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Digital Communications Channel Estimation Method

Field of the Invention

The present invention relates to a method for channel estimation in
5 communications systems.

Background of the Invention

Wireless OFDM (orthogonal frequency division multiplexing)
communications systems (such as described by the standard IEEE802.11a) are
systems in which communication devices, such as base stations, communicate
10 with other devices, such as mobile terminals, over a wireless communication
link. FIGURE 1 shows a typical OFDM wireless communications system 101 of
the prior art.

OFDM systems have several advantages over other systems. In an
OFDM system, the entire frequency bandwidth used for the transmission of a
15 signal is subdivided into a plurality of frequency carriers. These frequency
carriers are transmitted through a transmission channel (e.g. air). Adjacent
frequency carriers are orthogonal to each other. They utilize lower bandwidth
than spread spectrum systems due to high spectral efficiency. Additionally,
they utilize a cyclic prefix providing easy removal of inter-symbol interference
20 (ISI).

On the receiving side of an OFDM communication link, such as a mobile
terminal receiving signals from a base station, a channel estimation or
identification is performed for each transmission carrier in order to optimize the
demodulation in the receiver in view of the estimated channel response,
25 characteristics or condition.

Practical channels can have frequency-response in both amplitude and
group delay. Other imperfections, such as reflected, multipath signals, can
create similar phenomena. In the time domain, the result is inter-symbol
interference, whereby adjacent symbols in a serial stream interfere with one
30 another. The spreading of symbol energy can, and often does, extend beyond
directly adjacent symbols. Many channels have multipath reflection-delay

responses that vary with frequency and physical location (mobile). Reflections result in signal replicas of random amplitude and phase that arrive simultaneously at the receiver, while group-delay variation refers to the set of frequency components that make up a single signal, reaching their destination at different times. The time-domain result is ISI of some form in either case.

OFDM channel estimation methods can be classified into three categories: pilot-based methods, blind methods and semi-blind methods.

The pilot-based methods (such as Pilot Symbol Aided Method – “PSAM”) are based on the information obtained from pilot data. Pilot data is pre-known to both the transmitter and receiver and is multiplexed with user data in OFDM symbols before transmission. This pilot data is inserted into the user data in a fixed pattern in both the frequency and time domain. At the receiver, by analyzing the value of the received data, an estimation of the transmission channel at these frequency and time points can easily be obtained. Then, processing such as interpolation, filtering and prediction can be performed to estimate the channel response at other frequency and time points transferring user data. The Morelli et al. reference (Michele Morelli and Umberto Mengali. “A comparison of pilot-aided channel estimation methods for OFDM systems”. *IEEE Transactions on Signal Processing*, Vol. 49, No. 12, Pg. 3065-3073. December 2001) summarizes such methods. Also, US Published Patent Application US 2002/0034213 A1 to Wang et al. provides an example using pilot symbols. The problem with these prior-art pilot symbol methods is the limited amount of pilot data in practical systems. Since pilot data consumes part of the bandwidth, leading to a lower data rate, most existing systems use as little pilot data as possible (e.g. 4 out of 64 carriers are used for pilot data in the IEEE802.11a OFDM standard). This limited amount of pilot data leads to lower accuracy when interpolating to estimate the channel response for carriers between the pilot carriers (e.g. due to the edge effect).

FIGURES 2(a) and 2(b) show two prior art pilot insertion patterns that can be used with PSAM channel estimations. In the block-type pilot symbol arrangement (see FIGURE 2(a)), the pilot bits are transmitted as entire symbols at a given times. These pilot symbols are repeated over specific time periods.

In the comb-type pilot bit arrangements (see FIGURE 2(b)), several carriers are reserved for pilot bits. These pilot carriers transmit the pilot bits at every time interval or symbol transmission time.

The IEEE802.11a OFDM standard uses comb-type PSAM, and as
 5 mentioned above, 4 out of the 64 carriers are reserved as pilot carriers. Interpolation is performed to estimate the channel response for carriers between the known pilot carriers. There are several common interpolation schemes used.

In the linear interpolation method the frequency domain channel
 10 response $H_e(k)$ is estimated from the known channel response for the carriers carrying the pilot bits $H_p(k)$:

$$\begin{aligned} H_e(k) &= H_e(mL + l) \\ &= \left(H_p(m+1) - H_p(m) \right) \frac{l}{L} + H_p(m) \\ 0 \leq l &< L \end{aligned}$$

Other known interpolation methods include low pass interpolation, spline
 15 cubic interpolation, second order interpolation, and time domain interpolation.

As mentioned above, OFDM systems are substantially immune to ISI. The multi-path, or channel, distortion problem is taken care of by repeating the last few samples of each OFDM symbol at its beginning, prior to its transmission. This added guard interval is known as a cyclic prefix. In
 20 IEEE802.11a OFDM systems typically the last 16 data bits of a symbol are copied and inserted at the beginning of the symbol, resulting in an 80 bit symbol. Blind channel estimation methods can also take advantage of these cyclic prefixes and other redundancies introduced into the structure of transmitted data symbols, such as virtual carriers, to perform channel estimation
 25 through a statistical analysis. Keong et al. (Chin Keong Ho, B. Farhang-Boroujeny and Francois Chin, "A comparison of blind channel estimation schemes for OFDM in fading channels", *The Proceedings of IEEE Singapore International Conference on Communication Systems*, Nov 2000) provides a summary of blind channel estimation methods. These methods don't require
 30 pilot data and thus can achieve the full bandwidth efficiency of the system.

Unlike PSAM, blind equalization methods derive the channel response from the received signal(s) only, i.e. without access to the source signal. The problem with these methods is high complexity, low accuracy and low convergence speed. Also, there is no simple existing method for dealing with the situation where virtual carriers exist in the signal.

The following describes how the cyclic prefix is used in a blind channel estimation. The input digital data stream is divided into blocks, or OFDM symbols, of size N . Each symbol, at time n , is represented by a $N \times 1$ vector $\mathbf{x}(n)$. The OFDM modulation of the symbol $\mathbf{x}(n)$ includes an inverse discrete Fourier Transform (IDFT) and the appending of a cyclic prefix. After modulation, the symbol $\mathbf{x}(n)$ becomes $\mathbf{S}(n)$, the n^{th} transmitted OFDM symbol after modulation. The transform of $\mathbf{x}(n)$ to $\mathbf{S}(n)$ can be described by:

$$\mathbf{S}(n) = \mathbf{K}\mathbf{x}(n).$$

15

Here $\mathbf{K}$ describes the OFDM modulation and is determined from:

$$\mathbf{K} = \begin{bmatrix} \tilde{\mathbf{F}}^H \\ \mathbf{F}^H \end{bmatrix}.$$

$\mathbf{F}^H$ is the Hermitian of $\mathbf{F}$, where $\mathbf{F}$ represents the $N \times N$ discrete Fourier Transform (DFT) matrix. The sub-matrix $\tilde{\mathbf{F}}^H$ is formed by the last D rows of $\mathbf{F}^H$ where D is the length of the cyclic prefix.

