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Ma et al.

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(54) **SCATTERED PILOT PATTERN AND CHANNEL ESTIMATION METHOD FOR MIMO-OFDM SYSTEMS**

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(51) **Int. Cl.**

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H04Q 7/00	(2006.01)
H04B 7/216	(2006.01)
H04B 7/02	(2006.01)
H04L 27/00	(2006.01)

(52) **U.S. Cl.** **370/208**; 370/328; 370/335; 370/342; 370/441; 375/299; 375/316; 455/101

(58) **Field of Classification Search** 370/208, 370/203, 334, 435, 437, 465, 491, 500
See application file for complete search history.

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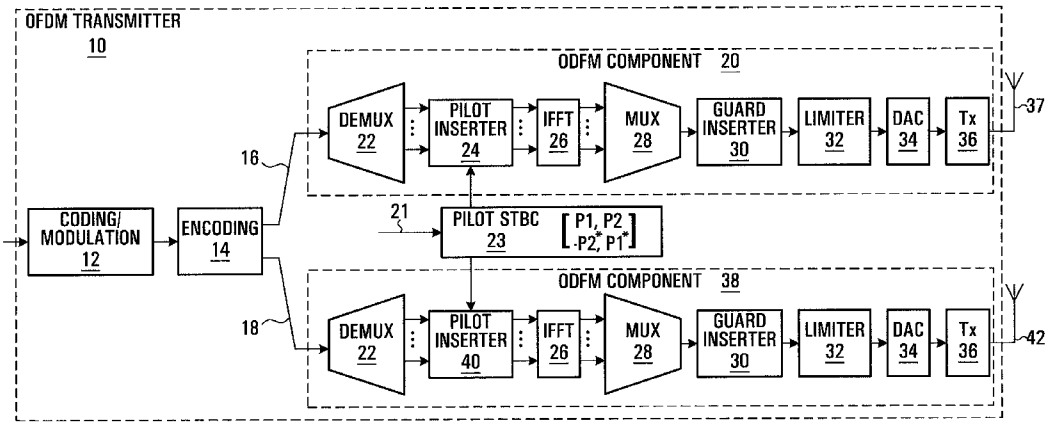
Assistant Examiner—Melanie Jagannathan

(57) **ABSTRACT**

A method and apparatus are provided for reducing the number of pilot symbols within a MIMO-OFDM communication system, and for improving channel estimation within such a system. For each transmitting antenna in an OFDM transmitter, pilot symbols are encoded so as to be unique to the transmitting antenna. The encoded pilot symbols are then inserted into an OFDM frame to form a diamond lattice, the diamond lattices for the different transmitting antennae using the same frequencies but being offset from each other by a single symbol in the time domain. At the OFDM receiver, a channel response is estimated for a symbol central to each diamond of the diamond lattice using a two-dimensional interpolation. The estimated channel responses are smoothed in the frequency domain. The channel responses of remaining symbols are then estimated by interpolation in the frequency domain.

44 Claims, 7 Drawing Sheets



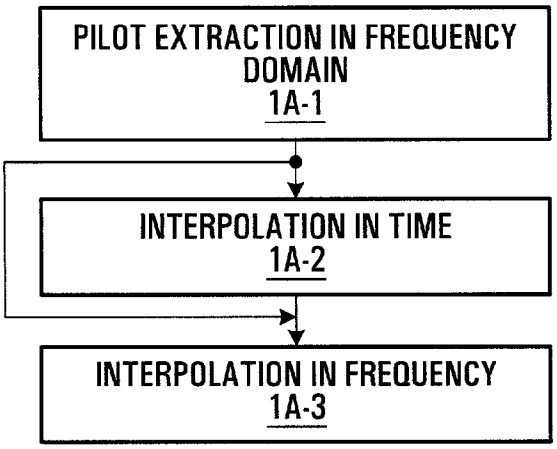


FIG. 1A
(PRIOR ART)

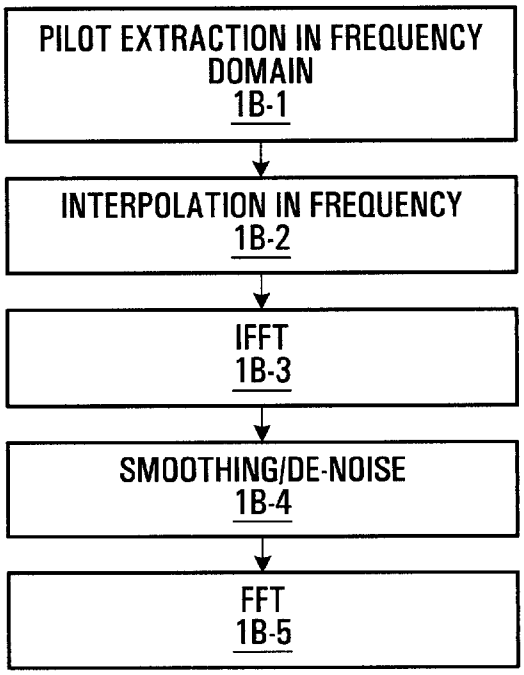


FIG. 1B
(PRIOR ART)

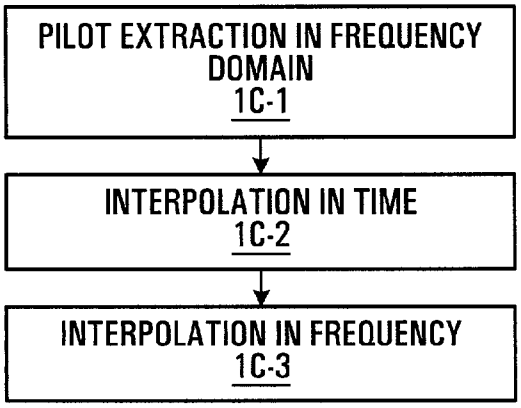


FIG. 1C
(PRIOR ART)

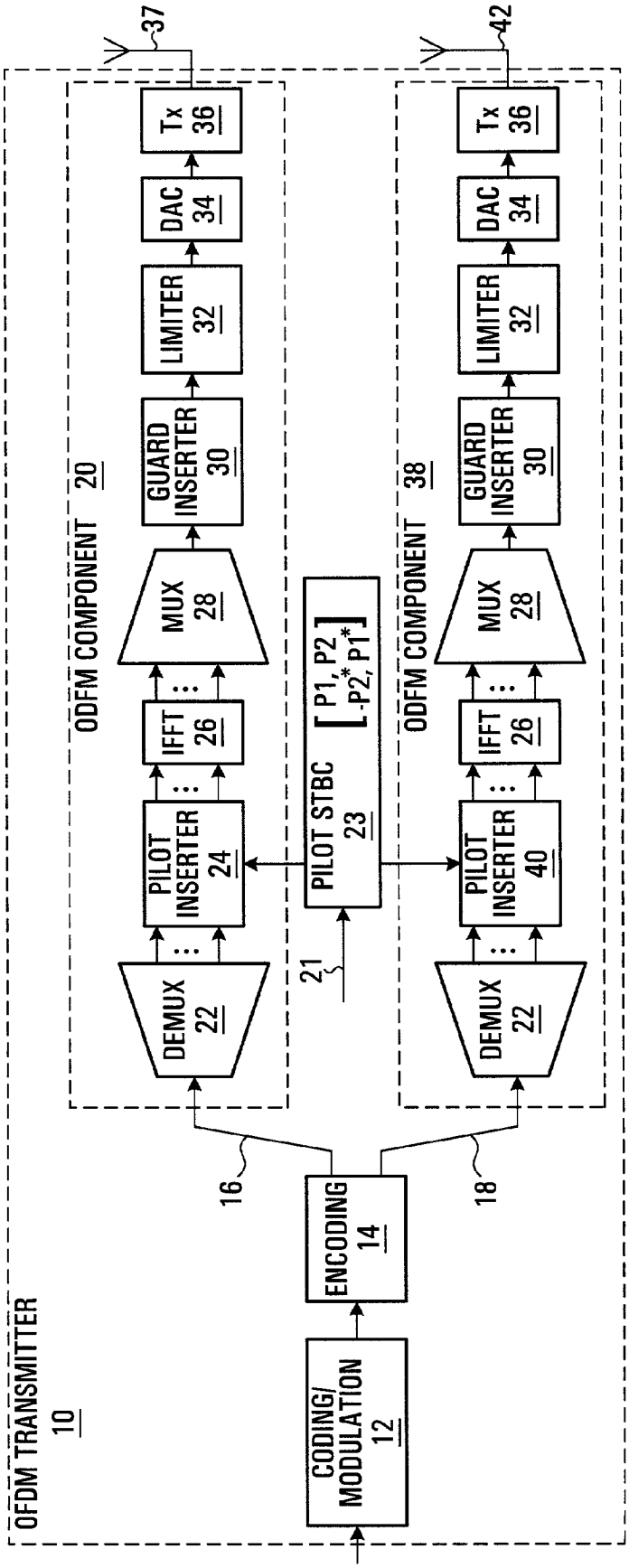

OFDM TRANSMITTER
10
CODING/
MODULATION
12
ENCODING
14
16
18
ODFM COMPONENT
20
DEMUX
22
PILOT
INSERTER
24
IFFT
26
MUX
28
GUARD
INSERTER
30
LIMITER
32
DAC
34
Tx
36
37
PILOT STBC
23
21
[P1, P2
-P2*, P1*]
ODFM COMPONENT
38
DEMUX
22
PILOT
INSERTER
40
IFFT
26
MUX
28
GUARD
INSERTER
30
LIMITER
32
DAC
34
Tx
36
42

