

SYSTEM AND METHOD FOR IMPROVING CHANNEL ESTIMATION OF AN OFDM-MIMO CHANNEL

Field of the Invention

This invention relates to a system and method for obtaining an improved channel estimation of an Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) channel. In particular, the system and method progressively computes channel estimations for each data symbol of a received packet and these updated channel estimations are then utilized to progressively improve the equalization of the packet's data symbols.

Summary of the Prior Art

The demand for high spectral efficiency and high speed broadband communication systems is increasing daily. To address this demand, most broadband communication systems have adopted the Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) modulation scheme. This scheme is widely adopted in broadband communication systems due to its robustness in the face of interference and multipath fading. Furthermore, the multi-carrier space time processing of the OFDM-MIMO scheme allows for multiple-transmit and multiple-receive communication paths which in turn enables the transmission of data through multiple parallel sub-channels at high data rates.

Communication systems that typically utilize OFDM MIMO schemes are wireless systems such as wireless local area networks (WLAN) or Wi-Fi networks, and/or digital audio/video broadcasting systems. In such communication systems, data is transmitted between multiple transmitters and an equal number of receivers via OFDM encoded data packets. These data packets are received and subsequently decoded at the front end of the receivers based on the channel estimation or channel state information (CSI) generated by the receiver. The channel estimation of the wireless channel provides the receiver with the channel properties of the MIMO wireless channel that was used to transmit the data packet from the transmitters to the receivers. The channel estimation of the wireless channel describes how the signal deteriorated, e.g. through fading, scattering, decay, bandwidth fluctuations, delay spread, thermal noise etc., as the signal propagates between the transmitters and the receivers. In summary, when an accurate estimation of the channel is obtained, this results in an accurate reconstruction of the transmitted signal at the front-end of the receivers.

Channel fading remains a challenging problem when estimating MIMO channels. Currently known channel estimation techniques are relatively complex and use training sequences in a relatively inefficient manner. In order to obtain an accurate channel estimation of wireless channels in Wi-Fi or WLAN networks, those skilled in the art have commonly performed channel estimation at the receivers' front-end by analysing training sequences or preamble sequences that are attached to the preamble of the data packet, or to the start of the data packet's frame, as the data packet is transmitted from the transmitters. These training fields or preamble/training sequences comprise patterns that are predetermined and known to the receivers' front-end. Variations of the received training fields or sequences that are known to the receivers' front-end are then utilized to obtain a channel estimation of the wireless channel.

For example, in a WLAN 802.11a/g system, the transmitted packet typically comprises a preamble portion and a data portion whereby the preamble portion is received first by the receivers' front-end before the data portion. The preamble portion will contain several types of fields including the training sequences or training fields that are known to the receiver. These known training sequences or training fields are then utilized by the front-end to obtain the channel estimations of the wireless channels. In this WLAN standard, as the wireless channel is expected to be static, the channel estimation is obtained once per data packet from the preamble portion of the packet. The obtained channel estimation is then subsequently used to decode all the data portions contained within the packet.

The downside of this method is that this method does not provide for the channel estimation to be updated across all the data portions throughout the received packet. The initial channel estimation is utilized to equalize all the data portions and does not take in consideration any variations that may have occurred during the multipath transmission of the packet. This omission may then result in the inaccurate equalization of the data portions in the received packet.

For the above reasons, those skilled in the art are constantly striving to come up with a system and method to obtain an improved channel estimation of the OFDM-MIMO wireless channel that takes into account the changes that affected the entire packet during the multipath transmission of the packet from the plurality of transmitters to the plurality of receivers.

Summary of the Invention

We provide systems and methods to improve the accuracy of the channel estimation of the overall OFDM MIMO wireless channel as set out by the embodiments in accordance with the invention.

A first advantage of embodiments of systems and methods in accordance with the invention is that the channel estimator module in the receiver is not limited to performing OFDM-MIMO channel estimation calculations using only the preamble sequence or training sequence from the received preamble portion of a received packet. As channel estimations for subsequent OFDM data symbols are continuously calculated and updated, this greatly improves the accuracy of the channel estimation of the overall OFDM MIMO wireless channel.

A second advantage of embodiments of systems and methods in accordance with the invention is that the proposed channel estimation method is compatible with various OFDM and OFDMA standards such as the 802.11a/g standard, the 802.11n HT-MF standard, 802.11n HT-GF standard and the 802.11 ac VHT standard.

According to a first aspect of the invention, a method for improving channel estimation of an Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) channel comprises receiving a transmitted packet via the OFDM-MIMO channel, wherein the received packet includes a preamble sequence and a first OFDM data symbol; using the preamble sequence to obtain a training channel estimation matrix H_T ; generating hard decision values for the first OFDM data symbol; constructing a first channel estimation matrix H_1 for the first OFDM data symbol based on the generated hard decision values for the first OFDM data symbol, the first OFDM data symbol and the training channel estimating matrix H_T ; and using the training channel estimation matrix H_T and the first channel estimation matrix H_1 to generate a first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol, wherein the first improved channel estimation matrix $H_{1_Improved}$ is used as the channel estimation for the first OFDM data symbol.