Due to the existence of inter-symbol interference (ISI), the OFDM symbol $\mathbf{S}(n-1)$ will be contained within the next OFDM symbol $\mathbf{S}(n)$. Normally the length of the channel is less than that of the cyclic prefix, so ISI happens only within the cyclic prefix of $\mathbf{S}(n)$.

The received signal $\mathbf{r}(n)$ at time n (with a length of $M = D + N$) after passing through the channel can be described as:

$$\mathbf{r}(n) = [\mathbf{C}_1 \ \mathbf{C}_0] \begin{bmatrix} \mathbf{S}(n-1) \\ \mathbf{S}(n) \end{bmatrix} + \mathbf{b}(n)$$

where $\mathbf{C}_0$ and $\mathbf{C}_1$ are matrices describing the effect of the channel according to:

$$\mathbf{C}_0 = \begin{bmatrix} c_0 & 0 & \cdots & 0 \\ c_1 & c_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ c_{M-1} & \cdots & c_1 & c_0 \end{bmatrix} \text{ and } \mathbf{C}_1 = \begin{bmatrix} 0 & c_{M-1} & \cdots & c_1 \\ \vdots & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & c_{M-1} \\ 0 & \cdots & \cdots & 0 \end{bmatrix}$$

- 5 and $\mathbf{b}(n)$ is a noise vector representing additional white Gaussian noise (AWGN).

Without loss of generality, the number of carriers, N , is set as four times the length of the cyclic prefix, $N = 4D$ for simplicity. The $D \times D$ upper left sub-matrix of $\mathbf{C}_0$ is described as $\tilde{\mathbf{C}}_0$. The $D \times D$ upper right sub-matrix of $\mathbf{C}_1$ is described as $\tilde{\mathbf{C}}_1$. $\tilde{\mathbf{S}}_i(n)$ and $\tilde{\mathbf{b}}_i(n)$ represent $D \times 1$ sub-vectors obtained from the $(D \times (i-1) + 1)^{\text{th}}$ to $(D \times i)^{\text{th}}$ elements of $\tilde{\mathbf{S}}(n)$ and $\mathbf{b}(n)$, respectively. $\tilde{\mathbf{S}}(n)$ is the result of the OFDM modulation of $\mathbf{x}(n)$.

Under noiseless conditions, $\mathbf{r}(n)$ can be written as:

$$15 \quad \mathbf{r}(n) = \begin{bmatrix} \tilde{\mathbf{C}}_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_0 \\ \mathbf{0} & \tilde{\mathbf{C}}_0 & \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_1 \\ \mathbf{0} & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_0 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_0 \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{S}}_4(n-1) \\ \tilde{\mathbf{S}}_1(n) \\ \tilde{\mathbf{S}}_2(n) \\ \tilde{\mathbf{S}}_3(n) \\ \tilde{\mathbf{S}}_4(n) \end{bmatrix} = \mathbf{C} \bullet \underline{\mathbf{S}}(n).$$

Here the symbol $\underline{\mathbf{S}}(n)$ denotes the vector

$[\tilde{\mathbf{S}}_4(n-1) \ \tilde{\mathbf{S}}_1(n) \ \tilde{\mathbf{S}}_2(n) \ \tilde{\mathbf{S}}_3(n) \ \tilde{\mathbf{S}}_4(n)]^T$ and the symbol $\mathbf{C}$ denotes the matrix.

The received signal auto-correlation matrix $\mathbf{R}_{rr}$ is obtained from the
20 noiseless $\mathbf{r}(n)$ equation as:

$$\begin{aligned}
\mathbf{R}_{rr} &= E[\mathbf{r}(n)\mathbf{r}(n)^H] \\
&= \mathbf{C}\mathbf{R}_{\underline{\mathbf{ss}}}\mathbf{C}^H + \sigma_b^2\mathbf{I} \\
&= \mathbf{C}\mathbf{C}^H + \sigma_b^2\mathbf{I} \\
&= \begin{bmatrix} \tilde{\mathbf{C}}_{0,0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_{0,0} \\ \mathbf{0} & \tilde{\mathbf{C}}_{0,0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_{0,0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_{0,0} & \mathbf{0} \\ \tilde{\mathbf{C}}_{0,0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_{0,0} \end{bmatrix} + \begin{bmatrix} \tilde{\mathbf{C}}_{1,1} & \tilde{\mathbf{C}}_{0,1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \tilde{\mathbf{C}}_{1,0} & \tilde{\mathbf{C}}_{1,1} & \tilde{\mathbf{C}}_{0,1} & \mathbf{0} & \tilde{\mathbf{C}}_{1,0} \\ \mathbf{0} & \tilde{\mathbf{C}}_{1,0} & \tilde{\mathbf{C}}_{1,1} & \tilde{\mathbf{C}}_{0,1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \tilde{\mathbf{C}}_{1,0} & \tilde{\mathbf{C}}_{1,1} & \tilde{\mathbf{C}}_{0,1} \\ \mathbf{0} & \tilde{\mathbf{C}}_{0,1} & \mathbf{0} & \tilde{\mathbf{C}}_{1,0} & \tilde{\mathbf{C}}_{1,1} \end{bmatrix} + \sigma_b^2\mathbf{I}
\end{aligned}$$

Where “ E ” is the expectation operation, the matrix $\tilde{\mathbf{C}}_{i,j} = \tilde{\mathbf{C}}_i \tilde{\mathbf{C}}_j^H$ and σ_b^2 is the noise variance. Due to the orthogonality of $\mathbf{F}$ and the assumption of white unit variance data input, $\mathbf{R}_{\underline{\mathbf{ss}}}$, the auto-correlation matrix of $\underline{\mathbf{S}}$, is approximated to be equal to the identity matrix, $\mathbf{I}$ as shown by:

$$\mathbf{R}_{\underline{\mathbf{ss}}} = \begin{bmatrix} \tilde{\mathbf{F}}^H & \mathbf{0} \\ \mathbf{0} & \mathbf{F}^H \end{bmatrix} \mathbf{R}_{\mathbf{xx}} \begin{bmatrix} \tilde{\mathbf{F}} & \mathbf{0} \\ \mathbf{0} & \mathbf{F} \end{bmatrix} = \mathbf{I}.$$

10 $\mathbf{R}_{rr}$ is therefore of the form:

$$\mathbf{R}_{rr} = \begin{bmatrix} \times & \times & \tilde{\mathbf{C}}_{0,0} \\ \times & \times & \times \\ \tilde{\mathbf{C}}_{0,0} & \times & \times \end{bmatrix} + \sigma_b^2\mathbf{I}$$

and the last D elements of the first column are:

15

$$\mathbf{V} = \begin{bmatrix} c_0^* c_0 \\ c_0^* c_1 \\ \vdots \\ c_0^* c_{D-1} \end{bmatrix}.$$

Thus, the time domain channel estimation can be determined directly from $\mathbf{R}_{rr}$ once the scalar indeterminacy c_0^* is known.

