
(If yes, please attach list)

15 **Are laboratory records and data available?** YES: X NO: ____

16 **What are the immediate and/or future applications for the invention?**
The algorithm can be used to form the training and synchronization sequence structure in all the current and future wireless systems that employ MIMO OFDM

17 **What are the advatages of the invention? Why is it better than present technology? What are its novel and unusual features? What problems does it solve?**
All the MIMO OFDM systems for wireless applications require synchronization and parameter estimation. Synchronization requires signals that have good correlation properties. We showed a way to perform accurate parameter estimation for MIMO OFDM systems in our patent # 2474. The technique for parameter estimation requires that each of the signal transmission matrices be unitary. In this invention we find a method to form efficient sequence structures that can be used for synchronization as well as parameter estimation hence improving the system throughput. The sequence structures so obtained have good correlation properties, they are suitable for parameter estimation and have a low PAPR.

18 **Are there any limitations to be overcome prior to practical application?**
No

19 **Is work on the invention continuing?** YES: X NO: ____

20 **Do you know of any appropriate industrial organizations which may be interested in licensing this technology?**

Company Name:	Wi-Lan Inc.	Contact:	
Company Name:	Nortel Networks	Contact:	
Company Name:	Broadcom Inc.	Contact:	
Company Name:		Contact:	
Company Name:		Contact:	

Please attach additional sheet if more space is required

Execution by Inventor(s).

I/We inventor(s) hereby solemnly swear and affirm under oath that I/we am/are the only inventor(s) of this invention and that I/we have not knowingly omitted the inclusion of any other inventor(s) besides me/us, and that the information provided in this disclosure is, to the best of my/our knowledge, true and accurate.

Signature(s) of inventor(s) and date:

Date 9/13/01
Date 9/15/2001
Date
Date
Date

Execution by Witnesses

This invention was disclosed and explained to me by the inventor(s) whose signature(s) apprears above on the 16 day of Sept. , 2001.

Signature of Witness Date: 9/16/2001

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Signature of Witness Date: 9/16/2001

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Efficient Training and Synchronization Sequence Structures for MIMO OFDM

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Abstract— **In this invention we present a general method of forming efficient sequence structures which can be used for parameter estimation as well as synchronization. As a specific example we fabricate a structure using directly modulatable orthogonal polyphase sequences. We presente a technique by which the transmission matrices for each subcarrier is made unitary hence satisfying the MMSE criterion for channel estimation. A search was then carried out for structures with lowest peak to average power ratios. For systems employing 2 transmit antennas, Alamouti' s structure and the simplified orthogonal structure are found to be optimal. The simplified structure obtained from orthogonal design is also optimal for systems employing 4 and 8 transmit antennas. For systems employing 3 transmit antennas, circulant structure is the most suitable.**

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has become popular for wireless communications [1]. A multicarrier system can be efficiently implemented in discrete time using Inverse Discrete Fourier Transform (IDFT) to act as a modulator. The actual data to be transmitted, now reperesent "frequency" domain coefficients of the signal and the samples at the output of the IDFT stage are in the "time" domain.

In this paper we present efficient training and synchronization sequence structures for Multi Input Multi Output (MIMO) OFDM systems. For OFDM systems synchronization must be carried out both in time and frequency. In addition, OFDM systems require parameter estimation of the channel and the noise variance. Parameter estimation is normally carried out using a suitable training sequence. An efficient sequence structure must be suitable for synchronization as well as parameter estimation. Additionally for OFDM systems the synchronization signal must have a low Peak to Average Power Ratio (PAPR).

In the IEEE 802.11a Standard [1] synchronization and training sequence consists of a short sequence followed by a long sequence. The short sequence is used for time synchronization and coarse frequency offset estimation whereas the long sequnce is used for fine frequency offset and channel estimation. This sequence is not designed for use in MIMO OFDM systems.

In this paper we will be using the words "training" and "synchronization" sequence interchangeably since we propose an efficient sequence structure that can be used for both synchronization as well as training. We propose to use directly modulatable orthogonal polyphase sequences to form the MIMO synchronization sequence. The sequence structure is modified such that it is also suitable for MIMO parameter estimation.

II. ANALYSIS

A block of N samples at the output of the OFDM modulator represents an OFDM symbol and the net time required to transmit one symbol is called the symbol time, T_s. Later, a cyclic prefix consisting of the last G samples of the output of the IDFT block are inserted in front of the OFDM symbol samples. The time length of the cyclic prefix should be greater than the maximum length of the channel impulse response. The main function of the cyclic prefix is to guard the OFDM symbol against Inter Symbol Interference (ISI), hence, this cyclic prefix is called the guard interval of the OFDM symbol and has a time duration T_g. The samples are then applied to a pair of balanced D/A converters, and the analog I and Q signals are later upconverted to RF. The OFDM signal is transmitted over the channel, received and downconverted to base band. The guard interval is removed from the received discretized downconverted signal and the signal is demodulated using a Discrete Fourier Transform (DFT) on a block of N sam-

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ples. In this paper, samples in the frequency domain are represented by *Capital* alphabet and those in the time domain are expressed using *small* alphabet.