With reference to the first aspect, in a first possible implementation manner of the first aspect, the received packet further comprises a second OFDM data symbol, the method further comprises: generating hard decision values for the second OFDM data symbol; constructing a second channel estimation matrix H_2 for the second OFDM data symbol based on the generated hard decision values for the second OFDM data symbol, the second OFDM data symbol and the first channel estimation matrix H_1 ; and using the first improved channel estimation matrix $H_{1_Improved}$ and the second channel estimation matrix H_2 to

generate a second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol, wherein the second improved channel estimation matrix $H_{2_Improved}$ is used as the channel estimation for the second OFDM data symbol.

With reference to the first aspect, in a third possible implementation manner of the first aspect, the generating the hard decision values for the first OFDM data symbol comprises mapping each complex symbol in the first OFDM data symbol to a nearest point in a Phase-Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) constellation diagram.

With reference to the third possible implementation manner of the first aspect, in a fourth possible implementation manner of the first aspect, the mapping comprises using a maximum likelihood detector or zero-forcing detector technique to map each complex symbol in the first OFDM data symbol to the nearest point in the PSK or QAM constellation diagram.

With reference to the first aspect, in a fifth possible implementation manner of the first aspect, the generating the first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol comprises determining:

$$H_{1_Improved} = (\alpha \cdot H_T) + (1 - \alpha) \cdot H_1$$

where α is a value <1.0 , and usually is large (larger than 0.9).

With reference to the first possible implementation manner of the first aspect, in a sixth possible implementation manner of the first aspect, the generating the second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol comprises determining:

$$H_{2_Improved} = (\alpha \cdot H_{1_Improved}) + (1 - \alpha) \cdot H_2$$

where α is a value <1.0 , and usually is large (larger than 0.9).

With reference to the first aspect, in a seventh possible implementation manner of the first aspect the first channel estimation matrix H_1 comprises a $(N \times N)$ matrix, whereby N represents a number of transmitter-receiver antenna pairs.

Brief Description of the Drawings

The above advantages and features in accordance with this invention are described in the following detailed description and are shown in the following drawings:

Figure 1 illustrating a block diagram of an OFDM-MIMO communication system that utilizes a channel estimation module in accordance with embodiments of the invention;

Figure 2 illustrating a block diagram representative of processing systems providing embodiments in accordance with embodiments of the invention;

Figure 3 illustrating a received packet in accordance with existing OFDM standards; and

Figure 4 illustrating for a flow diagram of a process for obtaining an improved channel estimation of the OFD-MIMO signal at the receivers in accordance with embodiments of the invention.

Detailed Description

This invention relates to a system and method for progressively obtaining an improved channel estimation of an Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) channel. In particular, the system and method computes channel estimations for each data symbol of a received packet and then uses these updated channel estimations to equalize respective data symbols in the received packet.

Figure 1 illustrates a typical block diagram of an Orthogonal Frequency Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) communication system that utilizes a channel estimation module in accordance with embodiments of the invention. In this description, the term MIMO is generally intended to refer to devices that utilizes multiple-transmit and multiple-receive antennas and employs space time coding. As for the term OFDM, this term is intended to include any frequency-division multiplexing and modulation scheme, such as OFDM, COFDM, OFDMA, SOFDMA, and etc. OFDM is a multi-carrier digital modulation scheme with multiple and closely spaced subcarriers. In such an OFDM modulation scheme, data to be transmitted, which is in digital form, is modulated across these subcarriers using a conventional modulation scheme, such as QAM or PSK. Each subcarrier relates to a frequency tone, and the spacing among these subcarriers is such that all subcarriers are orthogonal with respect to one another. OFDM and its variations as listed above are commonly known by those skilled in the art. For example, OFDM is employed in

the IEEE 802.11 Wireless LAN standard (WLAN) while both OFDM and OFDMA are employed in the IEEE 802.16 Wireless MAN standard, which is sometimes referred to as WiMAX.

The OFDM-MIMO system 100 as illustrated in Figure 1 comprises transmitting device 105 for processing a binary signal that is transmitted as a data packet and receiving device 110 for receiving the data packet and reversing the processing steps taken by the transmitter to recreate the transmitted binary signal. Transmitting device 105 is provided with a plurality of transmitters ranging from transmitter, T_1 to transmitter, T_n , whereby n represents the number of transmitting antennas belonging to transmitting device 105. As for receiving device 110, this device is also provided with a plurality of receivers ranging from receiver, R_1 to receiver, R_n , whereby n represents the number of transmitting antennas that are utilized in the OFDM-MIMO system. In other words, if transmitting device 105 is provided with five transmitters, e.g. T_1 - T_5 , receiving device 110 must also be provided with an equal number of receivers, e.g. R_1 - R_5 . One skilled in the art will recognize that transmitters T_1 to T_n need not be provided on a single transmitting device and may comprise of a plurality of individual transmitting devices whereby each transmitter T is a stand-alone transmitter. Similarly, one skilled in the art will recognize that receivers R_1 - R_n also do not necessarily need to be provided on a single receiving device and may comprise of an equal number of individual receiving devices accordingly.