However, this blind channel estimation method does not work in systems such as IEEE802.11a OFDM communications systems having virtual carriers.

5 Virtual carriers are at the edges of the transmission spectrum and are used in order to avoid aliasing problems at the receiver. The existence of virtual carriers means that some carriers transmitting the symbol $\mathbf{x}(n)$ actually transmit no power and thus in systems having virtual carriers it is no longer valid to make the assumption that $\mathbf{R}_{ss} = \mathbf{I}$.

10 In IEEE802.11a OFDM communications systems typically 12 bits of the 64 bit symbols are dedicated to virtual carriers. When combined with the 4 bits used for pilot carriers, only 48 of the 64 bits of each symbol are available for transmitting data. This makes it even more difficult to perform good channel estimation in such systems.

15 Since typical OFDM systems use both pilots and cyclic prefixes, semi-blind methods have also been proposed to make use of both information sources and achieve a good compromise between the two kinds of methods. In Muquet et al. (Bertrand Muquet, Marc de Courville and Pierre Duhamel, "Subspace-based blind and semi-blind channel estimation for OFDM systems",
20 *IEEE Transactions on Signal Processing*, Vol. 50, No. 7, Pg. 1699-1712, July 2002) information from pilots is used to remove the phase indetermination in blind estimation methods. However, the method in Muquet et al. is very complex and does not make full use of the information from pilots. The references of Thomas et al. (Timothy A. Thomas, Frederick W. Vook and Kevin
25 L. Baum. "Semi-blind channel identification in OFDM", *Proceedings of IEEE 55th Vehicular Technology Conference*, VTC, Spring 2002, Vol. 4, Pg. 1747-1750, 2002) and Al-Naffouri et al. (Tareq Y. Al-Naffouri, Dimitrios Toumpakaris, Ahmad Bahai and Arogyaswami Paulraj, "An adaptive semi-blind algorithm for channel identification in OFDM", *Conference Record of Thirty-Fifth Asilomar
30 Conference on Signals, Systems and Computers*, Vol. 2, Pg. 921-925, 2001) also propose semi-blind methods based on decision directed algorithms, but

these methods depend on the initial decoding accuracy of the symbols and the performance degrades drastically in low-to-medium SNR scenarios.

Returning to FIGURE 1, serial binary user data 103 enters a coding section 105 of a transmitter 102. The data is then converted from serial to parallel format by a serial to parallel converter 107. Next a pilot inserter 109 inserts pilot symbols into the user data in a fixed pattern in both the frequency and time domains to obtain the frequency domain signal $X(k)$ 111. An IDFT (inverse discrete Fourier Transform) section 113 then transforms the frequency domain transmitter signal $X(k)$ 111 into a time domain signal $x(n)$ 115 according to:

$$x(n) = IDFT\{X(k)\}$$

$$n = 0, 1, 2, \dots, N-1$$

Next, a D -point guard interval or cyclic prefix is inserted into the time domain signal $x(n)$ 115 by the guard insertion section 117 to eliminate any interference between adjacent OFDM symbols. The guard insertion section 117 outputs a signal $x_f(n)$ 119. The signal $x_f(n)$ 119 is determined by:

$$x_f(n) = \begin{cases} x(N+n), & n = -D, -D+1, \dots, -1 \\ x(n), & n = 0, 1, \dots, N-1 \end{cases}$$

The signal $x_f(n)$ 119 is converted from a parallel signal to a serial signal by a parallel/serial converter 121 before being transmitted into a channel 123 having a channel response $h(n)$ 125.

The channel 123 degrades the transmitted symbols, producing a received signal $y_f(n)$ 129 according to the equation:

$$y_f = x_f(n) \otimes h(n) + b(n)$$

where $b(n)$ 127 is additional white Gaussian noise (AWGN) introduced into the signal while passing through the channel 123. The signal enters a receiver 104 and is converted from serial to parallel form by a serial/parallel

converter 131. A guard removal section 133 removes the guard interval from the signal $y_f(n)$ 129 to produce the received time domain signal $y(n)$ 135 according to the equation:

$$y(n) = y_f(n) \quad n = 0, 1, \dots, N-1$$

A DFT (Discrete Fourier Transform) section 137 then transforms the time domain signal $y(n)$ 135 back to the frequency domain to produce the received frequency domain signal $Y(k)$ 139 according to:

$$Y(k) = DFT\{y(n)\}$$

$$k = 0, 1, 2, \dots, N-1$$

The channel estimation and equalization processing is performed by a channel estimation and equalization section 141. The passage of the signal through the OFDM system is described by the frequency domain equation:

$$Y(k) = X(k)H(k) + I(k) + B(k)$$

$$k = 0, 1, \dots, N-1$$

where $H(k)$ is the frequency domain channel response of the channel for the k^{th} carrier, $I(k)$ is the frequency domain inter-channel interference (ICI) for the k^{th} carrier and $B(k)$ is the frequency domain additional white Gaussian noise (AWGN) of the k^{th} carrier. Equalization is performed and the frequency domain estimated transmitter signal $X_e(k)$ 142 is determined from the frequency domain estimated channel response $H_e(k)$ according to:

$$X_e(k) = \frac{Y(k)}{H_e(k)} \quad k = 0, 1, \dots, N-1$$

The output from the channel estimation section 141 passes to a parallel to serial converter 143 to produce the estimated transmitted signal $x_e(n)$ 144.

The signal $x_e(n)$ 144 is demapped by the demapper 145 and finally user output data 147 is output by the receiver.

Until now there has been no completely satisfactory method for estimating the transmission channel in communications systems. The prior-art pilot symbol methods are limited in the amount of pilot data they can use due to bandwidth constraints. The limited number of pilot carriers reduces the quality of the channel estimations.

The blind channel estimation methods of the prior art have also proven unsatisfactory. These methods have high complexity, low accuracy and low convergence speed. Cyclic prefix information, introduced to solve the ISI problem, has been used to some extent to improve blind channel estimation methods, but has not been fully utilized. Also, although blind channel estimation methods have been proposed for dealing with the situation where virtual carriers exist in the signal, these methods are very complicated and not very practical.

Semi-blind channel estimation methods have been developed but have only made limited use of the pilot data.

It would be desirable to supplement the limited amount of pilot data used in practical communications systems with additional blind channel estimation data in order to provide an accurate, quickly converging channel estimation while efficiently utilizing bandwidth to optimize data transmission. It would also be desirable to perform the blind channel estimation data in a system having virtual carriers.