The general transmission format for a $Q \times L$ space-time system is shown in Fig. 1. Such a space-time system consists of Q Antennas at the transmitter and L Antennas at the receiver separated from each other in such a manner that the received signals have a minimum correlation. A system employing such a scheme can provide a diversity of the order of $Q \times L$. Let

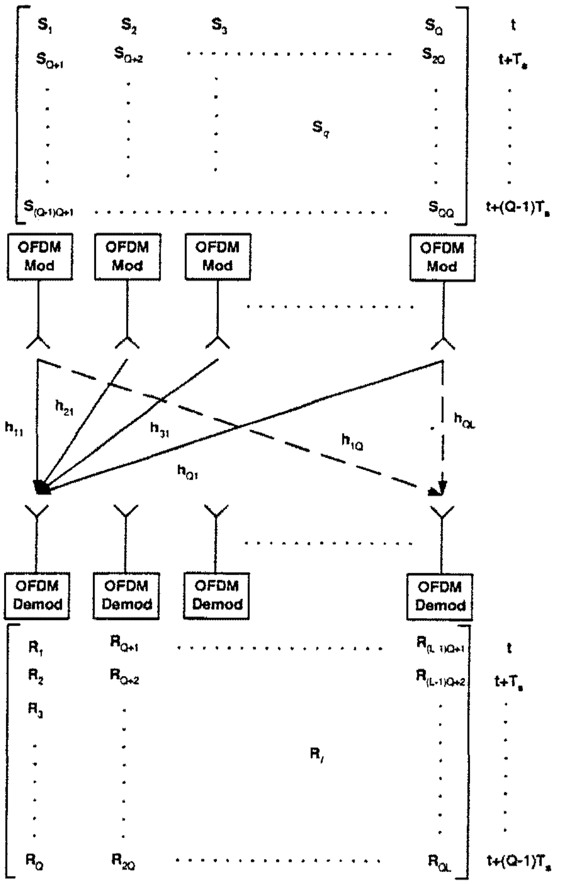

Fig. 1. Block diagram of a system with $Q \times L$ transmit-receive diversity

$\underline{S}_q$=(transmitted OFDM symbol), $\underline{\eta}_{ij}$= (vector of channel coefficients in the frequency domain between the ith transmit and the jth receive antenna) and $\underline{R}_l$=(the received demodulated OFDM symbol). Pilots in the form of known OFDM symbols are sent for at least Q symbol periods (QT_s) in order to obtain a unique solution for the channel coefficient estimates. If the pilots are sent for more than Q symbol periods then we would obtain a Least Squares (LS) solution at an expense of a larger overhead. The OFDM symbol period is given by $T_s = NT + T_g$ where $1/T$ is the sample rate into the OFDM modulator (bit rate for BPSK modulation). The time period T_g corresponds to the transmission of G samples. Often it is a good practice to double the length of the guard time in the training period [1]. This helps in synchronization, frequency offset estimation and equalization for channel shortening in case that the length of the channel exceeds the length of the guard time. An IDFT/ DFT pair is used as the OFDM modulator/ demodulator. The N point IDFT output sequence for the qth OFDM symbol is given by

$$s_{q,n} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_{q,k} \exp\left\{j\frac{2\pi nk}{N}\right\} \quad 0 \le n \le N-1 \qquad (1)$$

where $\{S_{q,k}\}_{k=0}^{N-1}$ is the transmitted data sequence from the ith transmit Antenna such that $q = (i-1)Q + c$ where $1 \le c \le Q$. The signal is then sent over the channel. The notation for the received signals vectors for the time instants $(t, t+T_s, \ldots, t+(Q-1)T_s)$ are $(\underline{r}_1, \underline{r}_2, \ldots, \underline{r}_Q)^T$, ..., $(\underline{r}_{Q\cdot(l-1)+1}, \underline{r}_{Q\cdot(l-1)+2}, \ldots, \underline{r}_{Q\cdot l})^T$,...., $(\underline{r}_{(L-1)\cdot Q+1}, \underline{r}_{(L-1)\cdot Q+2}, \ldots, \underline{r}_{QL})^T$ for the Antennas 1, 2, ..., L. The received sample sequence after the removal of the guard interval for the (vT_s)th training slot is

$$r_{l,n} = \sum_{i=1}^{Q} \sum_{m=0}^{M-1} h_{ij,m,v(N+G)+n}\, s_{i,(n-m)_N} + w_{l,n} \qquad (2)$$

where $h_{ij,m,v(N+G)+n}$ is the channel impulse response at lag m and instant $v(N+G)+n$ and l can be expressed as $l = (j-1)Q + d$ for $1 \le d \le Q$. The $w_{l,n}$ are complex additive white Gaussian noise samples with variance N_0. The received sample sequence $\{r_{l,n}\}_{n=0}^{N-1}$ is demodulated as [2]

$$R_{l,k} = \mathrm{DFT}\{r_l\}(k) \qquad (3)$$

$$= \sum_{i=1}^{Q} S_{i,k}\eta_{ij,k} + W_{l,k}. \qquad (4)$$

Hence the received demodulated OFDM sample matrix $\mathbf{R}_k$ of dimension $(Q \times L)$ for the kth subcarrier can be expressed in terms of the transmitted sample matrix $\mathbf{S}_k$ of dimension $(Q \times Q)$, the channel coefficient matrix $\boldsymbol{\eta}_k$ of dimension $(Q \times L)$ and the additive white Gaussian noise matrix $\mathbf{W}_k$ of dimension $(Q \times L)$ as

$$\mathbf{R}_{k,Q\times L} = \mathbf{S}_{k,Q\times Q} \cdot \boldsymbol{\eta}_{k,Q\times L} + \mathbf{W}_{k,Q\times L} \qquad (5)$$

$\mathbf{R}$, $\boldsymbol{\eta}$ and $\mathbf{W}$ can either be seen as N, $Q \times L$ dimensional matrices or as $Q \times L$ length-N vectors.

The total energy emenated from the Q transmit antennas is restricted to unity [2] such that,

$$\mathrm{E}\left\{\sum_{q=1}^{Q} |s_{q,n}|^2\right\} = 1 \qquad n = 0, 1, 2, ..., N. \qquad (6)$$

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