FIG. 2

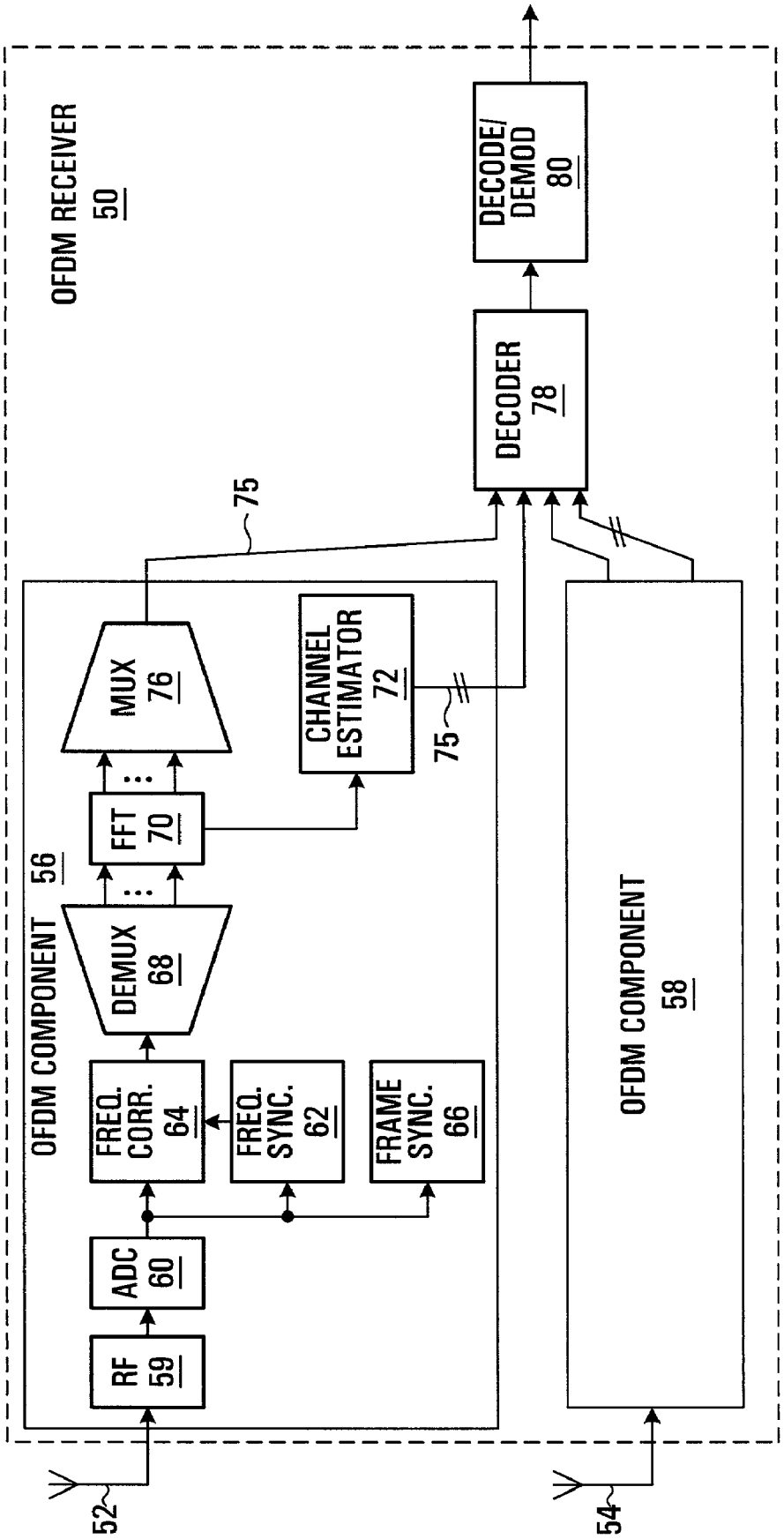

OFDM RECEIVER
50
OFDM COMPONENT
56
RF
59
ADC
60
FREQ. CORR.
64
FREQ. SYNC.
62
FRAME SYNC.
66
DEMUX
68
FFT
70
MUX
76
CHANNEL ESTIMATOR
72
75
75
DECODER
78
DECODE/ DEMOD
80
OFDM COMPONENT
58
52
54

FIG. 3

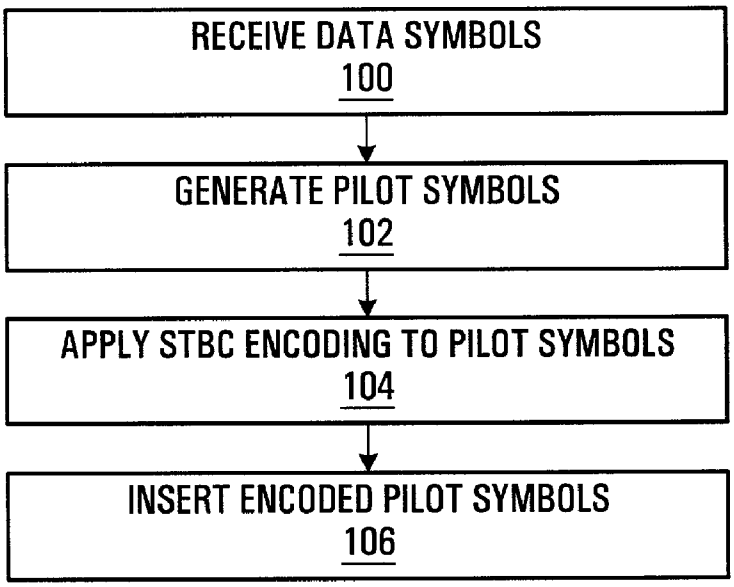

RECEIVE DATA SYMBOLS
100
GENERATE PILOT SYMBOLS
102
APPLY STBC ENCODING TO PILOT SYMBOLS
104
INSERT ENCODED PILOT SYMBOLS
106