In OFDM-MIMO system 100, data is transmitted from transmitting device 105 to receiving device 110 via multipath broadband channels. The multipath broadband channels may comprise a transmission medium that is able to support the simultaneous transmission of multiple frequency tones. This transmission medium may comprise of any medium that may act as a signal conduit, such as air. In system 100, transmit-receive links may be formed between the transmitters and the receivers and through each transmit-receive link, the broadband signal may be transmitted and received accordingly. For example, in a system that comprises of two transmitter-receiver pairs, i.e. transmitters T_1 , T_2 and receivers R_1 , R_2 , transmit-receive links of such a system may comprise of transmitter-receiver channels such as T_1R_1 , T_1R_2 , T_2R_1 , and T_2R_2 .

In accordance with embodiments of the invention, a digital signal that is to be transmitted from transmitting device 105 to receiving device 110 will first be encoded within an encoder module. The encoder module, which is provided within device 105, may encode the signal using a Viterbi encoder. After the binary signal has been encoded with the appropriate coding rate, the coded signal is then interleaved using an interleaving circuit. The encoded data is then provided to a modulation map module which then digitally

modulates and maps the encoded binary values onto BPSK, QPSK, 16-QAM or 64-QAM constellation maps according to the desired data rate of the system. Hence, by now, the original signal would have been mapped from a binary format, e.g. {0, 1... 1, 0} to a constellation map comprising of IQ samples, e.g. {-1, +1... +j, -j}. Preamble or training symbols are then added to the modulation mapped output to produce OFDM symbol, " $\mathbf{X}$ ", that is to be transmitted. The OFDM symbol, " $\mathbf{X}$ ", is then converted into a time-domain signal and this may be done using an Inverse Fast Fourier Transform (IFFT) module. The IFFT output is then provided to a multiplexer module to form the baseband discrete time samples which are then converted to analogue signals. These analogue signals are then up-converted to a higher frequency band before they are amplified and transmitted through each of the transmitters T_n .

As the data packet is transmitted over the wireless channels, the transmitted data packet will usually be corrupted by noise and/or may be distorted due to multi-path fading effects. Hence, when the data packet is received by receiving device 110, there is a high probability that the received data packet would be corrupted and/or mutated. Hence, in order to restore the received data packet to its original condition, the channel estimation or channel state information (CSI) of the wireless channel has to be first generated by the receiving device. The channel estimation of the wireless channel provides the receiving device with the channel properties of the MIMO wireless channel that was used to transmit the data packet from the transmitters to the receivers so that the noise and/or distortion introduced by the wireless channels may be removed from the received data packet. The exact working of this will be described in greater detail in a later section with reference to Figure 3.

The transmitted data packets are then received by each of receivers, R_n , and decoded using the corresponding signal processing modules in device 110. The received data packets are first converted from an analogue format to a digital format. The digitized signals are then de-multiplexed to reconstruct the received OFDM symbols in time-domain. The digital samples of the de-multiplexed signals are then Fast Fourier Transformed to recreate the frequency domain OFDM symbol, " $\mathbf{h}[\] \cdot \mathbf{X}[\]$ ", whereby $\mathbf{X}[\]$ is the OFDM symbol vector representing the OFDM symbols that were transmitted by the plurality of transmitters of transmitting device 105 and received by receiving device 110, and $\mathbf{h}[\]$ is the channel transfer function matrix or channel estimation matrix of the respective wireless channels. In an ideal situation, the values of $\mathbf{h}[\]$ would be equal to "1" and this would result in the pure transmission of $\mathbf{X}[\]$ vector from transmitting device 105 to receiving device 110.

It should be noted that the channel transfer function is also known in the art as the channel state information or channel estimation of a wireless channel. Also, in operation, the number of wireless channels is dependent on the number of transmitter-receiver channels. For example, for a communication system that comprises of two transmitter-receiver pairs, e.g. T_1 , T_2 , and R_1 , R_2 , there will be a total of four wireless channels, e.g. T_1 - R_1 , T_1 - R_2 , T_2 - R_1 and T_2 - R_2 . For system 100, the calculation or generation of the channel estimation matrix, $h[]$, takes place in channel estimator module 115. Once the channel estimations have been obtained for all the wireless channels in the channel estimation matrix, $h[]$, e.g. h_{11} , h_{12} , h_{21} and h_{22} , the channel estimations may then be used to decode the received OFDM symbols for each receiver in the system. The subsequent decoding of the plurality of received OFDM symbols are omitted for brevity as these decoding steps are known to one skilled in the art.

Figure 2 illustrates a block diagram showing a processing system and components of the processing system that may be included in or may be part of transmitting device 105 and receiving device 110 for implementing embodiments in accordance with embodiments of the invention. Processing system or electronic device 200 may include, but is not limited to, any computing device, such as a transmitter, a receiver, a transceiver or a terminal having a receiver and/or a transmitter, that is able to carry out communicative functions such as a smart phone, a tablet computer, a mobile computer, a netbook, a wearable electronic device such as smart watch, a router, a switch and etc. One skilled in the art will recognize that the exact configuration of each processing system in each electronic device may be different and the exact configuration of each processing system may vary and the illustration provided in Figure 2 is given by way of example only.

In embodiments of the invention, processing system 200 comprises controller 201 and user interface 202. User interface 202 is arranged to enable manual interactions between a user and processing system 200 and for this purpose includes the input/output components required for the user to enter instructions to control electronic device 200. A person skilled in the art will recognize that components of user interface 202 may vary from embodiment to embodiment but will typically include one or more of display 240, keyboard 235 and track-pad 236.

