US 20070058734A1

(19) United States

(12) Patent Application Publication (10) Pub. No.: US 2007/0058734 A1

Kao et al. (43) Pub. Date: Mar. 15, 2007

(54) CIRCUIT FOR IMPROVING CHANNEL IMPULSE RESPONSE ESTIMATION AND COMPENSATING FOR REMNANT FREQUENCY OFFSET IN THE ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING BASEBAND RECEIVER FOR IEEE 802.11A/G WIRELESS LAN STANDARD STANDARD

(75) Inventors: **Kai-Pon Kao**, Hsinchu City (TW); **Tien-Hui Chen**, Hsin-Tien (TW)

Correspondence Address:
THOMAS, KAYDEN, HORSTEMEYER & RISLEY, LLP
100 GALLERIA PARKWAY, NW
STE 1750
ATLANTA, GA 30339-5948 (US)

(73) Assignee: **VIA Technologies Inc.**

(21) Appl. No.: **11/224,757**

(22) Filed: **Sep. 13, 2005**

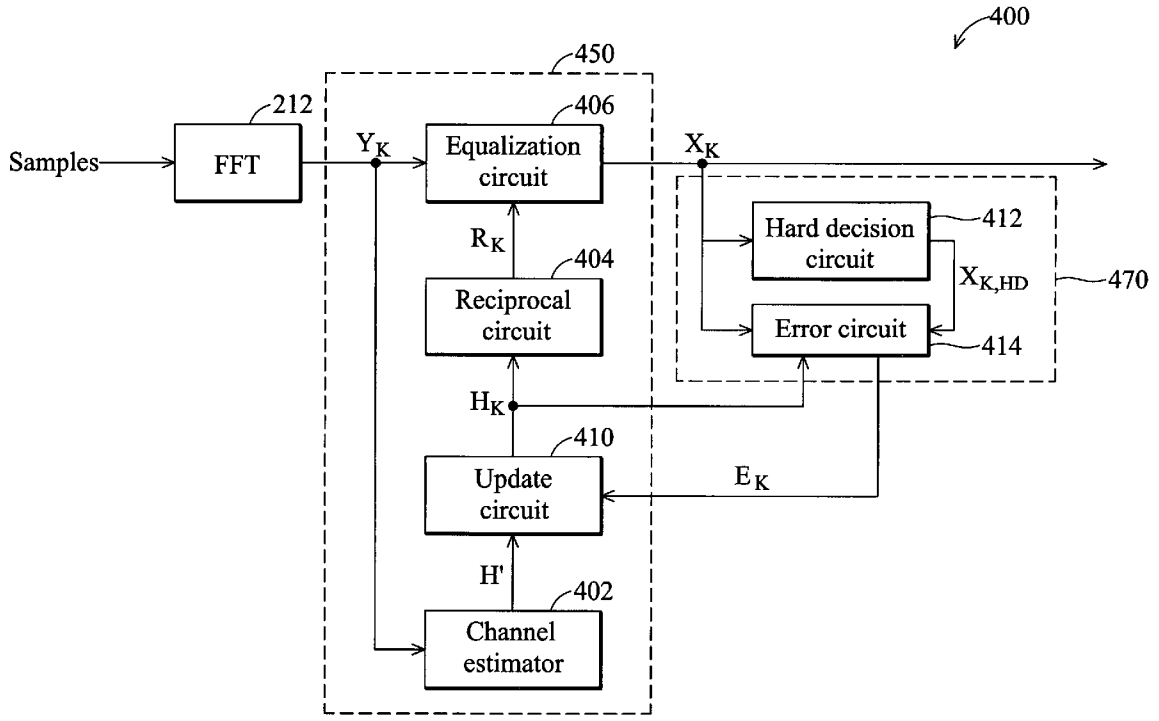
Publication Classification

(51) **Int. Cl.**
H04K 1/10 (2006.01)

(52) **U.S. Cl.** **375/260**

(57) **ABSTRACT**

A circuit for improving accuracy of channel impulse response estimation and compensating for remnant frequency offset in a receiver of an orthogonal frequency division multiplexing (OFDM) system is provided. The circuit comprises an equalizer, for compensating a first signal for channel distortion with the channel impulse response estimate to generate a second signal. The circuit also comprises a remnant frequency compensation module, coupled to the equalizer, for rotating a phase of the second signal with a phase angle of an phase offset coefficient calculated according to a plurality of pilot signals of the second signal to generate a third signal. The circuit further comprises a error estimation module, coupled to the remnant frequency compensation module, for generating an error estimate according to the third signal and its hard decision estimate, and the error estimate is further fed back to the equalizer to refine the channel impulse response estimate.