FIG. 4

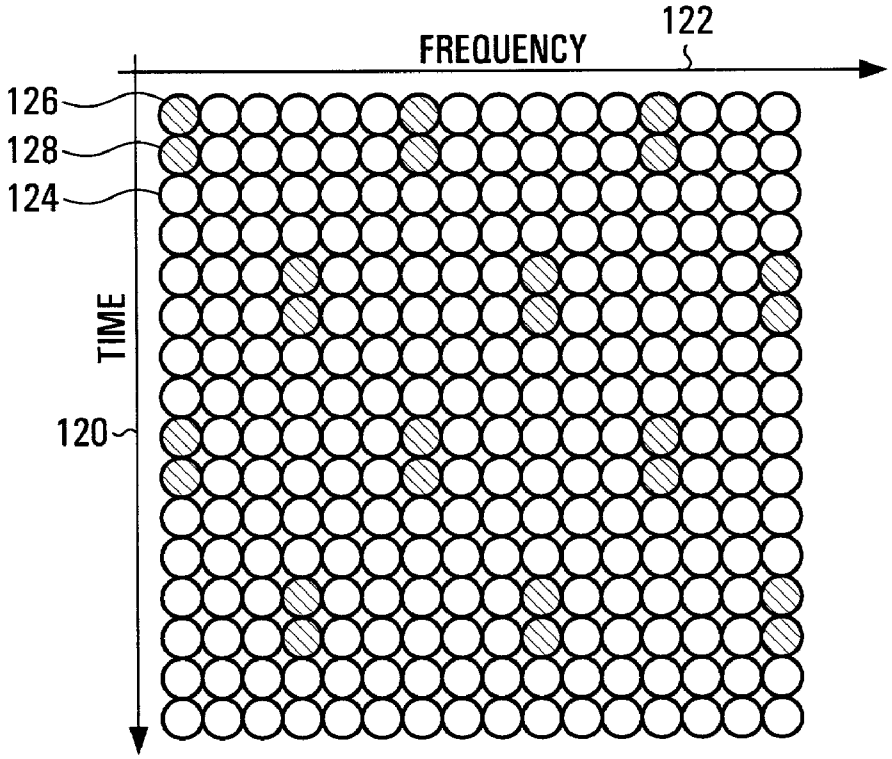

FREQUENCY
122
126
128
124
TIME
120

FIG. 5

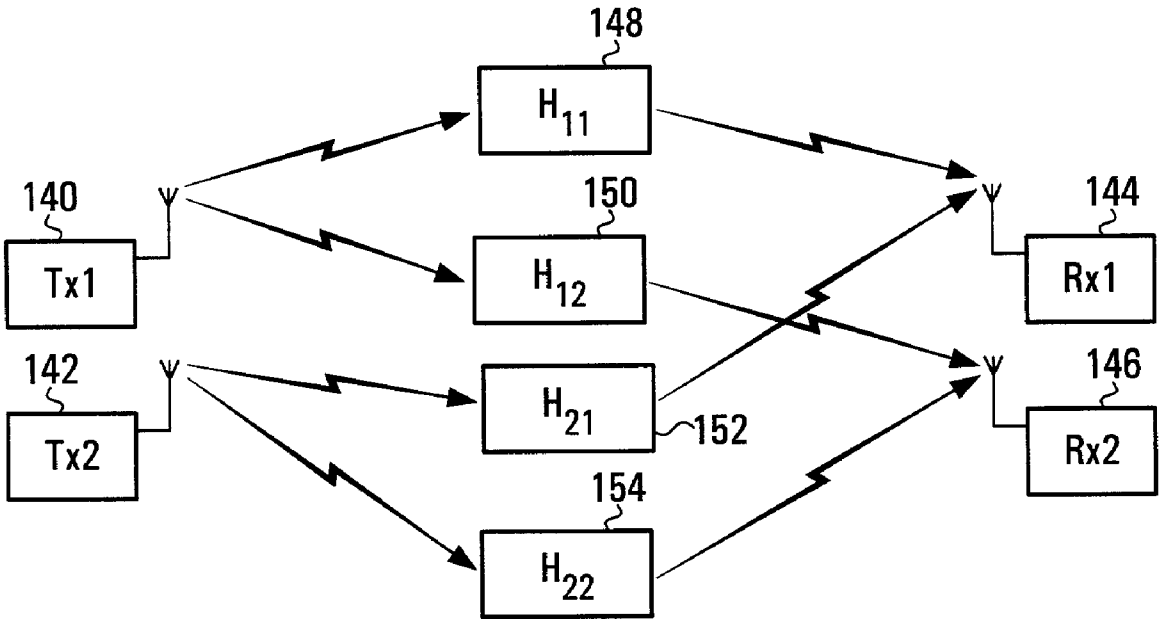


FIG. 6

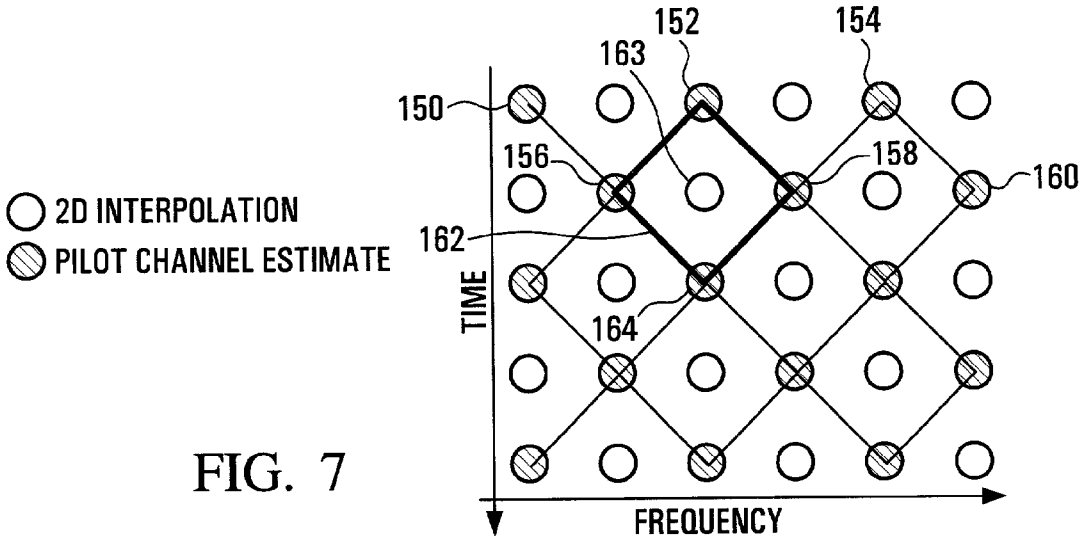


FIG. 7

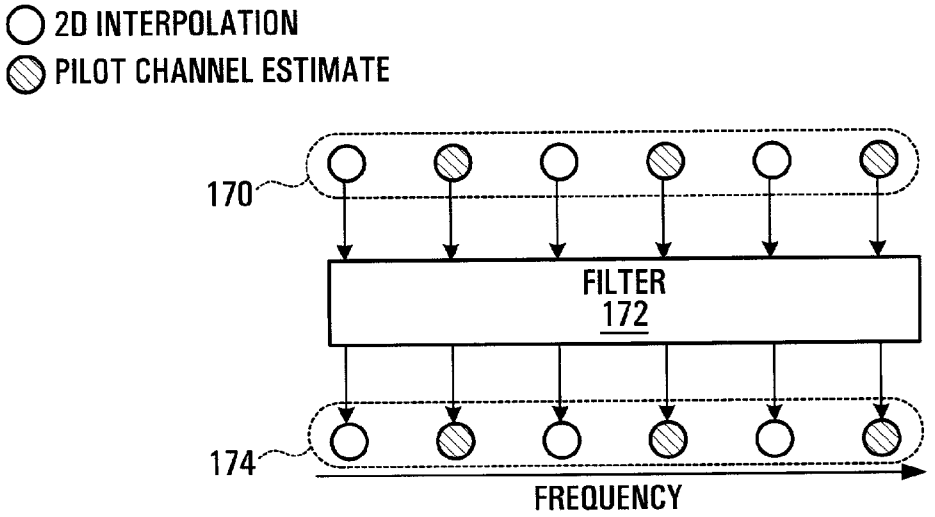


FIG. 8

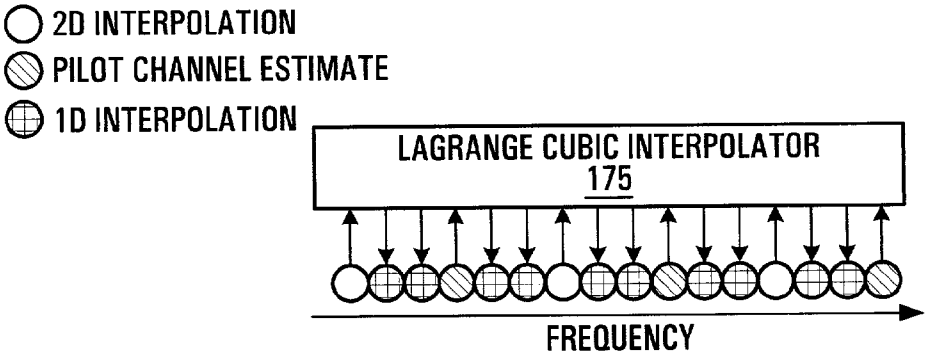


FIG. 9

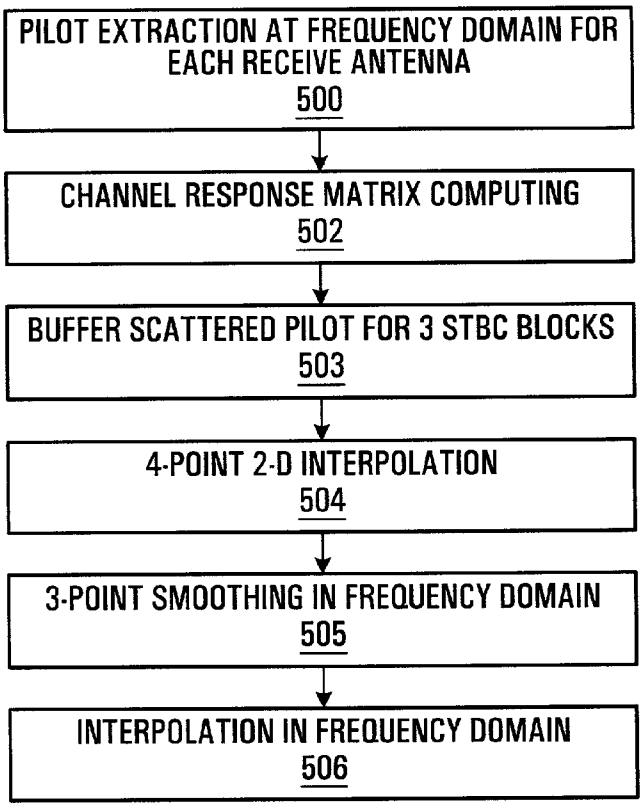

PILOT EXTRACTION AT FREQUENCY DOMAIN FOR EACH RECEIVE ANTENNA
500
CHANNEL RESPONSE MATRIX COMPUTING
502
BUFFER SCATTERED PILOT FOR 3 STBC BLOCKS
503
4-POINT 2-D INTERPOLATION
504
3-POINT SMOOTHING IN FREQUENCY DOMAIN
505
INTERPOLATION IN FREQUENCY DOMAIN
506

FIG. 10

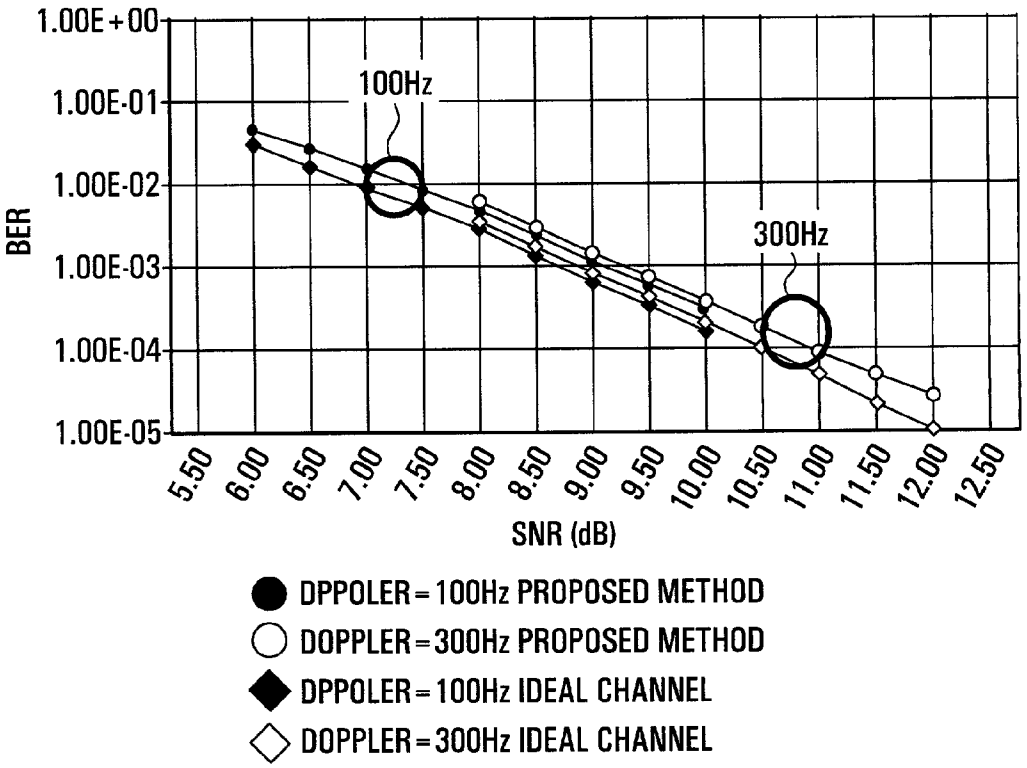

1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
BER
100Hz
300Hz
5.50
6.00
6.50
7.00
7.50
8.00
8.50
9.00
9.50
10.00
10.50
11.00
11.50
12.00
12.50
SNR (dB)
DPPOLER=100Hz PROPOSED METHOD
DOPPLER=300Hz PROPOSED METHOD
DPPOLER=100Hz IDEAL CHANNEL
DOPPLER=300Hz IDEAL CHANNEL

FIG. 11

SCATTERED PILOT PATTERN AND CHANNEL ESTIMATION METHOD FOR MIMO-OFDM SYSTEMS

RELATED APPLICATION

This application claims the benefit of U.S. provisional application No. 60/329,509 filed Oct. 17, 2001.

FIELD OF THE INVENTION

This invention relates to OFDM communication systems, and more particularly to a more efficient use of pilot symbols within such systems.