Controller 201 is in data communication with user interface 202 via bus 215 and includes memory 220, processor 205 mounted on a circuit board that processes instructions and data for performing the method of this embodiment, an operating system 206, an input/output (I/O) interface 230 for communicating with user interface 202 and a communications interface, in this embodiment in the form of a network card 250. Network

card 250 may, for example, be utilized to send data from processing system 200 via a wired or wireless network to other processing devices or to receive data via the wired or wireless network. Wireless networks that may be utilized by network card 250 include, but are not limited to, Wireless-Fidelity (Wi-Fi), Bluetooth, Near Field Communication (NFC), cellular networks, satellite networks, telecommunication networks, Wide Area Networks (WAN) and etc.

Memory 220 and operating system 106 are in data communication with processor 205 via bus 210. The memory components include both volatile and non-volatile memory and more than one of each type of memory, including Random Access Memory (RAM) 220, Read Only Memory (ROM) 225 and a mass storage device 145, the last comprising one or more solid-state drives (SSDs). One skilled in the art will recognize that the memory components comprise non-transitory computer-readable media and shall be taken to comprise all computer-readable media except for a transitory, propagating signal. Typically, the instructions are stored as program code in the memory components but can also be hardwired. Memory 220 may include a kernel and/or programming modules such as a software application that may be stored in either volatile or non-volatile memory.

Herein the term “processor” is used to refer generically to any device or component that can process such instructions and may include: a microprocessor, microcontroller, programmable logic device or other computational device. That is, processor 205 may be provided by any suitable logic circuitry for receiving inputs, processing them in accordance with instructions stored in memory and generating outputs (for example to the memory components or on display 240). In this embodiment, processor 205 may be a single core or multi-core processor with memory addressable space. In one example, processor 205 may be multi-core, comprising—for example—an 8 core processor.

Figure 3 illustrates an exemplary data packet that is transmitted from three transmitters, T_1 , T_2 , T_3 , to an equal number of receivers, R_1 , R_2 , R_3 , via an OFDM-MIMO scheme in accordance with embodiments of the invention. Further, as there are three transmitter-receiver pairs in the illustrated system, this means that there will be nine wireless channels or transmission paths. One skilled in the art will recognize that any number of transmitter-receiver pairs may be utilized without departing from this invention and that the illustration in Figure 3 is just an exemplary illustration. Data packet 300 comprises preamble portion 305 and OFDM data symbols 310, 315, 320 and so on. For illustration purposes, Figure 3 makes reference to only three OFDM data symbols however; one skilled in the art will recognize that data packet 300 may include any number of OFDM data symbols within the limitation of the selected OFDM coding rate.

Upon receiving data packet 300, channel estimator module 115 will first utilize preamble 305 of packet 300 together with a stored training or preamble sequence to obtain a training channel estimation matrix H_T . The stored training sequence may comprise a pre-determined number of preamble symbols on selected subcarriers while the rest of the symbols are set to a zero value. The frequency response of the remaining subcarriers can then be interpolated by obtaining an initial channel estimate, finding a time-domain channel estimate, and converting the result back to the frequency domain. The values of the known subcarriers are then replaced by the initial estimate to obtain the training channel estimation matrix H_T . In particular, training channel estimation matrix H_T may be obtained by solving the following equation:

$$r_p[] = H_T[] \cdot Pilot_Sequence[] \quad \dots (1)$$

whereby $r_p[]$ is the vector of the received preamble symbols (preamble 305); $H_T[]$ is the training channel estimation matrix and $Pilot_Sequence[]$ is the vector of preamble sequence symbols that has been pre-stored in module 115.

It should be noted that as the example illustrated in Figure 3 comprises of three transmitter-receiver pairs, this means that the training channel estimation matrix comprises a 3x3 matrix such as:

$$H_T[] = \begin{bmatrix} HT_{11} & HT_{12} & HT_{13} \\ HT_{21} & HT_{22} & HT_{23} \\ HT_{31} & HT_{32} & HT_{33} \end{bmatrix} \quad \dots (1)(a)$$

Once training channel estimation matrix $H_T[]$ has been obtained, the improved channel estimation matrix for the first OFDM data symbol, $H_{1_improved}$, may then be calculated. In order to generate the improved channel estimation matrix for the first OFDM symbol, the hard decision values of received OFDM data symbol 310 have to be first obtained. The hard decision process may be carried out by a slicer provided within channel estimator module 115. The slicer is essentially a decision making device that functions by receiving OFDM symbols as its input and does its best to project the received OFDM symbols to a nearest symbol value on a grid of constellation points. In other words, when OFDM data symbol 310 undergoes a hard decision process, the hard decision function maps the complex symbols of symbol 310 to nearest points on a Phase-Shift Keying (PSK) / Quadrature Amplitude Modulation (QAM) constellation map. The detailed working of the slicer that performs the hard decision function is omitted for brevity as such a device or function is known to a person skilled in the art.