25 **Summary of the Invention**

Results of a pilot channel estimation are supplemented with results of a blind channel estimation. Information from pilots is used to remove the scalar uncertainty in a blind estimation method and the resulting blind channel estimate is used to supplement the pilot information for better interpolation of the channel estimation for additional in-between carriers. The blind channel

estimation works even when the communications system signal has virtual carriers.

The present invention includes a method for estimating the channel response in a communications system based on a received signal. The method includes the steps of transmitting a signal through a channel; receiving the signal with a receiver of the communications system; statistically analyzing the received signal to determine a first estimate of the channel response for a first set of the carriers; analyzing pilot data in the received signal to determine an estimate of the channel response for pilot carriers; and combining the first estimate of the channel response for the first set of carriers with the estimate of channel response for the pilot carriers to estimate the channel response for an additional set of the carriers. Additionally, the method further includes removing the scalar uncertainty of the first estimate using the estimate of the channel response for the pilot carriers. The statistical analysis can be a blind channel estimation and the invention further includes a method for computing the auto-correlation matrix of the received signal to improve the blind channel estimation when virtual carriers exist in the signal.

The invention also includes a communications system having a receiver for receiving a signal transmitted through channels; a means for statistically analyzing the received signal to determine a first estimate of the channel response for a first set of the carriers; analyzing pilot data in the received signal to determine an estimate of the channel response for pilot carriers; a means for analyzing pilot data in the received signal to determine an estimate of the channel response for pilot carriers; and a means for combining the first estimate of the channel response for the first set of carriers with the estimate of channel response for the pilot carriers to estimate the channel response for an additional set of the carriers. The first estimate of the channel response has a scalar uncertainty; and so the invention also includes a means for removing the scalar uncertainty using the estimate of the channel response for the pilot carriers. The statistical analysis can be a blind channel estimation and the invention further includes a means for computing the auto-correlation matrix of the

received signal to improve the blind channel estimation when virtual carriers exist in the signal.

Brief Description of the Figures

5 Further preferred features of the invention will now be described for the sake of example only with reference to the following figures, in which:

FIGURE 1 shows a typical OFDM wireless communications system of the prior art.

10 FIGURES 2(a) and 2(b) illustrate a prior art block-type and a prior art comb-type pilot insertion pattern.

FIGURE 3 shows a schematic diagram of a wireless OFDM communications system implementing the present invention.

FIGURE 4 is of a flow chart showing the method steps of the present invention.

15 FIGURE 5 shows how PSAM estimated channel estimates are supplemented by blind channel estimates for determining the channel response for additional carriers defined in the IEEE802.11a OFDM standard.

20 FIGURE 6 shows details of the blind estimation method for processing an auto-correlation matrix when virtual carriers are present. This blind estimation method is for incorporation into the blind channel estimation method of FIGURE 5.

FIGURE 7 illustrates the processing of V to remove the effect of the virtual carriers.

Detailed Description of the Embodiments

25 FIGURE 3 shows a schematic diagram of a wireless OFDM communications system 149 implementing the present invention. In the prior

art of FIGURE 1, the cyclic prefix is removed by the guard removal section 133 prior to channel estimation. The invention of FIGURE 3, however, makes use of the carriers both before and after removal of the cyclic prefix. FIGURE 4 is a flow chart showing the method steps of the present invention.

- 5 A channel estimation section 153 of a receiver 151 samples the received signal after the signal passes through a down converter 155. The down converted signal enters a blind channel estimation processing section 156 where a blind channel estimation step 171 (see FIGURE 4) is performed, producing a vector $\tilde{\mathbf{h}}$ 177 representing the time domain estimation of the
- 10 channel response with a phase indetermination (or scalar uncertainty) c_0^* , given by:

$$\tilde{\mathbf{h}} = \begin{bmatrix} c_0^* c_0 \\ c_0^* c_1 \\ \vdots \\ c_0^* c_{D-1} \end{bmatrix}.$$

- 15 Part of the received signal also passes through an OFDM demodulation section 159 which removes the cyclic prefix in addition to performing a DFT. A PSAM processing section 157 of the channel estimation section 153 samples the signal after processing by the OFDM demodulation section 159. The PSAM processing section 157 performs a LS (least square) PSAM step 173, producing
- 20 the channel estimations for the pilot carriers $\hat{\mathbf{H}}_p$ 175. The LS estimation method is adopted in order to keep the complexity low. Thus, the channel response is the result of the received value divided by the corresponding value for the pilot carriers.

- The vector $\tilde{\mathbf{h}}$ 177 from the blind estimation section 156 and the vector
- 25 $\hat{\mathbf{H}}_p$ 175 from the PSAM processing section 157 are combined in a channel estimation processing section 161 to produce a channel estimation of the present invention.

As mentioned previously, the result of the blind channel estimation, $\tilde{\mathbf{h}}$ 177, has a scalar uncertainty c_0^* that must be removed. In the present invention the channel estimation processing section 161 performs a step 179 in which it uses the channel estimation $\hat{\mathbf{H}}_p$ 175 provided by the PSAM processing section 157 to remove the scalar uncertainty in the channel estimation $\tilde{\mathbf{h}}$ 177. First, $\tilde{\mathbf{h}}$ 177 is transferred into the frequency domain to produce the vector $\tilde{\mathbf{H}}$ 183. The scalar factor c_0^* is determined by comparing the estimation values $\tilde{\mathbf{H}}$ 183 for the pilot carriers obtained using the blind channel estimation of step 171 with the estimation values $\hat{\mathbf{H}}_p$ 175 for the pilot carriers obtained using the PSAM step 173. The scalar factor c_0^* is then determined using a least-square method such as described in the Muquet reference (see Background section above). The scalar uncertainty is then removed by dividing $\tilde{\mathbf{H}}$ 183 by the scalar factor c_0^* .

The channel estimation processing section 161 also performs a step 181 in which channel estimates determined from the step 179 and the PSAM step 173 are combined to produce the channel estimation of the present invention. Several additional points from $\tilde{\mathbf{H}}$ 183 are chosen to form a set of known data points to be combined together with the channel estimate for the pilot carriers $\hat{\mathbf{H}}_p$ 175. These additional points from $\tilde{\mathbf{H}}$ 183 become a blind channel estimate vector $\hat{\mathbf{H}}_b$ 185. With these known data points from $\hat{\mathbf{H}}_p$ 175 and $\hat{\mathbf{H}}_b$ 185, a piece-wise interpolation (the present invention can use a second-order interpolation for implementing the IEEE802.11a OFDM standard) can be done to generate more accurate channel estimates for the carriers between these known data points. The selection of the additional points $\hat{\mathbf{H}}_b$ 185 from the blind channel estimation adds more data points to the interpolation to increase the accuracy. The number of additional points and the positions of the additional points of $\hat{\mathbf{H}}_b$ 185 can be determined by choosing those which minimize the mean-square-error (MSE) in a Monte Carlo simulation.