BACKGROUND OF THE INVENTION

Multiple Input Multiple Output-Orthogonal Frequency Division Multiplexing (MIMO-OFDM) is a novel highly spectral efficient technology used to transmit high-speed data through radio channels with fast fading both in frequency and in time.

In wireless communication systems that employ OFDM, a transmitter transmits data to a receiver using many sub-carriers in parallel. The frequencies of the sub-carriers are orthogonal. Transmitting the data in parallel allows the symbols containing the data to be of longer duration, which reduces the effects of multi-path fading. The orthogonality of the frequencies allows the sub-carriers to be tightly spaced, while minimizing inter-carrier interference. At the transmitter, the data is encoded, interleaved, and modulated to form data symbols. Overhead information is added, including pilot symbols, and the symbols (data plus overhead) are organized into OFDM symbols. Each OFDM symbol typically uses 2^n frequencies. Each symbol is allocated to represent a component of a different orthogonal frequency. An inverse Fast Fourier Transform (IFFT) is applied to the OFDM symbol (hence the preference of 2^n frequencies) to generate time samples of a signal. Cyclic extensions are added to the signal, and the signal is passed through a digital-to-analog converter. Finally, the transmitter transmits the signal to the receiver along a channel.

When the receiver receives the signal, the inverse operations are performed. The received signal is passed through an analog-to-digital converter, and timing information is then determined. The cyclic extensions are removed from the signal. The receiver performs an FFT on the received signal to recover the frequency components of the signal, that is, the data symbols. Error correction may be applied to the data symbols to compensate for variations in phase and amplitude caused during propagation of the signal along the channel. The data symbols are then demodulated, de-interleaved, and decoded, to yield the transmitted data.

In systems employing differential detection, the receiver compares the phase and/or amplitude of each received symbol with an adjacent symbol. The adjacent symbol may be adjacent in the time direction or in the frequency direction. The receiver recovers the transmitted data by measuring the change in phase and/or amplitude between a symbol and the adjacent symbol. If differential detection is used, channel compensation need not be applied to compensate for variations in phase and amplitude caused during propagation of the signal. However, in systems employing coherent detection the receiver must estimate the actual d phase and amplitude of the channel response, and channel compensation must be applied.

The variations in phase and amplitude resulting from propagation along the channel are referred to as the channel response. The channel response is usually frequency and time dependent. If the receiver can determine the channel response, the received signal can be corrected to compensate for the channel degradation. The determination of the channel response is called channel estimation. The inclusion of pilot symbols in each OFDM symbol allows the receiver to carry out channel estimation. The pilot symbols are transmitted with a value known to the receiver. When the receiver receives the OFDM symbol, the receiver compares the received value of the pilot symbols with the known transmitted value of the pilot symbols to estimate the channel response.

The pilot symbols are overhead, and should be as few in number as possible in order to maximize the transmission rate of data symbols. Since the channel response can vary with time and with frequency, the pilot symbols are scattered amongst the data symbols to provide as complete a range as possible of channel response over time and frequency. The set of frequencies and times at which pilot symbols are inserted is referred to as a pilot pattern. The optimal temporal spacing between the pilot symbols is usually dictated by the maximum anticipated Doppler frequency, and the optimal frequency spacing between the pilot symbols is usually dictated by the anticipated delay spread of multi-path fading.

The existing pilot-assisted OFDM channel estimation approaches are designed for conventional one transmitter system. With a scattered pilot arrangement, there are three classes of algorithms:

1-D frequency interpolation or time interpolation

Transformed frequency 1-D interpolation

Independent time and frequency 1-D interpolation

The first class of algorithms is based on the pilot OFDM symbol (all the sub-carriers are used as the pilots) or comb-type of pilots. This approach shown in the flow chart of FIG. **1**A is simple but only suitable for channels with high frequency selectivity or channels with high time fading. The method involves pilot extraction in the frequency domain (step **1**A-**1**) followed by interpolation in time (step **1**A-**2**), or interpolation in frequency (step **1**A-**3**).

The second method shown in the flow chart of FIG. **1**B is aimed for channels with slow Doppler fading and fast frequency fading. It improves the first method by using FFT to reconstruct the channel response back to time domain for noise reduction processing at the expense of FFT/IFFT computing for the channel estimation separately. The method begins with pilot extraction in the frequency domain (step **1**B-**1**), which may be followed by interpolation in frequency (step **1**B-**2**). Then an inverse fast Fourier transform (step **1**B-**3**), smoothing/de-noise processing (step **1**B-**4**), and finally a fast Fourier transform (**1**B-**5**) steps are executed.

The third method shown in the flow chart of FIG. **1**C can be used to estimate channel for mobile applications, where both fast time fading and frequency fading exist. However it needs a relatively high density of pilots and a completed interpolator. This method involves pilot extraction in the frequency domain (step **1**C-**1**) this is followed by interpolation in time (step **1**C-**2**) and interpolation in frequency (step **1**C-**3**).

In the propagation environment with both high frequency dispersion and temporal fading, the channel estimation performance can be improved by the increase of pilot symbol density at the price of the reduction of the spectral efficiency of the data transmission. To interpolate and recon-

struct the channel response function from the limited pilots to achieve reliable channel estimation with the minimum overhead is a challenging task.

There are a variety of existing standard pilot patterns. In environments in which the channel varies only slowly with time and frequency, the pilot symbols may be inserted cyclically, being inserted at an adjacent frequency after each time interval. In environments in which the channel is highly frequency dependent, the pilot symbols may be inserted periodically at all frequencies simultaneously. However, such a pilot pattern is only suitable for channels that vary very slowly with time. In environments in which the channel is highly time dependent, the pilot symbols may be inserted continuously at only specific frequencies in a comb arrangement to provide a constant measurement of the channel response. However, such a pilot pattern is only suitable for channels that vary slowly with frequency. In environments in which the channel is both highly frequency and highly time dependent (for example, mobile systems with much multi-path fading), the pilot symbols may be inserted periodically in time and in frequency so that the pilot symbols form a rectangular lattice when the symbols are depicted in a time-frequency diagram.

In OFDM communication systems employing coherent modulation and demodulation, the receiver must estimate the channel response at the frequencies of all sub-carriers and at all times. Although this requires more processing than in systems that employs differential modulation and demodulation, a significant gain in signal-to-noise ratio can be achieved using coherent modulation and demodulation. The receiver determines the channel response at the times and frequencies at which pilot symbols are inserted into the OFDM symbol, and performs interpolations to estimate the channel response at the times and frequencies at which the data symbols are located within the OFDM symbol. Placing pilot symbols more closely together (in frequency if a comb pattern is used, in time if a periodic pattern is used, or in both frequency and in time if a rectangular lattice pattern is used) within a pilot pattern results in a more accurate interpolation. However, because pilot symbols are overhead, a tighter pilot pattern is at the expense of the transmitted data rate.

Existing pilot patterns and interpolation techniques are usually sufficient if the channel varies slowly with time (for example for nomadic applications). However, if the channel varies quickly with time (for example, for mobile applications), the time interval between pilot symbols must be reduced in order to allow an accurate estimation of the channel response through interpolation. This increases the overhead in the signal.

The problem of minimizing the number of pilot symbols while maximizing the accuracy of the interpolation is also particularly cumbersome in Multiple-Input Multiple-Output (MIMO) OFDM systems. In MIMO OFDM systems, the transmitter transmits data through more than one transmitting antenna and the receiver receives data through more than one receiving antenna. The binary data is usually divided between the transmitting antennae, although the same data may be transmitted through each transmitting antenna if spatial diversity is desired. Each receiving antenna receives data from all the transmitting antennae, so if there are M transmitting antennae and N receiving antennae, then the signal will propagate over M×N channels, each of which has its own channel response. Each transmitting antenna inserts pilot symbols into the same sub-carrier location of the OFDM symbol which it is transmitting. In order to minimize interference at the receiver between the pilot symbols of each transmitting antenna, each transmitting antenna typically blinks its pilot pattern on and off. This increases the temporal separation of the pilot symbols for each transmitter, reducing the accuracy of the interpolation used to estimate the channel response. In MIMO-OFDM systems a simple and fast channel estimation method is particularly crucial because of the limitation of the computational power for estimating M×N channels, while in SISO-OFDM system only one channel needs to be estimated.

SUMMARY OF THE INVENTION

Channel estimation methods are provided which are based on the partial interpolation of a scattered pilot by using true 2-D interpolation; and additionally, simple 1-D interpolation is used reconstruct the entire channels. This method has a reduced scattered pilot overhead, and is at least an order of magnitude less computationally complex than some existing methods. In general, the proposed method of channel estimation is more robust in channels with high Doppler spread, and provides better performance than some existing methods and requires the less buffering of the OFDM symbols for the coherent detection at the receiver than in some methods.

The methods allow fewer pilot symbols to be placed within each OFDM symbol, while still allowing accurate interpolation of the channel response. The data rate of an MIMO-OFDM system is thereby improved.

A first broad aspect of the invention provides a method of inserting pilot symbols into Orthogonal Frequency Division Multiplexing (OFDM) frames at an OFDM transmitter having at least one transmitting antenna, the OFDM frames having a time domain and a frequency domain, each OFDM frame comprising a plurality of OFDM symbols. The method involves, for each antenna, inserting scattered pilot symbols in an identical scattered pattern in time-frequency.

In some embodiments, the identical scattered pattern is a regular diagonal-shaped lattice.

In some embodiments, inserting pilot symbols in an identical diagonal-shaped lattice involves for each point in the identical diagonal shaped lattice inserting a number of pilot symbols on a single sub-carrier for N consecutive OFDM symbols, where N is the number of transmitting antennae.

In some embodiments, diagonal shaped lattice is a diamond shaped lattice.

In some embodiments for each point in the diagonal-shaped lattice, L uncoded pilot symbols are generated. Space time block coding (STBC) is performed on the group of L uncoded pilot symbols to produce an N×N STBC block, L and N determining an STBC code rate. Then, one row or column of the STBC block is transmitted on each antenna on a specific sub-carrier.

In some embodiments, transmitting the pilot symbols is done with a power level greater than a power level of data symbols, depending upon a value reflective of channel conditions.