In the example illustrated in Figure 3, this means that the hard decision values for OFDM data symbol 310 may be obtained as follows:

$$S310_1 = \text{hard_decision}(r310_1)$$

$$S310_2 = \text{hard_decision}(r310_2)$$

$$S310_3 = \text{hard_decision}(r310_3)$$

whereby $S310_1$ is the hard decision of OFDM data symbol 310, $r310_1$, received at receiver R_1 , $S310_2$ is the hard decision of OFDM data symbol 310, $r310_2$, received at receiver R_2 and $S310_3$ is the hard decision of OFDM data symbol 310, $r310_3$, received at receiver R_3 .

In embodiments of the invention, only a subset of subcarriers is utilized for the calculation of the channel estimations. In particular, for hard decision values that produce values “*very near*” to the (0,0) point on the constellation map, the corresponding channel estimation for that subcarrier would not be computed. In this embodiment, “*very near*” refers to a normalized minimum distance of a complex symbol from (0,0), i.e. $\text{distance} = (I-0)^2 + (Q-0)^2$. In this embodiment, the channel estimation is not updated if the $\text{distance} < 0.1$.

Returning to the example illustrated in Figure 3, once the hard decision values for OFDM data symbol 310 have been obtained, the next step is to then calculate the channel estimation matrix H_1 for OFDM data symbol 310. The H_1 channel estimation matrix is then averaged by an Infinite-Impulse Response (IIR) filtering function provided in module 115 to produce the improved channel estimation matrix, $H_{1_improved}$, for OFDM data symbol 310. Returning to the example illustrated in Figure 3, the channel estimation matrix, H_1 , may be obtained by solving the following equation for H_1 :

$$r_{310}[] = H_1[] \cdot S_{310}[] \quad \dots (2)$$

whereby $r_{310}[]$ is the matrix for the received OFDM data symbol 310, $S_{310}[]$ is the previously computed hard decision vectors for symbol 310, i.e. values $S310_1$, $S310_2$ and $S310_3$, and $H_1[]$ is the channel estimation matrix for symbol 310. To solve equation (2) to obtain the values of $H_1[]$, values from the previously obtained training channel matrix, $H_T[]$, as obtained in equation (1)(a) are combined with equation (2) to generate the following equations:

$$\begin{bmatrix} r310_1 \\ r310_2 \\ r310_3 \end{bmatrix} = \begin{bmatrix} H1_{11} & HT_{12} & HT_{13} \\ H1_{21} & HT_{22} & HT_{23} \\ H1_{31} & HT_{32} & HT_{33} \end{bmatrix} \cdot \begin{bmatrix} s310_1 \\ s310_2 \\ s310_3 \end{bmatrix} \quad \dots (2)(a)$$

$$\begin{bmatrix} r310_1 \\ r310_2 \\ r310_3 \end{bmatrix} = \begin{bmatrix} HT_{11} & H1_{12} & HT_{13} \\ HT_{21} & H1_{22} & HT_{23} \\ HT_{31} & H1_{32} & HT_{33} \end{bmatrix} \cdot \begin{bmatrix} s310_1 \\ s310_2 \\ s310_3 \end{bmatrix} \quad \dots (2)(b)$$

$$\begin{bmatrix} r310_1 \\ r310_2 \\ r310_3 \end{bmatrix} = \begin{bmatrix} HT_{11} & HT_{12} & H1_{13} \\ HT_{21} & HT_{22} & H1_{23} \\ HT_{31} & HT_{32} & H1_{33} \end{bmatrix} \cdot \begin{bmatrix} s310_1 \\ s310_2 \\ s310_3 \end{bmatrix} \quad \dots (2)(c)$$

whereby equations (2)(a), (2)(b) and 2(c) are solved simultaneously to obtain the values of the H_1 channel estimation matrix, i.e. $H1_{11}$, $H1_{21}$, $H1_{31}$, $H1_{12}$, $H1_{22}$, $H1_{32}$, $H1_{13}$, $H1_{23}$, $H1_{33}$.

Once the values of the channel estimation matrix H_1 for symbol 310 has been calculated, the matrixes $H_1[]$ and $H_T[]$ are utilized in the following equation to obtain the improved channel estimation matrix $H_{1_improved}[]$.

$$H_{1_improved}[] = (\alpha \times H_T[]) + (1 - \alpha) \cdot H_1[] \quad \dots (3)$$

whereby α is a value <1.0 , and usually is large (larger than 0.9). The obtained improved channel estimation matrix, $H_{1_improved}[]$, may then be used in the equalization of OFDM data symbol 310.

In order to obtain the improved channel estimation matrix, $H_{2_improved}$, for the subsequent OFDM data symbol, i.e. OFDM data symbol 315, the hard decision values for OFDM data symbol 315 first has to be obtained as mentioned above. This means that the hard decision value for symbol 315 is obtained as:

$$S315_1 = \text{hard_decision}(r315_1)$$

$$S315_2 = \text{hard_decision}(r315_2)$$

$$S315_3 = \text{hard_decision}(r315_3)$$

whereby $S315_1$ is the hard decision of OFDM data symbol 315, $r315_1$, received at receiver R_1 , $S315_2$ is the hard decision of OFDM data symbol 315, $r315_2$, received at receiver R_2 , and $S315_3$ is the hard decision of OFDM data symbol 315, $r315_3$, received at receiver R_3 . The obtained hard decision values are then combined with the previously obtained improved channel estimation matrix, $H_{1_improved}[]$, to generate the following equations that are then solved to obtain the channel estimation matrix, $H_2[]$, for data symbol 315.