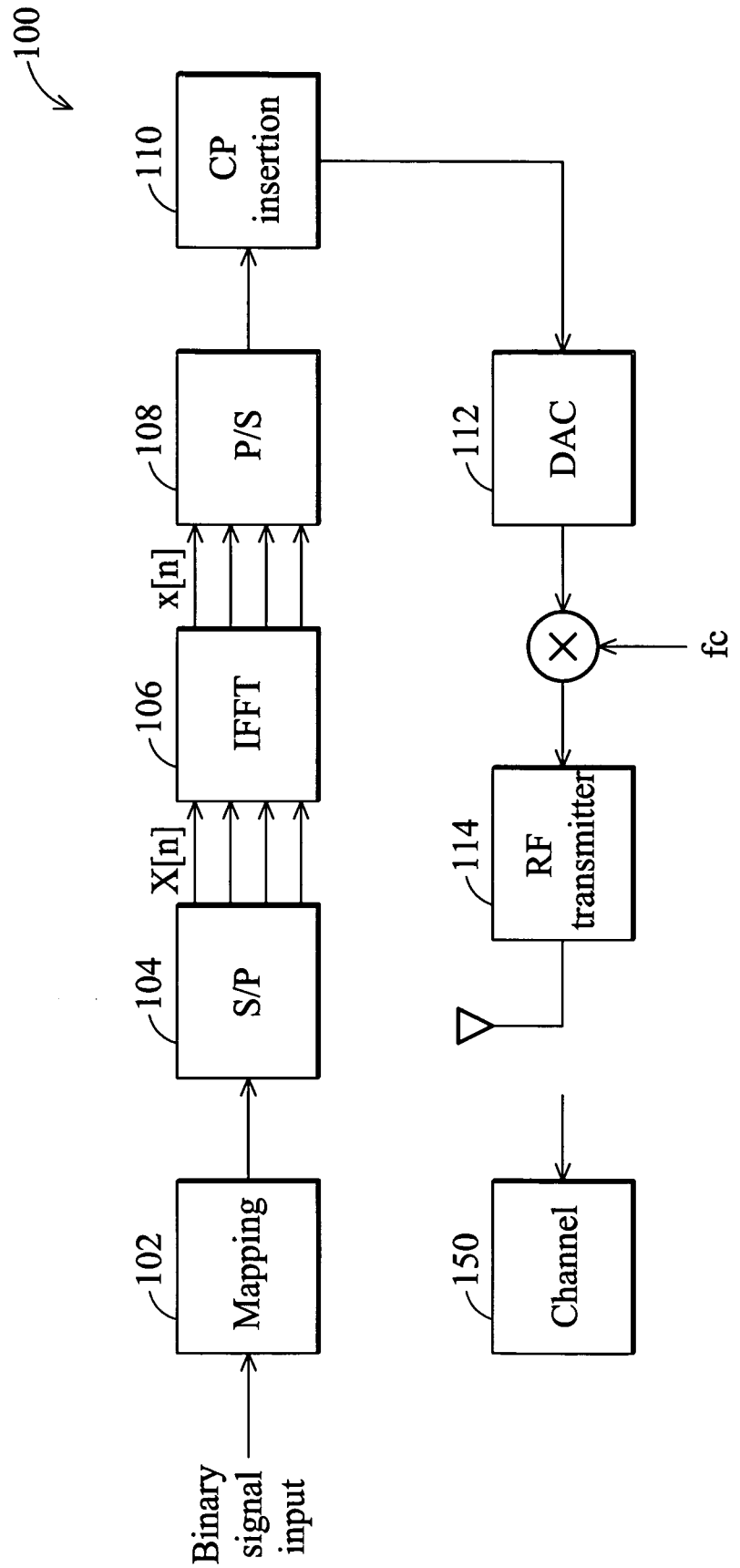


FIG. 1 (RELATED ART)