FIGURE 5 shows how the points from the PSAM estimated channel estimate are supplemented by points from the blind channel estimate for

providing an improved channel estimation for additional carrier frequencies defined in the IEEE802.11a OFDM standard. The vector $\hat{H}_p$, 175 provides a channel estimate for the pilot carriers at 8, 22, 44 and 58 of the 64 total carriers. The value of p is set at $p = (8, 22, 44, 58)$. The vector $\hat{H}_b$, 185 provides values for the carriers at 1, 15, 29, 37, 51, 64. The value of b is set at $b = (1, 15, 29, 37, 51, 64)$. Thus estimation results of the channel for the 6 carriers determined from the blind channel estimation are combined with the estimation results for the 4 pilot carriers. A channel estimate for other carriers is then calculated by interpolation based on these 10 results.

10 The channel estimation output 165 from the channel estimation processing section 161 is passed to a channel compensator 163 for correcting the data received from the OFDM demodulator section 159 to provide channel compensated user data 167.

The blind estimation section 156 for performing the blind estimation step 171 can use any known blind estimation scheme. The method of FIGURE 4 will remove the scalar indeterminacy c_0^* (as described at step 179) and improve the accuracy of the PSAM step 173 by combining the result of the blind channel estimation method (as described at step 171) with the result determined using the pilot-method (as described at step 181). However, as explained above, prior-art blind channel estimation methods do not work well in systems having virtual carriers (the IEEE802.11a OFDM communication standard makes use of 12 virtual carriers). Therefore, the present invention also includes a processing method that improves the accuracy of the blind channel estimation in the presence of virtual carriers in the signal.

25 In the presence of virtual carriers, $\mathbf{R}_{ss}$, the auto-correlation matrix of $\mathbf{s}$, is no longer equal to the identity matrix $\mathbf{I}$ as it is in the prior art described above because, due to unequal power transmitted on the carriers:

$$\mathbf{R}_{ss} = \begin{bmatrix} \tilde{\mathbf{F}}^H & 0 \\ 0 & \mathbf{F}^H \end{bmatrix} \mathbf{R}_{xx} \begin{bmatrix} \tilde{\mathbf{F}} & 0 \\ 0 & \mathbf{F} \end{bmatrix} \neq \mathbf{I}$$

With the existence of virtual carriers, some elements of the symbol $\mathbf{x}(n)$ are always zero (at the virtual carrier frequencies) and these elements can be removed in calculation. The vector $\mathbf{x}_p$ is used to stand for the vector formed by the non-zero elements of $\mathbf{x}(n)$. The matrix $\mathbf{F}_p$ is used to stand for the DFT matrix operating on the non-zero elements.

The OFDM modulation is described by a matrix $\mathbf{K}_p$ defined by:

$$\mathbf{K}_p = \begin{bmatrix} \tilde{\mathbf{F}}_p^H \\ \mathbf{F}_p^H \end{bmatrix}$$

where $\mathbf{F}_p^H$ is the Hermitian of $\mathbf{F}_p$.

The received signal auto-correlation matrix $\mathbf{R}_{rr}$ is obtained from the noiseless $\mathbf{r}(n)$ equation as:

$$\mathbf{R}_{rr} = E(\mathbf{r}\mathbf{r}^H) = \mathbf{C}\mathbf{R}_{\underline{s}_p\underline{s}_p}\mathbf{C}^H + \sigma_b^2\mathbf{I}$$

where $\mathbf{I}$ is the identity matrix and σ_b^2 is the power of the noise and

$$\mathbf{R}_{\underline{s}_p\underline{s}_p} = \begin{bmatrix} \tilde{\mathbf{F}}_p^H & 0 \\ 0 & \mathbf{F}_p^H \end{bmatrix} \mathbf{R}_{\mathbf{x}_p\mathbf{x}_p} \begin{bmatrix} \tilde{\mathbf{F}}_p & 0 \\ 0 & \mathbf{F}_p \end{bmatrix}$$

is the auto-correlation matrix of $\underline{s}_p$. $\mathbf{R}_{\underline{s}_p\underline{s}_p}$ includes only the carriers which transmit signals (i.e. it does not include virtual carriers). $\tilde{\mathbf{F}}_p$ and $\tilde{\mathbf{F}}_p^H$ are formed by the last D rows of $\mathbf{F}_p$ and $\mathbf{F}_p^H$, respectively, where D is the length of the cyclic prefix. Also, assuming a white unit variance data input, $\mathbf{R}_{\mathbf{x}_p\mathbf{x}_p} = \mathbf{I}_p$. However, now the elimination of $\mathbf{R}_{\underline{s}_p\underline{s}_p}$ is not possible as it was for $\mathbf{R}_{\underline{s}\underline{s}}$ in the case with no virtual carriers because $\mathbf{F}_p$ is not the full DFT matrix anymore:

$$\mathbf{R}_{\underline{s}_p\underline{s}_p} = \begin{bmatrix} \tilde{\mathbf{F}}_p^H \tilde{\mathbf{F}}_p & 0 \\ 0 & \mathbf{F}_p^H \mathbf{F}_p \end{bmatrix} \neq \mathbf{I}.$$

It is very difficult to solve for $\mathbf{C}\mathbf{C}^H$ in the conventional manner to provide a blind channel estimation because $\mathbf{R}_{\mathbf{s}_p\mathbf{s}_p}$ remains between the two matrices as $\mathbf{C}\mathbf{R}_{\mathbf{s}_p\mathbf{s}_p}\mathbf{C}^H$. To make the sub-matrix method work, it's necessary to remove the
 5 effect of $\mathbf{R}_{\mathbf{s}_p\mathbf{s}_p}$ in $E(\mathbf{r}\mathbf{r}^H)$ to get an estimation of $\mathbf{C}\mathbf{C}^H$.

The present invention uses observations about the structures of the matrix $\mathbf{C}$ and of $T = \begin{bmatrix} \tilde{\mathbf{F}}_p^H \tilde{\mathbf{F}}_p & 0 \\ 0 & \mathbf{F}_p^H \mathbf{F}_p \end{bmatrix}$ to allow low-complexity processing. Due to the structure of the symbol, the matrix $\mathbf{C}$ is organized as:

$$\begin{bmatrix} \tilde{\mathbf{C}}_1 & 0 & 0 & 0 & \tilde{\mathbf{C}}_0 \\ 0 & \tilde{\mathbf{C}}_0 & 0 & 0 & \tilde{\mathbf{C}}_1 \\ 0 & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_0 & 0 & 0 \\ 0 & 0 & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_0 & 0 \\ 0 & 0 & 0 & \tilde{\mathbf{C}}_1 & \tilde{\mathbf{C}}_0 \end{bmatrix}$$

where, as discussed above with respect to the prior art:

$$\tilde{\mathbf{C}}_0 = \begin{bmatrix} c_0 & 0 & \cdots & 0 \\ c_1 & c_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ c_{D-1} & \cdots & c_1 & c_0 \end{bmatrix} \text{ and } \tilde{\mathbf{C}}_1 = \begin{bmatrix} 0 & c_{D-1} & \cdots & c_1 \\ \vdots & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & c_{D-1} \\ 0 & \cdots & \cdots & 0 \end{bmatrix}.$$