$$\begin{bmatrix} r315_1 \\ r315_2 \\ r315_3 \end{bmatrix} = \begin{bmatrix} H2_{11} & H1_improved_{12} & H1_improved_{13} \\ H2_{21} & H1_improved_{22} & H1_improved_{23} \\ H2_{31} & H1_improved_{32} & H1_improved_{33} \end{bmatrix} \cdot \begin{bmatrix} s315_1 \\ s315_2 \\ s315_3 \end{bmatrix} \quad \dots (4)(a)$$

$$\begin{bmatrix} r315_1 \\ r315_2 \\ r315_3 \end{bmatrix} = \begin{bmatrix} H1_improved_{11} & H2_{12} & H1_improved_{13} \\ H1_improved_{21} & H2_{22} & H1_improved_{23} \\ H1_improved_{31} & H2_{32} & H1_improved_{33} \end{bmatrix} \cdot \begin{bmatrix} s315_1 \\ s315_2 \\ s315_3 \end{bmatrix} \quad \dots (4)(b)$$

$$\begin{bmatrix} r315_1 \\ r315_2 \\ r315_3 \end{bmatrix} = \begin{bmatrix} H1_improved_{11} & H1_improved_{12} & H2_{13} \\ H1_improved_{21} & H1_improved_{22} & H2_{23} \\ H1_improved_{31} & H1_improved_{32} & H2_{33} \end{bmatrix} \cdot \begin{bmatrix} s315_1 \\ s315_2 \\ s315_3 \end{bmatrix} \quad \dots (4)(b)$$

Once the values of H_2 channel estimation matrix, i.e. $H2_{11}$, $H2_{21}$, $H2_{31}$, $H2_{12}$, $H2_{22}$, $H2_{32}$, $H2_{13}$, $H2_{23}$, $H2_{33}$, for symbol 315 have been obtained, the values of $H_2[]$ and $H1_improved[]$ are then utilized in the following equation to obtain the improved channel estimation matrix $H2_improved[]$.

$$H2_improved[] = (\alpha \times H1_improved[]) + (1 - \alpha) \cdot H2[] \quad \dots (5)$$

whereby α is a value <1.0 , and usually is large (larger than 0.9). The obtained improved channel estimation matrix, $H2_improved[]$, may then be used in the equalization of OFDM data symbol 315. These steps, from the step of obtaining the hard decision values of the subsequent OFDM data symbol in the received packet, may then be repeated to progressively calculate the improved channel estimation matrix for each subsequent data symbol in received data packet 300. In other words, an earlier obtained improved channel estimation matrix is utilized in the computation of the improved channel estimation matrix for a subsequent data symbol in received packet 300.

Packet Error Rate (PER) Performance

The table below illustrates the simulated signal to noise ratio (SNR) of a system that utilizes the method in accordance with embodiments of the invention as compared with the simulated SNR of a conventional system. The simulation was applied to a 2x2 MIMO Additive White Gaussian Noise (AWGN) channel whereby the encoding/decoding utilized a 801.11ac - 20 MHz standard.

Modulation Types	A system in accordance with embodiments of the invention / SNR (dB)	Conventional System / SNR (dB)	Improvement achieved / SNR (dB)
BPSK 1/2	5.59	6.07	0.48
QPSK 1/2	8.95	9.28	0.33
QPSK 3/4	11.22	11.73	0.51
16QAM 1/2	14.71	14.88	0.17
16QAM 3/4	17.81	18.16	0.35
64QAM 2/3	22.68	22.71	0.03
64QAM 3/4	24.12	24.30	0.18
64QAM 5/6	26.03	26.31	0.28
256QAM 3/4	30.90	30.95	0.05

Table 1

In accordance with an embodiment of the invention, a method for obtaining an improved channel estimation of an Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) channel is provided, whereby the method comprises the following five steps:

Step 1, receiving a transmitted packet via the OFDM-MIMO channel, wherein the received packet includes a preamble sequence and a first OFDM data symbol;

Step 2, using the preamble sequence to obtain a training channel estimation matrix H_T ;

Step 3, generating hard decision values for the first OFDM data symbol;

Step 4, constructing a first channel estimation matrix H_1 for the first OFDM data symbol based on the generated hard decision values for the first OFDM data symbol, the first OFDM data symbol and the training channel estimating matrix H_T ;

Step 5, using the training channel estimation matrix H_T and the first channel estimation matrix H_1 to generate a first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol, wherein the first improved channel estimation matrix $H_{1_Improved}$ is used as the channel estimation for the OFDM-MIMO channel

In order to provide such a system or method, a process is needed for obtaining an improved channel estimation of an OFDM-MIMO channel in a WLAN or Wi-Fi receiver. The

following description and Figure 4 describes embodiments of processes that provide processes in accordance with this invention.