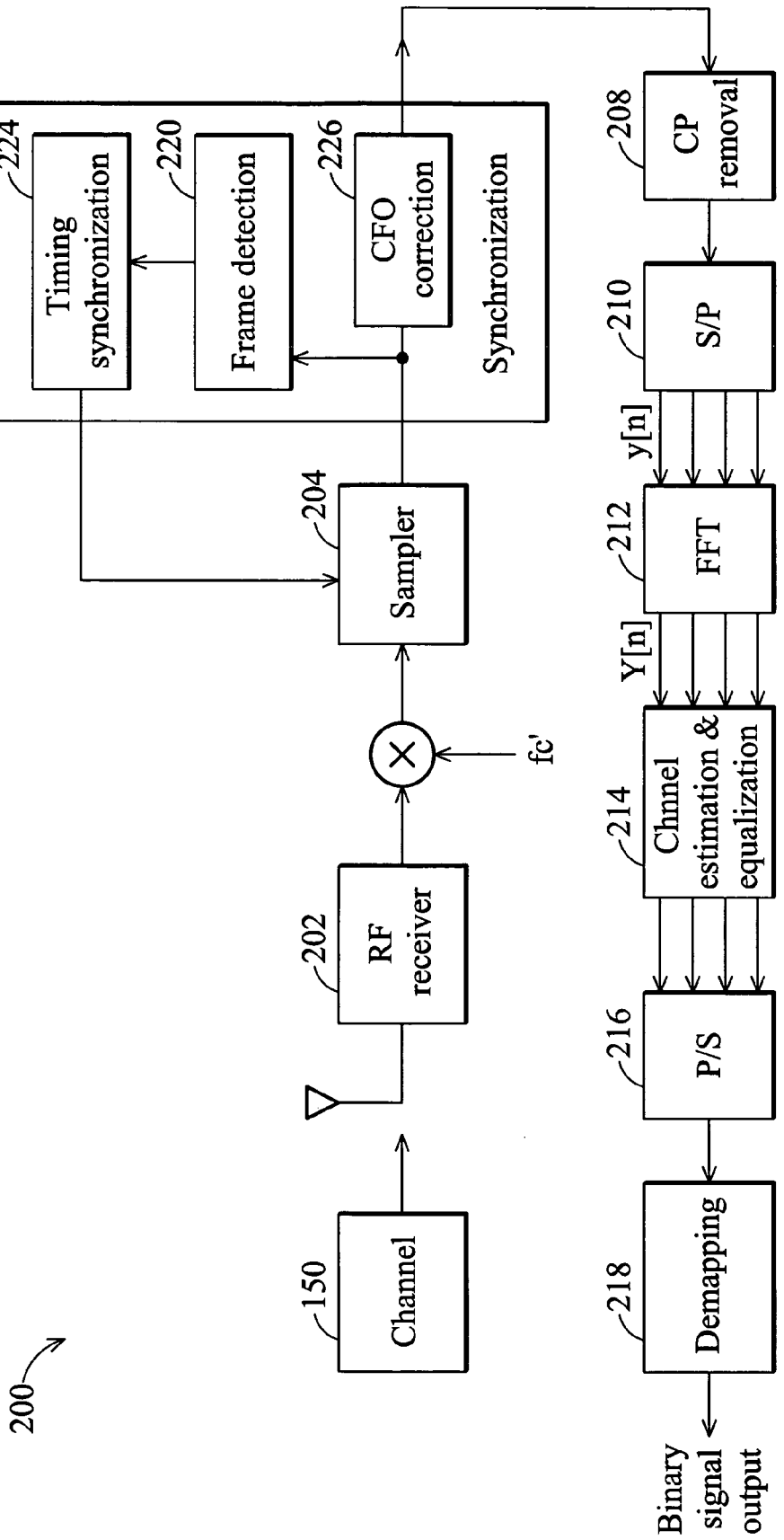


FIG. 2 (RELATED ART)