In some embodiments, transmitting the pilot symbols is done with a power level which is dynamically adjusted to ensure sufficiently accurate reception as a function of a modulation type applied to the sub-carriers carrying data.

In some embodiments, the diagonal shaped lattice pattern has a first plurality of equally spaced sub-carrier positions, and a second plurality of equally spaced sub-carrier positions offset from said first plurality. The pilot symbols are inserted alternately in time using the first plurality of equally spaced sub-carrier positions and the second plurality of equally spaced sub-carrier positions.

In some embodiments, the second plurality of sub-carriers is offset from the first plurality of equally spaced-sub-carrier positions by half the spacing between adjacent sub-carriers of the first plurality of sub-carrier positions thereby forming a diamond shaped lattice pattern.

In some embodiments, the pilot pattern is cyclically offset, both in a time direction and in a frequency direction, for at least one adjacent base station to form re-use patterns.

Another broad aspect of the invention provides an OFDM transmitter. The OFDM transmitter has a plurality of transmit antennas, and is adapted to insert pilot symbols into Orthogonal Frequency Division Multiplexing (OFDM) frames having a time domain and a frequency domain, each OFDM frame comprising a plurality of OFDM symbols by, for each antenna, inserting pilot symbols in an identical scattered pattern in time-frequency.

In some embodiments, the identical scattered pattern is a diagonal-shaped lattice.

In some embodiments, inserting pilot symbols in an identical scattered pattern involves for each point in the identical scattered pattern inserting a number of pilot symbols on a single sub-carrier for N consecutive OFDM symbols, where N is the number of transmitting antennae, where N>=1.

In some embodiments, the scattered pattern is a diamond shaped lattice.

In some embodiments, for each point in the scattered pattern, the OFDM transmitter is adapted to generate L uncoded pilot symbols, perform space time block coding (STBC) on the group of L pilot symbols to produce an N×N STBC block, and transmit one row or column of the STBC block on each antenna.

In some embodiments, the OFDM transmitter is further adapted to transmit the pilot symbols with a power level greater than a power level of data symbols depending on a value reflective of channel conditions.

In some embodiments in which the diamond shaped lattice pattern is employed, the diamond shaped lattice pattern has a first plurality of equally spaced sub-carrier positions and a second plurality of equally spaced sub-carrier positions offset from said first plurality. The pilot symbols are inserted alternately in time using the first plurality of equally spaced sub-carrier positions and the second plurality of equally spaced sub-carrier positions.

Another broad aspect of the invention provides a method of estimating a plurality of channel responses at an Orthogonal Frequency Division Multiplexing (OFDM) receiver having at least one receive antenna. The method involves at each receive antenna receiving OFDM frames transmitted by at least one transmitting antenna, the OFDM frames having a time domain and a frequency domain, the OFDM frames transmitted by each antenna having pilot symbols inserted in an identical scattered pattern in time-frequency, each OFDM frame comprising a plurality of OFDM symbols. For each transmit antenna, receive antenna combination: a) the pilot symbols of the received OFDM frames are used to estimate a channel response for each point in the scattered pattern; b) the channel response is estimated for of a plurality of points not on the scattered pattern by performing a two-dimensional (time direction, frequency direction) interpolation of channel responses determined for points in the scattered pattern; c) an interpolation is performed in the frequency direction to estimate the channel responses corresponding to remaining OFDM sub-carriers within each OFDM symbol.

In some embodiments, a filtering function is performed on the channel responses prior to performing the interpolation in the frequency direction to estimate the channel responses corresponding to remaining OFDM sub-carriers within each OFDM symbol.

In some embodiments, estimating the channel response of a plurality of points not on the scattered pattern by performing a two-dimensional (time direction, frequency direction) interpolation of channel responses determined for points in the scattered pattern lattice involves for each sub-carrier to be estimated averaging channel responses of the given channel estimation period of a sub-carrier before the sub-carrier to be estimated in frequency (when present) and a sub-carrier after the sub-carrier to be estimated in frequency (when present) and the channel response for a previous estimation period (when present) and a following estimation period (when present).

In some embodiments, the method is applied to a single transmitter, single receiver system.

In other embodiments the method is applied to a single transmitter system wherein each point in the scattered pattern contains a single pilot symbol.

In some embodiments, the method is applied to a system in which there are N>=2 antennas, and each point in the scattered pattern contains a number N of consecutive encoded pilot symbols transmitted on a sub-carrier, a single channel estimate being determined for each N encoded pilot symbols.

In some embodiments, the N encoded pilot symbols contain L pilot symbols which were STBC block coded, where N and L together determine a STBC code rate.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying Figures.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in greater detail with reference to the accompanying Figures, in which:

FIG. **1** illustrates flow-charts for three examples of conventional OFDM Channel Estimation;

FIG. **2** is a block diagram of a Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (OFDM) transmitter provided by an embodiment of the invention;

FIG. **3** is a block diagram of an OFDM receiver;

FIG. **4** is a flowchart of a method by which an OFDM transmitter inserts pilot symbols into an OFDM frame according to one embodiment of the invention;

FIG. **5** is a diagram of a pilot pattern generated using the method of FIG. **4**;

FIG. **6** is a block diagram of a MIMO system showing the channel transfer functions between two transmit antennas and two receive antennas;

FIG. **7** is a time frequency diagram showing channel estimate positions for pilot channel estimation;

FIG. **8** schematically illustrates a step of filtering estimated and interpolated pilot channel estimates;

FIG. **9** shows schematically the step of interpolating between the channel estimates previously determined to provide channel estimates for all sub-carriers and all times;

FIG. **10** is a flow chart summarizing the overall channel estimation method provided by an embodiment of the invention; and

FIG. **11** is an example of a set of performance results obtained using the method of FIG. **10**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following sections describe a MIMO-OFDM transmitter/receiver and scattered pilot insertion. By way of introduction, a OFDM frame consists of the preamble OFDM symbols and regular OFDM symbols. Each OFDM symbol uses a set of orthogonal sub-carriers. When there are two transmit antennas, two OFDM symbols form a STTD block. For regular OFDM symbols, some sub-carriers are used as pilot sub-carriers to carry pilot symbols while the others are used as data sub-carriers to carry data symbols. The pilot sub-carriers are modulated by pilot symbols generated by QPSK. The data sub-carriers are modulated by complex data symbols generated by QAM mapping. STTD coding is applied to the pilot sub-carrier pairs located at the same frequency within one STTD block.

Referring to FIG. **2**, a block diagram of a Multiple-Input Multiple-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) transmitter provided by an embodiment of the invention is shown. The OFDM transmitter shown in FIG. **2** is a two-output OFDM transmitter, though more generally there may be a plurality of M transmitting antennae. An OFDM transmitter **10** takes binary data as input but data in other forms may be accommodated. The binary data is passed to a coding/modulation primitive **12** responsible for encoding, interleaving, and modulating the binary data to generate data symbols, as is well known to those skilled in the art. The coding/modulation primitive **12** may include a number of processing blocks, not shown in FIG. **2**. An encoder **14** applies Space-Time Block Coding (SBTC) to the data symbols. The encoder **14** also separates the data symbols into a first processing path **16** and a second processing path **18**, by sending alternate data symbols along each of the two processing paths. In the more general case in which the OFDM transmitter **10** includes M transmitting antennae, the encoder **14** separates the data symbols into M processing paths.

The data symbols sent along the first processing path **16** are sent to a first OFDM component **20**. The data symbols are first passed to a demultiplexer **22** in the first OFDM component **20**, after which the data symbols are treated as sub-carrier components. The data symbols are then sent to a pilot inserter **24**, where pilot symbols are inserted among the data symbols. Collectively, the data symbols and pilot symbols are referred to hereinafter simply as symbols. The symbols are passed to an Inverse Fast Fourier Transform (IFFT) processor **26**, then to a multiplexer **28** where they are recombined into a serial stream. A guard inserter **30** adds prefixes to the symbols. Finally, the OFDM signals are passed through a hard limiter **32**, a digital-to-analog converter **34**, and a radio frequency (RF) transmitter **36** which transmits OFDM symbols as a signal through a first transmitting antenna **37**. In most embodiments, each element in the first OFDM component **20** is a processor, a component of a larger processor, or a collection of processors or any suitable combination of hardware, firmware and software. These might include general purpose processors, ASICs, FPGAs, DSPs to name a few examples.

The pilot inserter **24** is connected to receive space-time coded pilot symbols from pilot STBC function **23** which performs STBC on pilot symbols **21**. The pilot STBC block **23** takes two pilot symbols at a time for example P_1 and P_2 as indicated in FIG. **2** and generates an STBC block consisting of a two by two matrix having (P_1, P_2) in the first row and having $(-P_2^*, P_1^*)$ in the second row. It is the first row of this STBC block that is inserted by the pilot inserter **24**.

The data symbols sent along the second processing path **18** are sent to a second OFDM component **38** which includes processors similar to those included in the first OFDM component **20**. However, the pilot inserter **40** inserts encoded pilot symbols from the second row of the STBC block produced by the pilot STBC function **23**. The symbols sent along the second processing path **18** are ultimately transmitted as a signal through a second transmitting antenna **42**.

Referring now to FIG. **3**, a block diagram of an MIMO-OFDM receiver is shown. An OFDM receiver **50** includes a first receiving antenna **52** and a second receiving antenna **54** (although more generally there will be one or more receiving antennae). The first receiving antenna **52** receives a first received signal. The first received signal is a combination of the two signals transmitted by the two transmitting antennae **37** and **42** of FIG. **2**, although each of the two signals will have been altered by a respective channel between the respective transmitting antenna and the first receiving antenna **52**. The second receiving antenna **54** receives a second received signal. The second received signal is a combination of the two signals transmitted by the two transmitting antennae **37** and **42** of FIG. **2**, although each of the two signals will have been altered by a respective channel between the respective transmitting antenna and the second receiving antenna **54**. The four channels (between each of the two transmitting antennae and each of the two receiving antennae) may vary with time and with frequency, and will usually be different from each other.