Figure 4 illustrates process 400 that is performed by a processing system in a channel estimator module provided in a wireless receiver to obtain improved channel estimations for OFDM-MIMO channels in accordance with embodiments of this invention. Process 400 begins at step 405 whereby the channel estimator receives the data packet from the plurality of receiving devices or receiver antennas connected to the channel estimator module. Process 400 then proceeds to calculate the training channel estimation matrix, $H_T[]$, for the received data packet using: (i) the preamble portion of the received data packet; and (ii) a preamble or training sequence vector stored within the channel estimator module. Once process 400 has obtained the training channel estimation matrix, $H_T[]$, for the data packet, process 400 then proceeds to select the first OFDM data symbol in the received data packet. This takes place at step 415. Process 400 will then, at step 420, proceed to obtain hard decision values for the complex symbols contained within the first OFDM data symbol. The obtained hard decision values are then utilized by process 400, at step 425, together with the training channel estimation matrix, $H_T[]$, and the received first OFDM data symbol to construct the channel estimation matrix, $H_1[]$, for the first OFDM data symbol. Process 400 then proceeds to step 430 whereby the channel estimation matrix, $H_1[]$, and the training channel estimation matrix, $H_T[]$, are averaged using an IIR function to obtain the improved channel estimation matrix, $H_{1_improved}[]$. The improved channel estimation matrix, $H_{1_improved}[]$ is then utilized by process 400 at step 435 to reconstruct the first OFDM data symbol.

Process 400 then proceeds to step 440 whereby process 400 determines if there is another OFDM data symbol in the received packet. If process 400 determines that there is another OFDM data symbol in the data packet, process 400 then proceeds to step 445 whereby the next OFDM data symbol is then selected. Process 400 then returns to step 420 whereby process 400 obtains the hard decision values for the selected OFDM symbol. Steps 420-440 are repeated by process 400 until all the OFDM data symbols in the received data packet have been selected and processed by process 400. Process 400 then ends.

The above is a description of embodiments of a system and process in accordance with the present invention as set forth in the following claims. It is envisioned that others may and will design alternatives that fall within the scope of the following claims.

CLAIMS:

1. A method for improving channel estimation of an Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) channel, the method comprising:

receiving a transmitted packet via the OFDM-MIMO channel, wherein the received packet includes a preamble sequence and a first OFDM data symbol;

using the preamble sequence to obtain a training channel estimation matrix H_T ;

generating hard decision values for the first OFDM data symbol;

constructing a first channel estimation matrix H_1 for the first OFDM data symbol based on the generated hard decision values for the first OFDM data symbol, the first OFDM data symbol and the training channel estimating matrix H_T ; and

using the training channel estimation matrix H_T and the first channel estimation matrix H_1 to generate a first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol, wherein the first improved channel estimation matrix $H_{1_Improved}$ is used as the channel estimation for the first OFDM data symbol.

2. The method according to claim 1, wherein the received packet further comprises a second OFDM data symbol, the method further comprising:

generating hard decision values for the second OFDM data symbol;

constructing a second channel estimation matrix H_2 for the second OFDM data symbol based on the generated hard decision values for the second OFDM data symbol, the second OFDM data symbol and the first channel estimation matrix H_1 ; and

using the first improved channel estimation matrix $H_{1_Improved}$ and the second channel estimation matrix H_2 to generate a second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol, wherein the second improved channel estimation matrix $H_{2_Improved}$ is used as the channel estimation for the second OFDM data symbol.

3. The method according to claim 1, wherein the using the preamble sequence to obtain the training channel estimation matrix H_T comprises:

dividing the preamble sequence in the received packet by a stored preamble sequence.

4. The method according to claim 1, wherein the generating the hard decision values for the first OFDM data symbol comprises:

mapping each complex symbol in the first OFDM data symbol to a nearest point in a Phase-Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) constellation diagram.

5. The method according to claim 4, wherein the mapping comprises:
 using a maximum likelihood detector or zero-forcing detector technique to map each complex symbol in the first OFDM data symbol to the nearest point in the PSK or QAM constellation diagram.

6. The method according to claim 1, wherein the generating the first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol comprises determining:

$$H_{1_Improved} = (\alpha \cdot H_T) + (1 - \alpha) \cdot H_1$$

where α is a value $0.9 < \alpha < 1.0$.

7. The method according to claim 2, wherein the generating the second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol comprises determining:

$$H_{2_Improved} = (\alpha \cdot H_{1_Improved}) + (1 - \alpha) \cdot H_2$$

where α is a value $0.9 < \alpha < 1.0$.

8. The method according to claim 1 wherein the first channel estimation matrix H_1 comprises a $(N \times N)$ matrix, whereby N represents a number of transmitter-receiver antenna pairs.

9. A system for improving channel estimation of an Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) channel, the system comprising:

a processing unit; and

a non-transitory media readable by the processing unit, the media storing instructions that when executed by the processing unit, cause the processing unit to:

receive a transmitted packet via the OFDM-MIMO channel, wherein the received packet includes a preamble sequence and a first OFDM data symbol;

use the preamble sequence to obtain a training channel estimation matrix H_T ;

generate hard decision values for the first OFDM data symbol;

construct a first channel estimation matrix H_1 for the first OFDM data symbol based on the generated hard decision values for the first OFDM data symbol, the first OFDM data symbol and the training channel estimating matrix H_T ; and

use the training channel estimation matrix H_T and the first channel estimation matrix H_1 to generate a first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol, wherein the first improved channel estimation matrix $H_{1_Improved}$ is used as the channel estimation for the first OFDM data symbol.