Based on the result of calculating T (for the IEEE802.11a standard) and the structure of $\mathbf{F}_p$ given the positions of the virtual carriers, the matrix $\mathbf{C}$ can approximately be organized as:

$$\begin{bmatrix} \mathbf{A}_4 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_1 & \mathbf{0} & \mathbf{0} & \mathbf{B}_1 \\ \mathbf{0} & \mathbf{0} & \mathbf{A}_2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{A}_3 & \mathbf{0} \\ \mathbf{0} & \mathbf{B}_1 & \mathbf{0} & \mathbf{0} & \mathbf{A}_4 \end{bmatrix}$$

where $\mathbf{A}_4 = \tilde{\mathbf{F}}_p^H \tilde{\mathbf{F}}_p$ and based on the calculation result:

$$\mathbf{F}_p^H \mathbf{F}_p \approx \begin{bmatrix} \mathbf{A}_1 & \mathbf{0} & \mathbf{0} & \mathbf{B}_1 \\ \mathbf{0} & \mathbf{A}_2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{A}_3 & \mathbf{0} \\ \mathbf{B}_1 & \mathbf{0} & \mathbf{0} & \mathbf{A}_4 \end{bmatrix}.$$

In most blind estimation methods only the bottom left sub-matrix of $E(\mathbf{r}\mathbf{r}^H)$ is needed. Thus, due to the simplifications, the blind channel estimation can be performed by calculating the result of $\tilde{\mathbf{C}}_0 \mathbf{A}_4 \tilde{\mathbf{C}}_0^H$ instead of the full result of $\mathbf{C}\mathbf{R}_{\underline{s_p s_p}} \mathbf{C}^H$.

Additional simplifications can be achieved by utilizing the structure of $\tilde{\mathbf{C}}_0$ and $\mathbf{A}_4$. Here, the direct sub-matrix method is used as an example to illustrate the present invention, but other blind channel estimation methods can also be used. By definition $\tilde{\mathbf{C}}_0$ is a lower-triangular matrix and $\mathbf{A}_4$ is a symmetrical matrix having identical values along all of its diagonals. Based on these observations, it can be deduced that the resulting vector $\mathbf{V}$ used in the sub-matrix method (the last D elements of the first column) is no longer the channel

vector $\begin{bmatrix} c_0 \\ c_1 \\ \vdots \\ c_{D-1} \end{bmatrix}$ multiplied by a scalar c_0^* as described with respect to the prior art

above and in the Chin reference. Instead $\mathbf{V}$ is determined from:

$$V = \begin{bmatrix} U_0 c_0^* c_0 \\ U_0 c_0^* c_1 + U_1 c_0^* c_0 \\ \vdots \\ U_0 c_0^* c_{D-1} + U_1 c_0^* c_{D-2} + \dots + U_{D-1} c_0^* c_0 \end{bmatrix}$$

where U_i is the value of the i^{th} diagonal in A_4 forming a vector:

$$U = [U_0 \quad U_1 \quad \dots \quad U_{D-1}]^T.$$

Iterative loop processing is performed on V (with U_i pre-stored in memory for calculation) before removal of the phase indetermination (or scalar uncertainty) from V . After this inventive processing, the resulting vector is the time domain estimation of the channel response with a phase indetermination given by:

$$V = \begin{bmatrix} c_0^* c_0 \\ c_0^* c_1 \\ \vdots \\ c_0^* c_{D-1} \end{bmatrix}$$

which is output from the blind estimation section 171 in FIGURE 4 as the vector $\tilde{h}$ 177 for continued processing.

FIGURE 6 shows the blind channel estimation method for use in the presence of a signal having virtual carriers. This blind estimation method is for incorporation into the blind channel estimation step 171 of FIGURE 5. A received symbol $r(n)$ is received as input at step 187. Next an update of the calculation of the vector V in R_{rr} is performed at the step 189. Processing of V is performed at the step 191 and then the estimated channel response $\tilde{h}$ 177 is output at step 193. In some blind estimation methods other than the direct sub-matrix method, the whole sub-matrix is used (such as in methods based on Cholesky decomposition). The iterative processing method of the present invention can also include all the columns of the sub-matrix using the same

analysis. The iterative processing can still be implemented iteratively column by column.

The processing of $\mathbf{V}$ to remove the effects of the virtual carriers is illustrated in more detail in the flowchart of FIGURE 7. This processing method
 5 computes the terms of the vector given above:

$$\mathbf{V} = \begin{bmatrix} U_0 c_0^* c_0 \\ U_0 c_0^* c_1 + U_1 c_0^* c_0 \\ \vdots \\ U_0 c_0^* c_{D-1} + U_1 c_0^* c_{D-2} + \dots + U_{D-1} c_0^* c_0 \end{bmatrix}$$

The updated vector $\mathbf{V}$ from the step 189 of FIGURE 6 is input to the step 195
 10 which divides the vector $\mathbf{V}$ by the U_0 of the vector $\mathbf{U} = [U_0 \ U_1 \ \dots \ U_{D-1}]^T$ described above according to the equation $V_0 = V_0/U_0$. Next, an iterative loop is entered according to the counter 197 wherein k is incremented from 1 to $D-1$ and the operation $V_k = (V_k - \sum_{i=1}^{k-1} U_i * V_{k-i})/U_0$ is iteratively performed as shown in block 199. Finally the processed vector $\mathbf{V}$ is output as the estimated channel
 15 response $\tilde{\mathbf{h}}$ 177 at step 201.

In another embodiment of the present invention the blind channel estimation method for use in the presence of a signal having virtual carriers can be used without using the PSAM output to remove the scalar indeterminacy. Also, in addition or alternatively, the blind channel estimation method for use in
 20 the presence of a signal having virtual carriers can be used without the additional channel estimations provided by the PSAM output.

Also, while the preferred embodiment refers to PSAM channel estimation, the pilot bit patterns used can be block type, comb type or other pattern types known to those skilled in the art.

25 Although the invention has been described above using particular embodiments, many variations are possible within the scope of the claims, as will be clear to a skilled reader.