The OFDM receiver **50** includes a first OFDM component **56** and a second OFDM component **58** (although in general there will be N OFDM components, one for each receiving antenna). The first OFDM component **56** includes a RF receiver **59**, and an analog-to-digital converter **60**, which converts the first received signal into digital signal samples. The signal samples are passed to a frequency synchronizer **62** and a frequency offset corrector **64**. The signal samples are also fed to a frame/time synchronizer **66**. Collectively, these three components produce synchronized signal samples.

The synchronized signal samples represent a time sequence of data. The synchronized signal samples are passed to a demultiplexer **68**, then passed in parallel to a Fast Fourier Transform (FFT) processor **70**. The FFT processor **70** performs an FFT on the signal samples to generate estimated received symbols which are multiplexed in MUX **76** and sent as received symbols to decoder **78**. Ideally, the received symbols would be the same as the symbols fed into the IFFT processor **26** at the OFDM transmitter **10**. However, as the received signals will have likely been altered by the various propagation channels, the first OFDM component **56** must correct the received symbols by taking into account the channels. The received symbols are passed to a channel estimator **72**, which analyses received pilot symbols located at known times and frequencies within the OFDM frame. The channel estimator **72** compares the received pilot symbols with what the channel estimator **72** knows to be the values of the pilot symbols as transmitted by the OFDM transmitter **10**, and generates an estimated channel response for each frequency and time within the OFDM symbol. The estimated channel responses are passed to decoder **78**. The channel estimator **72** is described in detail below.

The second OFDM component **58** includes similar components as are included in the first OFDM component **56**, and processes the second received signal in the same manner

as the first OFDM component **56** processes the first received signal. Each OFDM component passes OFDM symbols to the decoder **78**.

The decoder **78** applies STBC decoding to the OFDM symbols, and passes the symbols to a decoding/demodulating primitive **80** responsible for decoding, de-interleaving, and demodulating the symbols to generate output binary data, as is well known to those skilled in the art. The decoding/demodulation primitive **80** which may include a number of additional processing blocks, not shown in FIG. **2**. Each element in the OFDM components **56** and **58** is a processor, a component of a larger processor, or a collection of processors.

Referring now to FIG. **4**, a method by which each of the pilot inserters **24** and **40** of FIG. **2** inserts pilot symbols among the data symbols is shown. The method will be described with reference to the pilot inserter **24** in the first OFDM component **20**. At step **100**, the pilot inserter **24** receives data symbols from the demultiplexer **22**. At step **102** the pilot STBC function **23** generates (or receives) two pilot symbols. At step **104** the pilot STBC function **23** applies STEC encoding to the pilot symbols, so as to generate an STBC block of encoded pilot symbols. The encoded pilot symbols generated for the first transmitting antenna **37** will be one row of the STBC block and will have a number equal to the number of transmitting antennae in the OFDM transmitter. Thus, for a two antenna system a 2×2 STBC block is generated.

At step **106** the pilot inserter **24** inserts the encoded pilot symbols within the OFDM symbol. Encoded pilot symbols are inserted in a diamond lattice pattern. The diamond lattice pattern uses the same frequencies as the other diamond lattice patterns, but has a temporal offset from the other diamond lattice patterns. Preferably, the temporal offset for each diamond lattice pattern is one symbol (in the time direction) from another diamond lattice pattern, so that the diamond lattice patterns use consecutive symbols in the time direction of the OFDM frame.

The diamond lattice pattern in which each encoded pilot symbol is inserted within the OFDM frame is preferably a perfect diamond lattice pattern. To achieve this, the encoded pilot symbol is inserted at each of a first subset of frequencies. The frequencies within the first subset of frequencies are spaced equally apart by a pilot spacing. The encoded pilot symbol is inserted at each of the first subset of frequencies for an STBC block (two OFDM symbols). At some later time, the encoded pilot symbols are inserted at each of a second subset of frequencies. The frequencies within the second subset of frequencies are shifted from the frequencies within the first subset of frequencies by half of the pilot spacing within the frequency direction. The pilot inserter **24** continues to insert encoded pilot symbols, alternating between the first subset of frequencies and the second subset of frequencies.

Alternatively, a different pilot pattern can be used, as long as the same pilot pattern is used for each of the at least one encoded pilot symbols unique to the transmitting antenna **37**, and as long as the pilot patterns for the encoded pilot symbols are offset from each other in the time direction of the OFDM frame. For example, a regular diagonal lattice pattern may be used, the diamond shaped lattice being a special case of this.

The pilot inserter **40** inserts pilot symbols using the same method, although the pilot symbols will be the other half of the STBC block **42**. The encoded pilot symbols unique to the second transmitting antenna **42** are inserted in the OFDM frame at the same symbol locations at which the encoded pilot symbols corresponding to the first transmitting antenna **37** are inserted.

Referring to FIG. **5**, an example pilot pattern generated using the method of FIG. **4** is shown. Pilot and data symbols are spread over the OFDM frame in a time direction **120** and a frequency direction **122**. Most symbols within the OFDM frame are data symbols **124**. A first set of encoded pilot symbols **126** corresponding to the first transmitting antenna **37** is inserted in a diamond lattice pattern. A second set of encoded pilot symbols **128** corresponding to the first transmitting antenna **37** is inserted in a diamond lattice structure at the same frequencies as the first set of encoded pilot symbols, but offset by one OFDM symbol location in the time direction **120**. In the illustrated example two of every four OFDM symbols carry encoded pilot symbols. Each other transmitting antenna transmits using the same pattern. The pairs of consecutive pilot symbols on a sub-carrier consist of two raw pilot symbols STBC encoded. The same pattern is transmitted by the second antenna.

The power of the encoded pilot symbols **126**, **128** may be increased compared to the traffic data symbol **124**. The power increase of the encoded pilot can be dynamically adjusted with respect to the transmitting data symbol power level or modulation type (QAM size), or as a function of channel quality. The location of diamond lattice pattern may also be optimized to allow a fast extraction of scattered pilot without using the computing. This may be achieved if the pilot subcarriers are spaced in the frequency direction by 2 ^n. In the multiple base station transmission arrangement, the location of the diamond lattice pattern can be cyclic offset both in time direction and in frequency direction amongst adjacent base stations to form a diamond lattice re-use pattern.

Referring now to FIGS. **6** to **10**, a channel estimation method is described which is based on the pilot insertion method above. This invention presents a simple 2-dimensional channel interpolator for MIMO-OFDM system with low pilot density for fast fading channels both in time and in frequency. The goal of channel estimation is to estimate the channel characteristics for each sub-carrier and at each time for each possible transmit antenna, receive antenna combination. Referring to FIG. **13**, for the two transmit antenna, two receive antenna example, shown are two transmit antennas Tx**1** **140** and Tx**2** **142** and two receive antennas Rx**1** **144** and Rx**2** **146**. Channel estimation estimates a channel for each sub-carrier and at each time between Tx**1** **140** and Rx**1** **144** indicated as each H_{11} **148**, a channel between Tx**1** **140** and Rx**2** **146** indicated by transfer function H_{12} **150**, a channel estimate for transmitter Tx**2** **142** to Rx**1** **144** indicated as transfer function H_{22} **152** and finally, a channel estimate for transmitter Tx**2** **142** to receiver Rx**2** **146** indicated as transfer function H_{21} **154**.

Some advantages for the proposed method compared to some existing methods are: (1) robust to high mobility-speed (2) a reduction of the scattered pilot grid density and therefore a reduction of the pilot overhead.

Let P_1 and P_2 be the two pilot symbols encoded in an STBC block and transmitted by two antennas on one sub-carrier in consecutive OFDM symbols. Then at the first receive antenna, the following relationship exists for each sub-carrier on which pilot symbols are transmitted, where it is assumed the channel response H_{ij} is constant over two OFDM frames:

$$\begin{bmatrix} Y_{1,1} \\ Y_{1,2} \end{bmatrix} = \begin{bmatrix} P_1 & P_2 \\ -P_2^* & P_1^* \end{bmatrix} \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix}$$

$Y_{1,1}$ is the received data on the first antenna on the sub-carrier in the first of the two consecutive OFDM symbols, and $Y_{1,2}$ is the received data on the first antenna on the sub-carrier in the second of the two consecutive symbols. This can be solved for H_{11}, H_{21} to yield:

$$\begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix} = \frac{1}{|P_1|^2 + |P_2|^2} \begin{bmatrix} P_1^* & -P_2 \\ P_2^* & P_1 \end{bmatrix} \begin{bmatrix} Y_{1,1} \\ Y_{1,2} \end{bmatrix}$$

A similar process for the second antenna yields

$$\begin{bmatrix} H_{12} \\ H_{22} \end{bmatrix} = \frac{1}{|P_1|^2 + |P_2|^2} \begin{bmatrix} P_1^* & -P_2 \\ P_2^* & P_1 \end{bmatrix} \begin{bmatrix} Y_{2,1} \\ Y_{2,2} \end{bmatrix}$$

where $Y_{2,1}$ is the received data on the second antenna on the sub-carrier in the first of the two consecutive OFDM symbols, and $Y_{2,2}$ is the received data on the second antenna on the sub-carrier in the second of the two consecutive OFDM symbols.

Using this techniques, a channel estimate is made for each pilot sub-carrier, and for each pair of OFDM symbols used to transmit STBC blocks.

For the example of FIG. **12**, the result is a channel estimate, for each of the possible channels (these are for channels in this example as shown in FIG. **13**) for each pair of pilot symbols transmitted. This is illustrated in FIG. **14** where only sub-carriers used to transmit pilots are shown. A channel estimate **150** is generated for each pair of (consecutive in time) OFDM frames for each pilot sub-carrier. This results in channel estimates **150**, **152**, **154** for the first and second frames, and channel estimates **156**, **158**, **160** for the fifth and sixth frames and so on.