10. The system according to claim 9, wherein the received packet further comprises a second OFDM data symbol, the system further comprises:

instructions for directing the processing unit to:

generate hard decision values for the second OFDM data symbol;

construct a second channel estimation matrix H_2 for the second OFDM data symbol based on the generated hard decision values for the second OFDM data symbol, the second OFDM data symbol and the first channel estimation matrix H_1 ; and

use the first improved channel estimation matrix $H_{1_Improved}$ and the second channel estimation matrix H_2 to generate a second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol, wherein the second improved channel estimation matrix $H_{2_Improved}$ is used as the channel estimation for the second OFDM data symbol.

11. The system according to claim 9, wherein the instructions to use the preamble sequence to obtain the training channel estimation matrix H_T comprises:

instructions for directing the processing unit to:

divide the preamble sequence in the received packet by a stored preamble sequence.

12. The system according to claim 9, wherein the instructions to generate the hard decision values for the first OFDM data symbol comprises:

instructions for directing the processing unit to:

map each complex symbol in the first OFDM data symbol to a nearest point in a Phase-Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) constellation diagram.

13. The system according to claim 12, wherein the instructions to map each complex symbol comprises:

instructions for directing the processing unit to:

use a maximum likelihood detector or zero-forcing detector technique to map each complex symbol in the first OFDM data symbol to the nearest point in the PSK or QAM constellation diagram.

14. The system according to claim 9, wherein the instructions to generate the first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol comprises determining:

$$H_{1_Improved} = (\alpha \cdot H_T) + (1 - \alpha) \cdot H_1$$

where α is a value $0.9 < \alpha < 1.0$.

15. The system according to claim 10, wherein the instructions to generate the second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol comprises determining:

$$H_{2_Improved} = (\alpha \cdot H_{1_Improved}) + (1 - \alpha) \cdot H_2$$

where α is a value $0.9 < \alpha < 1.0$.

16. The system according to claim 9 wherein the first channel estimation matrix H_1 comprises a $(N \times N)$ matrix, whereby N represents a number of transmitter-receiver antenna pairs.

17. A terminal for receiving Orthogonal Frequency-Division Multiplexing (OFDM) Multiple-In and Multiple-Out (MIMO) communications, the terminal comprising:

a receiver configured to receive a transmitted packet via the OFDM-MIMO channel, wherein the received packet includes a preamble sequence and a first OFDM data symbol;

a processor configured to perform operations of:

using the preamble sequence to obtain a training channel estimation matrix H_T ;

generating hard decision values for the first OFDM data symbol;

constructing a first channel estimation matrix H_1 for the first OFDM data symbol based on the generated hard decision values for the first OFDM data symbol, the first OFDM data symbol and the training channel estimating matrix H_T ; and

using the training channel estimation matrix H_T and the first channel estimation matrix H_1 to generate a first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol, wherein the first improved channel estimation matrix $H_{1_Improved}$ is used as the channel estimation for the first OFDM data symbol.

18. The terminal according to claim 17, wherein the received packet further comprises a second OFDM data symbol, the processor further configured to perform the operations of:

generating hard decision values for the second OFDM data symbol;

constructing a second channel estimation matrix H_2 for the second OFDM data symbol based on the generated hard decision values for the second OFDM data symbol, the second OFDM data symbol and the first channel estimation matrix H_1 ; and

using the first improved channel estimation matrix $H_{1_Improved}$ and the second channel estimation matrix H_2 to generate a second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol, wherein the second improved channel estimation matrix $H_{2_Improved}$ is used as the channel estimation for the second OFDM data symbol.

19. The terminal according to claim 17, wherein the operation of using the preamble sequence to obtain the training channel estimation matrix H_T comprises:

the processor configured to perform the operations of:

dividing the preamble sequence in the received packet by a stored preamble sequence.

20. The terminal according to claim 17, wherein the operation of generating the hard decision values for the first OFDM data symbol comprises:

the processor configured to perform the operations of:

mapping each complex symbol in the first OFDM data symbol to a nearest point in a Phase-Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) constellation diagram.

21. The terminal according to claim 20, wherein the operation of mapping each complex symbol comprises:

the processor configured to perform the operations of:

using a maximum likelihood detector or zero-forcing detector technique to map each complex symbol in the first OFDM data symbol to the nearest point in the PSK or QAM constellation diagram.

22. The terminal according to claim 17, wherein the operation of generating the first improved channel estimation matrix $H_{1_Improved}$ for the first OFDM data symbol comprises the processor being configured to perform the operation of determining:

$$H_{1_Improved} = (\alpha \cdot H_T) + (1 - \alpha) \cdot H_1$$

where α is a value $0.9 < \alpha < 1.0$.

23. The terminal according to claim 18, wherein the operation of generating the second improved channel estimation matrix $H_{2_Improved}$ for the second OFDM data symbol comprises the processor being configured to perform the operation of determining:

$$H_{2_Improved} = (\alpha \cdot H_{1_Improved}) + (1 - \alpha) \cdot H_2$$

where α is a value $0.9 < \alpha < 1.0$.

24. The terminal according to claim 17 wherein the first channel estimation matrix H_1 comprises a $(N \times N)$ matrix, whereby N represents a number of transmitter-receiver antenna pairs.