Claims

We claim:

1. A method for estimating channel response in a communications system
 5 based on a received signal comprising the steps of:
 transmitting a signal through a channel;
 receiving the signal with a receiver of the communications system;
 statistically analyzing the received signal to determine a first estimate of
 the channel response for a first set of the carriers;
 10 analyzing pilot data in the received signal to determine an estimate of
 channel response for pilot carriers; and
 combining the first estimate of the channel response for the first set of
 carriers with the estimate of channel response for the pilot carriers to estimate
 the channel response for an additional set of the carriers.
 15
2. The method of Claim 1, wherein the first estimate of the channel
 response has a scalar uncertainty; and
 the method further comprising the step of:
 removing the scalar uncertainty using the estimate of the channel
 20 response for the pilot carriers.
3. The method of Claim 1, wherein the first estimate of the channel
 response has a scalar uncertainty; and
 the method further comprises the step of:
 25 removing the scalar uncertainty by performing the steps of:
 transferring the first estimate of the channel response for the first set of
 carriers into the frequency domain using a discrete Fourier Transfer;
 comparing the frequency domain first estimate to a frequency domain
 estimate of channel response for the pilot carriers and using a least-square
 30 method to calculate a scalar factor for the pilot carriers; and
 removing the scalar uncertainty by dividing the frequency domain first
 estimate by the scalar factor.

4. The method of Claim 1, wherein the estimate of channel response for the pilot carriers is a frequency domain channel response determined by performing a least square method on the received signal.
- 5
5. The method of Claim 1, wherein a blind channel estimation method is used to statistically analyze the received signal to determine a first estimate of the channel response.
- 10
6. The method of Claim 5, wherein the communications system includes virtual carriers transmitting substantially no power.
7. The method of Claim 5, wherein the communications system includes carriers transmitting different levels of power.
- 15
8. The method of Claim 1, wherein interpolation is used to combine the first estimate of the channel response for the first set of the carriers with the estimate of channel response for the pilot carriers to estimate the channel response of the additional set of the carriers.
- 20
9. The method of Claim 1 wherein the communications system is an OFDM system.
10. The method of Claim 9, wherein the OFDM system has 64 carriers
- 25
- including 4 pilot carriers and 12 virtual carriers.
11. The method of Claim 1, wherein the received signal contains a cyclic prefix used to prevent the interference of bits of adjacent symbols and also used by the step of statistically analyzing the received signal to determine a first
- 30
- estimate of the channel response for the first set of carriers.

12. The method of Claim 1, wherein the first set of the carriers consists of 6 carriers.

13. The method of Claim 6 wherein the blind channel estimation method
5 evaluates the auto-correlation matrix of the received signal to determine the first estimate of the channel response for the first set of the carriers.

14. The method of Claim 13, wherein the auto-correlation matrix of the received signal is given by:

$$10 \quad \mathbf{R}_{rr} = E(\mathbf{r}\mathbf{r}^H) = \mathbf{C}\mathbf{R}_{\underline{s}_p\underline{s}_p}\mathbf{C}^H + \sigma_b^2\mathbf{I}$$

wherein:

E is the expectation operation,

$\mathbf{r}$ is the received signal,

$\mathbf{r}^H$ is the Hermitian of $\mathbf{r}$,

15 $\mathbf{C}$ is a matrix describing the effect of the channel,

$\mathbf{C}^H$ is the Hermitian of $\mathbf{C}$,

$\mathbf{I}$ is the identity matrix,

σ_b^2 is the power of the noise, and

$\mathbf{R}_{\underline{s}_p\underline{s}_p}$ is the auto-correlation matrix of the vector $\underline{s}_p$,

20 $\underline{s}_p$ represents a transmitted symbol and has some vector elements representing the virtual carriers removed, and wherein

$$\mathbf{R}_{\underline{s}_p\underline{s}_p} \neq \mathbf{I}.$$

15. The method of Claim 13, wherein the received signal contains a cyclic
25 prefix having a length of D bits used to prevent the interference of bits of adjacent symbols;

and the blind channel estimation method further comprises the step of:

evaluating a D element vector of the auto-correlation matrix of the

received signal to determine the first estimate of the channel response for the

30 first set of the carriers.

16. The method of Claim 15, wherein the D-element vector is evaluated by:
pre-storing D coefficients determined from the structure of the received
signal; and
performing iterative processing on the D-element vector using the pre-
5 stored coefficients to determine the first estimate of the channel response for
the first set of the carriers.
17. A method for estimating the frequency domain channel response in a
communications system having a channel transmitting a signal having carriers
10 of different power levels comprising the steps of:
transmitting a signal through a channel;
receiving the signal with a receiver of the communications system;
statistically analyzing the received signal to determine an estimate of the
channel response on a set of the carriers from the carriers of different power
15 levels.
18. The method of Claim 17, wherein a blind channel estimation method is
used to statistically analyze the received signal to determine a first estimate of
the channel response.
20
19. The method of Claim 17, wherein the communications system includes
virtual carriers.
20. The method of Claim 17, wherein the communications system includes
25 carriers transmitting substantially no power.
21. The method of Claim 17 wherein the communications system is an
OFDM system.
- 30 22. The method of Claim 21, wherein the OFDM system has 64 carriers
including 4 pilot carriers and 12 virtual carriers.

23. The method of Claim 17, wherein the received signal contains a cyclic prefix used to prevent the interference of bits of adjacent symbols and also used by the step of statistically analyzing the received signal to determine an estimate of the channel response for a set of carriers.

5

24. The method of Claim 17, wherein the first set of the carriers consists of 6 carriers.

25. The method of Claim 18 wherein the blind channel estimation method
10 evaluates the auto-correlation matrix of the received signal to determine the first estimate of the channel response for the first set of carriers.

26. The method of Claim 25, wherein the auto-correlation matrix of the received signal is given by:

$$15 \quad \mathbf{R}_{rr} = E(\mathbf{r}\mathbf{r}^H) = \mathbf{C}\mathbf{R}_{\underline{s_p s_p}}\mathbf{C}^H + \sigma_b^2\mathbf{I}$$

wherein:

E is the expectation operation,

$\mathbf{r}$ is the received signal,

$\mathbf{r}^H$ is the Hermitian of $\mathbf{r}$,

20 $\mathbf{C}$ is a matrix describing the effect of the channel,

$\mathbf{C}^H$ is the Hermitian of $\mathbf{C}$,

$\mathbf{I}$ is the identity matrix,

σ_b^2 is the power of the noise, and

$\mathbf{R}_{\underline{s_p s_p}}$ is the auto-correlation matrix of the vector $\underline{s_p}$,

25 $\underline{s_p}$ represents a transmitted symbol and has vector elements representing the virtual carriers removed, and wherein

$$\mathbf{R}_{\underline{s_p s_p}} \neq \mathbf{I}.$$

27. The method of Claim 25, wherein the received signal contains a cyclic
30 prefix having a length of D bits used to prevent the interference of bits of adjacent symbols;

and the blind channel estimation method further comprises the step of:
evaluating a D element vector of the auto-correlation matrix of the
received signal to determine the first estimate of the channel response for the
first set of carriers.

5

28. The method of Claim 27, wherein the D-element vector is evaluated by:
pre-storing D coefficients determined from the structure of the received
signal; and

performing iterative processing on the D-element vector using the pre-
stored coefficients to determine the first estimate of the channel response for
the first set of carriers.