The channel estimates are made on a STBC block by block basis so that the pattern of channel estimate shown in FIG. **7** develops over time. The next step in the process is to perform an interpolation based on the channel estimate of FIG. **7** to obtain channel estimates for the places in FIG. **7** which do not represent pilot channel positions. The manner in which this is done will be described for a single example, namely the unknown channel estimate indicated at **163** of FIG. **7**. Channel estimates are buffered on an ongoing basis and when the four channel estimates **152**, **156**, **158** and **164** forming a diamond **162** surrounding the unknown channel estimate **163** have been computed, it is time to interpolate to obtain a channel estimate for the unknown point **163**. The channel transfer function at the sub-carrier located at the centre of the diamond can be obtained from a simple 4 points two-dimensional interpolator. Three points two-dimensional interpolators can be used to obtain the channel estimates corresponding to the first or last useful sub-carrier:

$$H_{new}(n+1, k) = \frac{1}{4}(H(n, k) + H(n+2, k) + H(n+1, k-1) + H(n+1, k+1))$$

-continued

where $(k = 2, \ldots, N_{pilot} - 1)$

$$H_{new}(n+1, 1) = \frac{1}{4}(H(n, 1) + H(n+2, 1) + 2H(n+1, 2))$$

$$H_{new}(n+1, N_{pilot}) = \frac{1}{4}(H(n, N_{pilot}) + H(n+2, N_{pilot}) + 2H(n, N_{pilot} - 1))$$

where k is the pilot sub-carrier index, n is the channel estimate index (or STBC block number—one channel estimate per sub-carrier for every two symbols), and N_{pilot} is the number of pilot sub-carriers (**6** in the example of FIG. **7**). H_{new} is the newly interpolated channel estimate for the ith channel estimation period, and the jth pilot sub-carrier. H(i, j) is the channel estimate determined as described previously from the pilot symbols. A three points interpolator would also be performed for the last STBC blocks in the OFDM frame (i.e. the last two OFDM symbols).

These calculations are done for each transmit antenna, receiver antenna combination. It is noted that this is just one example of how the channel estimates can be interpolated.

If the original distance between pilot sub-carriers in the frequency direction is D_f, after first step of interpolation described above, the pilot sub-carriers' separation becomes

$$\frac{D_f}{2}.$$

In some embodiments, to remove noise, the channel estimates thus computed are filtered at each channel estimation period. This is shown in FIG. **6** where the channel estimates **170** for one channel estimation period are shown entering filter **172** to produce filtered channel estimates. For example, a simple 3 point moving iterative smoothing algorithm may be applied to H':

$$H'_{sm}(n, k) = H'_{sm}(n, k-1) + \frac{1}{3}(H'(n, k+1) + H'_{sm}(n, k-2))$$

where k=3, . . . , 2 N_{pilot}−2. It is to be understood that other filtering algorithms may be employed.

After the interpolation of the pilot channel estimate as summarized in FIG. **7**, there will be a channel estimate for each sub-carrier on which pilot channel information was transmitted and for each two OFDM symbol period over which pilot channelling information was transmitted. Referring to FIG. **5**, this means that there will be a channel estimate for each antenna for time frequency points which are shaded to indicate that pilot channel information was transmitted. There will also be channel estimates for the time frequency point in the centre of the diamond shaped lattice structure of FIG. **7**. However, for points which are not pilot symbol transmission time-frequency points nor points which are at the centre of a diamond shaped lattice of such points, there will be no channel estimate yet computed. The next step is to perform a further interpolation step to develop channel estimates for these other points.

In some embodiments, Cubic Lagrange interpolation and linear interpolation (for the sub-carriers near the first and the last useful sub-carrier) in the frequency direction are used to

obtain the channel transfer function at all sub-carriers for each STBC block (for each pair of OFDM symbols).

The coefficients of the Cubic Lagrange interpolator can be calculated as

$$\mu(i) = \frac{i}{D_f/2} \quad i = 1, 2, \ldots, \frac{D_f}{2}$$

$$q_{-1}(\mu) = -\frac{1}{6}\mu^3 + \frac{1}{2}\mu^2 - \frac{1}{3}\mu$$

$$q_0(\mu) = \frac{1}{2}\mu^3 - \mu^2 - \frac{1}{2}\mu + 1$$

$$q_1(\mu) = -\frac{1}{2}\mu^3 + \frac{1}{2}\mu^2 + \mu$$

$$q_2(\mu) = -\frac{1}{6}\mu^3 - \frac{1}{6}\mu$$

The channel transfer functions at data sub-carriers are given by

$$H_{interp}\left((j-1)\cdot\frac{D_f}{2} + i\right) = \sum_{n=-1}^{2} q_n(\mu(i))\cdot H'_{sm}(j+n)$$

where j=2, . . . , $N_{pilot}-2$.

This is illustrated in FIG. **9** where the estimated channel responses are fed to the Legrange cubic interpolator function **175** which outputs values for all intermediate sub-carriers. Other interpolations may alternatively be employed.

In some embodiments, every OFDM symbol contains some pilot insertion points and as such this completes the interpolation process. In other embodiments, there are some OFDM symbols which do not have any pilot insertion points. To get channel estimates for these OFDM symbols, an interpolation in time of the previously computed channel estimates is performed. In high mobility applications, pilots should be included in every OFDM symbol avoiding the need for this last interpolation in time step.

FIG. **10** presents an overall block diagram of the interpolation method proposed for two transmit antennas. An example set of performance results for the proposed MIMO-OFDM channel estimation algorithm is shown in FIG. **10**. The performance of the 2-D channel estimation algorithm is close to the performance of ideal channel (only 0.5 dB loss) at very high Doppler spread.

Referring now to FIGS. **10** and **3**, the channel estimation method is carried out by the channel estimator **72** in order to estimate a channel response for each sub-carrier and each OFDM symbol within an OFDM frame. The channel estimation method starts at step **500** by extracting the pilot symbols in the frequency domain for each receive antenna. This is followed by a channel response matrix computing step **502**; whereby the received signal received by the receiving antenna is decoded, which in effect performs a time average of the encoded pilot symbols at each point in the pilot pattern. For example, suppose the receiving antenna receives an OFDM frame having a pilot pattern as shown in FIG. **5** (although the symbol **126** will now be a linear combination of the encoded pilot symbol transmitted at this location by each of the transmitting antenna, and the symbol **128** will be a linear combination of the encoded pilot symbol transmitted at this location by each of the transmitting antenna). Following decoding, the pilot symbol at symbol location **126** will be an average of the pilot symbol received at symbol location **126** and the pilot symbol received at symbol location **128**. The time averaging effect produced by the STBC decoding, during step **503**, can be viewed as a pre-processing step, as can steps **500** and **502**. The actual channel estimation method can be described broadly in four steps. Following step **503**, during step **504** the channel estimator **72** estimates the channel response for each of a plurality of pilot symbols. For a diamond lattice pattern, the plurality of pilot symbols will be four pilot symbols forming a single diamond pattern. The channel estimator **72** estimates the channel response of a central symbol, the central symbol having a time direction value and a frequency direction value bounded by the time direction values and the frequency direction values of the plurality of pilot symbols. The central symbol preferably has a frequency direction value equal to the frequency direction values of two of the plurality of pilot symbols, and has a time direction value midway between the time direction values of the two pilot symbols having the same frequency direction value as the central symbol. This can generally be described as a four-point 2-D interpolation of the channel response between pilot symbols. Third, the channel estimator **72** smoothes the channel responses (corresponding to both encoded pilot symbols and to the central symbol) in the frequency direction, preferably by performing a three-point smoothing, as per step **505**. Fourth, the channel estimator **72** performs an interpolation in the frequency direction to estimate the channel response for remaining symbols, as per step **506**. The interpolation may be a linear interpolation for symbols having a frequency direction value equal to a first or a last useful sub-carrier within the OFDM symbol, and a cubic Lagrange interpolation otherwise.

The method of inserting pilot symbols (described above with reference to FIG. **4**) and the channel estimation method (described above with reference to FIG. **10**) need not be used together. Any channel estimation method may be used by the OFDM receiver to estimate the channel responses for an OFDM frame containing encoded pilot symbols inserted using the method described above. However, due to the sparse distribution of the pilot symbols in the pilot pattern described above with reference to FIG. **4** and FIG. **5**, a two-dimensional interpolation method is preferable over a one-dimensional interpolation method. Similarly, the channel estimation method may be applied to an OFDM frame containing any pattern of pilot symbols.

The invention has been described with respect to an MIMO-OFDM communication system. The invention may also be used with advantage in a single input-multiple output OFDM communication system, as the method of inserting pilot symbols (described with reference to FIG. **4**) and the channel estimation method (described with reference to FIG. **10**) do not depend on the number of receiving antenna. Each receiving antenna within the OFDM receiver **50** performs channel estimation independently, regardless of the number of receiving antennae present.

The channel estimation method described with reference to FIG. **10** will also be advantageous in an OFDM communication system having only one transmitting antenna, as the method provides an improved interpolation of the channel response regardless of the number of transmitting antenna. The method of inserting pilot symbols described with reference to FIG. **11** may be used in an OFDM communication system having only one transmitting antenna, but will not be as advantageous as in an OFDM communication system having more than one transmitting antenna as there will be no reduction in overhead.

The method of inserting pilot symbols and the channel estimation method are preferably implemented on the OFDM transmitter and on the OFDM receiver respectively in the form of software instructions readable by a digital signal processor. Alternatively, the methods may be implemented as logic circuitry within an integrated circuit. More generally, any computing apparatus containing logic for executing the described functionality may implement the methods. The computing apparatus which implements the methods (in particular the pilot inserter or the channel estimator) may be a single processor, more than one processor, or a component of a larger processor. The logic may comprise external instructions stored on a computer-readable medium, or may comprise internal circuitry.

What has been described is merely illustrative of the application of the principles of the invention. Other arrangements and methods can be implemented by those skilled in the art without departing from the spirit and scope of the present invention.

We claim:

1. A method of inserting pilot symbols into Orthogonal Frequency Division Multiplexing (OFDM) frames at an OFDM transmitter having at least two transmitting antennas, the OFDM frames having a time domain and a frequency domain, each OFDM frame comprising a plurality of OFDM symbols, the method comprising the steps of:

for each antenna, inserting scattered pilot symbols in a respective scattered pattern in time-frequency, the scattered patterns for the antennas being identical, the scattered pattern of each antenna having an offset with respect to the scattered pattern of each other antenna.