29. A communications system comprising:
a receiver for receiving a signal transmitted through a channel;
means for statistically analyzing the received signal to determine a first
estimate of the channel response for a first set of carriers;

means for analyzing pilot data in the received signal to determine an
estimate of channel response for a pilot carrier; and

means for combining the first estimate of the channel response for the
first set of carriers with the estimate of channel response for the pilot carriers to
estimate the channel response for an additional set of carriers.

30. The system of Claim 29, wherein the first estimate of the channel
response has a scalar uncertainty; and further comprising a means for removing
the scalar uncertainty using the estimate of the channel response for the pilot
carriers.

31. The system of Claim 29, wherein the first estimate of the channel
response has a scalar uncertainty; and further comprising a means for removing
the scalar uncertainty by:

transferring the first estimate of the channel response for the first set of
carriers into the frequency domain using a discrete Fourier Transfer;

30

comparing the frequency domain first estimate to a frequency domain estimate of channel response for the pilot carriers and using a least-square method to calculate a scalar factor for the pilot carriers; and

5 removing the scalar uncertainty by dividing the frequency domain first estimate by the scalar factor.

32. The system of Claim 29, wherein the estimate of channel response for the pilot carriers is a frequency domain channel response determined by performing a least square method on the received signal.

10

33. The system of Claim 29, the means for statistically analyzing further comprises a blind channel estimation means for statistically analyze the received signal to determine a first estimate of the channel response.

15 34. The system of Claim 33, wherein the communications system includes virtual carriers transmitting substantially no power.

35. The system of Claim 33, wherein the communications system includes carriers transmitting different levels of power.

20

36. The system of Claim 29, wherein interpolation is used to combine the first estimate of the channel response for the first set of carriers with the estimate of channel response for the pilot carriers to estimate the channel response of the additional set of carriers.

25

37. The system of Claim 29 wherein the communications system is an OFDM system.

38. The system of Claim 37, wherein the OFDM system has 64 carriers
30 including 4 pilot carriers and 12 virtual carriers.

39. The system of Claim 29, wherein the received signal contains a cyclic prefix used to prevent the interference of bits of adjacent symbols and also used by the step of statistically analyzing the received signal to determine a first estimate of the channel response for a first set of carriers.

5

40. The system of Claim 29, wherein the first set of carriers consists of 6 carriers.

41. The system of Claim 34 wherein the blind channel estimation means
10 evaluates the auto-correlation matrix of the received signal to determine the first estimate of the channel response for the first set of carriers.

42. The system of Claim 41, wherein the auto-correlation matrix of the received signal is given by:

15
$$\mathbf{R}_{rr} = E(\mathbf{r}\mathbf{r}^H) = \mathbf{C}\mathbf{R}_{\underline{s_P s_P}}\mathbf{C}^H + \sigma_b^2\mathbf{I}$$

wherein:

E is the expectation operation,

r is the received signal,

r^H is the Hermitian of r ,

20 C is a matrix describing the effect of the channel,

C^H is the Hermitian of C ,

I is the identity matrix,

σ_b^2 is the power of the noise, and

$\mathbf{R}_{\underline{s_P s_P}}$ is the auto-correlation matrix of the vector $\underline{s_P}$,

25 $\underline{s_P}$ represents a transmitted symbol and has vector elements representing the virtual carriers removed, and wherein

$$\mathbf{R}_{\underline{s_P s_P}} \neq \mathbf{I}.$$

43. The system of Claim 41, wherein the received signal contains a cyclic
30 prefix having a length of D bits used to prevent the interference of bits of adjacent symbols;

and the blind channel estimation means further performs the function of:
evaluating a D element vector of the auto-correlation matrix of the
received signal to determine the first estimate of the channel response for the
first set of carriers.

5

44. The system of Claim 43, wherein the D-element vector is evaluated by:
pre-storing D coefficients determined from the structure of the received
signal; and

performing iterative processing on the D-element vector using the pre-
stored coefficients to determine the first estimate of the channel response for
the first set of carriers.

10

45. A system for estimating the frequency domain channel response in a
communications system having carriers transmitting different levels of power
comprising:

15

a receiver for receiving a signal transmitted through a channel; and
means for statistically analyzing the received signal to determine a first
estimate of the channel response for a first set of carriers.

20

46. The system of Claim 45, wherein a blind channel estimation means is
used to statistically analyze the received signal to determine a first estimate of
the channel response.

47. The system of Claim 45, wherein the communications system includes
virtual carriers.

25

48. The system of Claim 45, wherein the communications system includes
carriers transmitting different levels of power.

49. The system of Claim 45 wherein the communications system is an
OFDM system.

30

50. The system of Claim 49, wherein the OFDM system has 64 carriers including 4 pilot carriers and 12 virtual carriers.

51. The system of Claim 45, wherein the received signal contains a cyclic prefix used to prevent the interference of bits of adjacent symbols and also used means for statistically analyzing to determine an estimate of the channel response for a set of carriers.

52. The system of Claim 45, wherein the first set of carriers consists of 6 carriers.

53. The system of Claim 46 wherein the blind channel estimation means evaluates the auto-correlation matrix of the received signal to determine the first estimate of the channel response for the first set of carriers.

54. The system of Claim 53, wherein the auto-correlation matrix of the received signal is given by:

$$\mathbf{R}_{rr} = E(\mathbf{r}\mathbf{r}^H) = \mathbf{C}\mathbf{R}_{\mathbf{s}_p\mathbf{s}_p}\mathbf{C}^H + \sigma_b^2\mathbf{I}$$

wherein:

E is the expectation operation,

$\mathbf{r}$ is the received signal,

$\mathbf{r}^H$ is the Hermitian of $\mathbf{r}$,

$\mathbf{C}$ is a matrix describing the effect of the channel,

$\mathbf{C}^H$ is the Hermitian of $\mathbf{C}$,

$\mathbf{I}$ is the identity matrix,

σ_b^2 is the power of the noise, and

$\mathbf{R}_{\mathbf{s}_p\mathbf{s}_p}$ is the auto-correlation matrix of the vector $\mathbf{s}_p$,

$\mathbf{s}_p$ represents a transmitted symbol and has vector elements representing the virtual carriers removed, and wherein

$$\mathbf{R}_{\mathbf{s}_p\mathbf{s}_p} \neq \mathbf{I}.$$

55. The system of Claim 53, wherein the received signal contains a cyclic prefix having a length of D bits used to prevent the interference of bits of adjacent symbols;

and the blind channel estimation means further performs:

5 evaluating a D element vector of the auto-correlation matrix of the received signal to determine the first estimate of the channel response for the first set of carriers.

56. The system of Claim 55, wherein the D-element vector is evaluated by:

10 pre-storing D coefficients determined from the structure of the received signal; and

performing iterative processing on the D-element vector using the pre-stored coefficients to determine the first estimate of the channel response for the first set of carriers.

15