2. A method according to claim **1** wherein each scattered pattern is a regular diagonal-shaped lattice.

3. A method according to claim **2** wherein for each antenna, inserting pilot symbols in a regular diagonal-shaped lattice comprises for each point in the diagonal shaped lattice inserting a N pilot symbols on a single sub-carrier for N consecutive OFDM symbols, where N is the number of transmitting antennae, the N pilot symbols consisting of one pilot symbol per antenna.

4. A method according to claim **3** wherein the diagonal shaped lattice is a diamond shaped lattice.

5. A method of claim **4** further comprising transmitting the pilot symbols with a power level which is dynamically adjusted to ensure sufficiently accurate reception as a function of a modulation type applied to the sub-carriers carrying data.

6. A method according to claim **3** further comprising for each point in the diagonal-shaped lattice:

generating L uncoded pilot symbols;

performing space time block coding (STBC) on the group of L uncoded pilot symbols to produce an N×N STBC block, L and N determining an STBC code rate;

transmitting one row or column of the STBC block on each antenna on a specific sub-carrier.

7. A method according to claim **3** further comprising for each point in the diagonal-shaped lattice:

generating L uncoded pilot symbols;

performing coding on the group of L uncoded pilot symbols to produce a coded block;

transmitting one row or column of the block on each antenna on a specific sub-carrier.

8. A method according to claim **2** wherein the diagonal shaped lattice pattern comprises:

a first plurality of equally spaced sub-carrier positions;

a second plurality of equally spaced sub-carrier positions offset from said first plurality;

wherein the pilot symbols are inserted alternately in time using the first plurality of equally spaced sub-carrier positions and the second plurality of equally spaced sub-carrier positions.

9. A method according to claim **8** wherein the second plurality of sub-carriers is offset from the first plurality of equally spaced-subcarrier positions by half the spacing between adjacent sub-carriers of the first plurality of sub-carrier positions thereby forming a diamond shaped lattice pattern.

10. A method of claim **1** further comprising transmitting the pilot symbols with a power level greater than a power level of data symbols, depending upon a value reflective of channel conditions.

11. The method of claim **1** wherein the pilot pattern is cyclically offset, both in a time direction and in a frequency direction, for at least one adjacent base station to form re-use patterns.

12. A method according to claim **1** wherein for each antenna, inserting pilot symbols comprises:

for each point in a scattered pattern inserting a number N of pilot symbols where N is the number of transmitting antennae.

13. A method comprising:

providing a first OFDM transmitter for implementing the method of claim **1**;

providing at least one other OFDM transmitter for implementing the method of claim **1** using scattered patterns offset from those used by the first OFDM transmitter.

14. The method of claim **1** further comprising inserting scattered pilots with spacing and a frequency domain optimized to allow a fast extraction of scattered pilot symbols without requiring the computation of a complete FFT.

15. An OFDM transmitter comprising:

a plurality of transmit antennas;

the OFDM transmitter operable to insert pilot symbols into Orthogonal Frequency Division Multiplexing (OFDM) frames having a time domain and a frequency domain, each OFDM frame comprising a plurality of OFDM symbols by, for each antenna, inserting pilot symbols in a respective scattered pattern in time-frequency, the scattered patterns for the antennas being identical, the scattered pattern of each antenna having an offset with respect to the scattered pattern of each other antenna.

16. A transmitter according to claim **15** wherein the identical scattered pattern is a diagonal-shaped lattice.

17. An OFDM transmitter according to claim **15** wherein for each antenna, inserting pilot symbols in a respective scattered pattern comprises for each point in a diagonal-shaped lattice inserting a number of N pilot symbols on a single sub-carrier for N consecutive OFDM symbols, where N is the number of transmitting antennae, where N>=2, the N pilot symbols consisting of a one pilot symbol per antenna.

18. An OFDM transmitter according to claim **17** wherein the scattered pattern is a diamond shaped lattice.

19. An OFDM transmitter to claim **15** further operable to, for each point in the scattered pattern:

generate L uncoded pilot symbols;

perform space time block coding (STBC) on the group of L pilot symbols to produce an N×N STBC block;

transmit one row or column of the STBC block on each antenna.

20. An OFDM transmitter according to claim **19** wherein the scattered pattern is a diamond-shaped lattice.

21. An OFDM transmitter according to claim **20** wherein the diamond shaped lattice pattern comprises:

a first plurality of equally spaced sub-carrier positions;

a second plurality of equally spaced sub-carrier positions offset from said first plurality;

wherein the pilot symbols are inserted alternately in time using the first plurality of equally spaced sub-carrier positions and the second plurality of equally spaced sub-carrier positions.

22. An OFDM transmitter according to claim **21** wherein spacing between locations of the diamond lattice pattern are optimized to allow a fast extraction of scattered pilot symbols without requiring the computation of a complete FFT.

23. An OFDM transmitter according to claim **15** further operable to transmit the pilot symbols with a power level greater than a power level of data symbols depending on a value reflective of channel conditions.

24. An OFDM transmitter according to claim **15** further operable to transmit the pilot symbols with a power level which is dynamically adjusted to ensure sufficiently accurate reception.

25. The OFDM transmitter of claim **15** wherein the transmitter is adapted to insert pilots in a respective scattered pattern in time-frequency for each antenna by:

for each point in a scattered pattern inserting a number N of pilot symbols where N is the number of transmitting antennae, the N pilot symbols consisting of one pilot symbol per antenna.

26. The OFDM transmitter of claim **15** wherein the transmitter is adapted to insert scattered pilots with spacing in a frequency domain optimized to allow a fast extraction of scattered pilot symbols without requiring the competition of a complete FFT.

27. A method of estimating a plurality of channel responses at an Orthogonal Frequency Division Multiplexing (OFDM) receiver having at least two receive antennas, the method comprising:

at each receive antenna receiving OFDM frames transmitted by at least two transmitting antennas, the OFDM frames having a time domain and a frequency domain, the OFDM frames transmitted by each antenna having pilot symbols inserted in a respective scattered pattern in time-frequency, the scattered patterns for the antennas being identical, the scattered pattern of each antenna having an offset with respect to the scattered pattern of each other antenna, each OFDM frame comprising a plurality of OFDM symbols;

for each transmit antenna, receive antenna combination:

a) using the pilot symbols of the received OFDM frames to estimate a channel response for each point in the scattered pattern;

b) estimating the channel response of a plurality of points not on the scattered pattern by performing a two-dimensional (time direction, frequency direction) interpolation of channel responses determined for points in the scattered pattern;

c) performing an interpolation in the frequency direction to estimate the channel responses corresponding to remaining OFDM sub-carriers within each OFDM symbol.

28. A method according to claim **27** further comprising:

performing a filtering function on the channel responses prior to performing the interpolation in the frequency direction to estimate the channel responses corresponding to remaining OFDM sub-carriers within each OFDM symbol.

29. A method according to claim **27** wherein the scattered pattern is a regular diamond shaped lattice.

30. A method according to claim **29** wherein estimating the channel response of a plurality of points not on the scattered pattern by performing a two-dimensional (time direction, frequency direction) interpolation of channel responses determined for points in the scattered pattern lattice comprises:

for each sub-carrier to be estimated averaging channel responses of the given channel estimation period of a sub-carrier before the subcarrier to be estimated in frequency (when present) and a sub-carrier after the subcarrier to be estimated in frequency (when present) and the channel response for a previous estimation period (when present) and a following estimation period (when present).

31. A method of claim **28** wherein filtering the channel responses comprises performing a three-point smoothing operation.

32. A method of claim **27** wherein performing an interpolation in the frequency domain comprises performing a linear interpolation for sub-carriers at a lowest or highest useful frequency within the OFDM symbol and performing a cubic Lagrange interpolation for sub-carriers at frequencies not equal to the first or the last useful frequency.

33. A method according to claim **21** applied to a system in which there are N>=2 transmit antennas, and wherein each point in the scattered pattern contains a number N of consecutive encoded pilot symbols transmitted on a sub-carrier, the N pilot symbols consisting of one pilot symbol per antenna, a single channel estimate being determined for each of the N encoded pilot symbols.

34. A method according to claim **33** wherein the N encoded pilot symbols contain L pilot symbols which were STBC block coded, where N and L together determine a STBC code rate.

35. A method according to claim **27** wherein the scattered pattern is a regular diagonal-shaped lattice.

36. A method according to claim **35** wherein the regular diagonal-shaped lattice is a diamond shaped lattice.

37. A method of inserting pilot symbols into Orthogonal Frequency Division Multiplexing (OFDM) frames transmitted by a plurality of transmitting antenna, the OFDM frames having a time domain and a frequency domain, each OFDM frame comprising a plurality of OFDM symbols, the method comprising the steps of:

for each antenna, transmitting a respective OFDM signal comprising pilot symbols inserted in a respective scattered pattern in time-frequency, the respective patterns being identical and being offset from each other.

38. The method of claim **37** wherein the scattered patterns are offset in time.

39. The method of claim **38** wherein the antennas are on different transmitters.

40. The method of claim **37** wherein the scattered patterns are offset in frequency.

41. The method of claim **37** wherein the scattered patterns are offset in both time and frequency.

42. The metho of claim **41** further comprising performing coding to produce an NxN block to be transmitted as part of the scattered pattern.

43. The metho of claim **41** further comprising:

for each antenna, performing space time block coding a group of uncoded pilot symbols to produce an NxN STBC block to be transmitted as part of the scattered pattern.

44. The method of claim **37** wherein the plurality of antennas comprise antennas on a single base station.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,248,559 B2 Page 1 of 1
APPLICATION NO. : 10/038883
DATED : July 24, 2007
INVENTOR(S) : Jianglei Ma et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

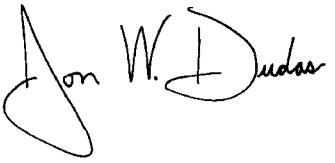
Column 18, Claim 33, line 23, "...claim 21..." should be -- claim 27--.

Column 18, Claim 42, line 56, "...metho..." should be -- method --.

Column 18, Claim 43, line 59, "...metho..." should be -- method --.

Signed and Sealed this

First Day of April, 2008



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