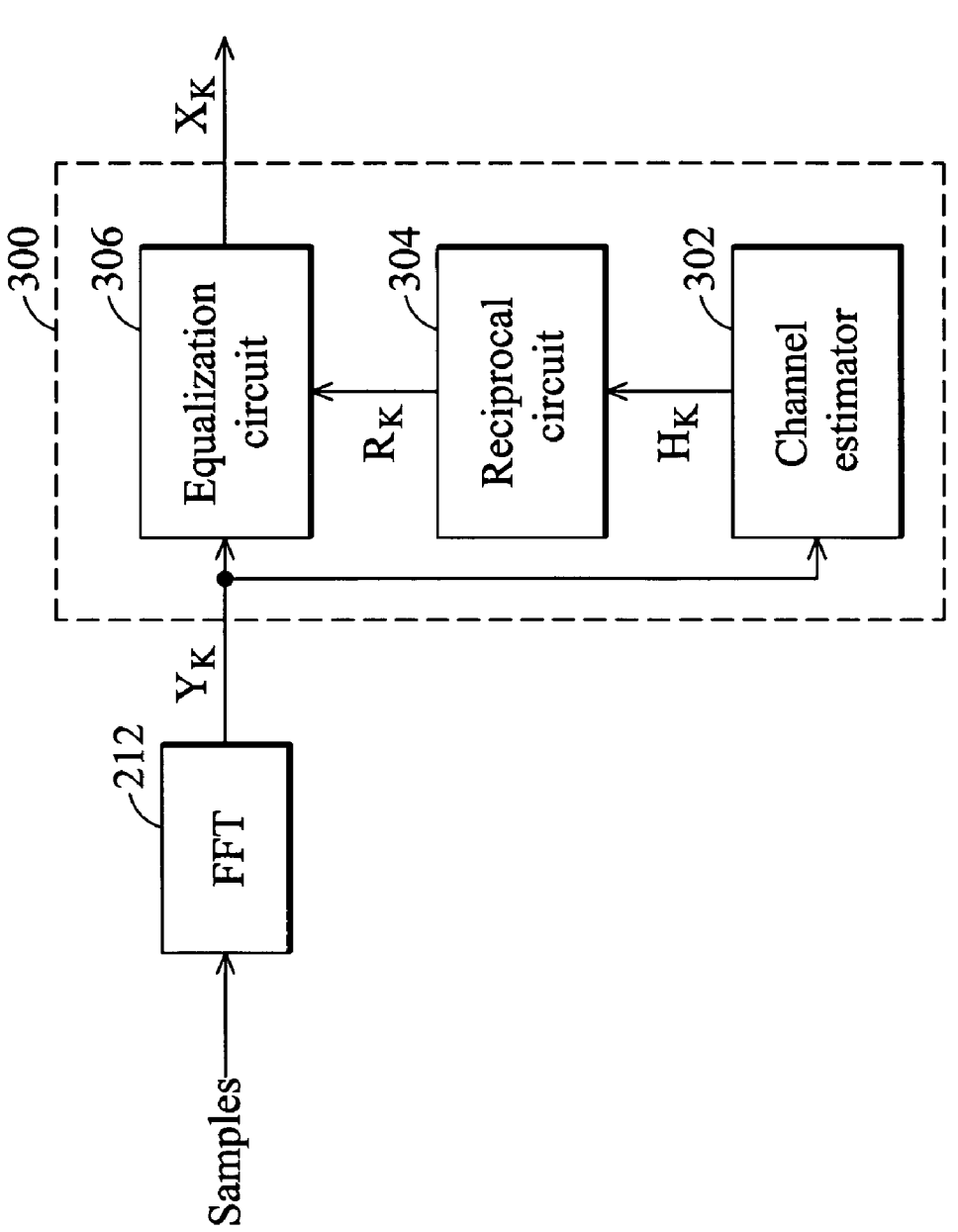


FIG. 3 (RELATED ART)

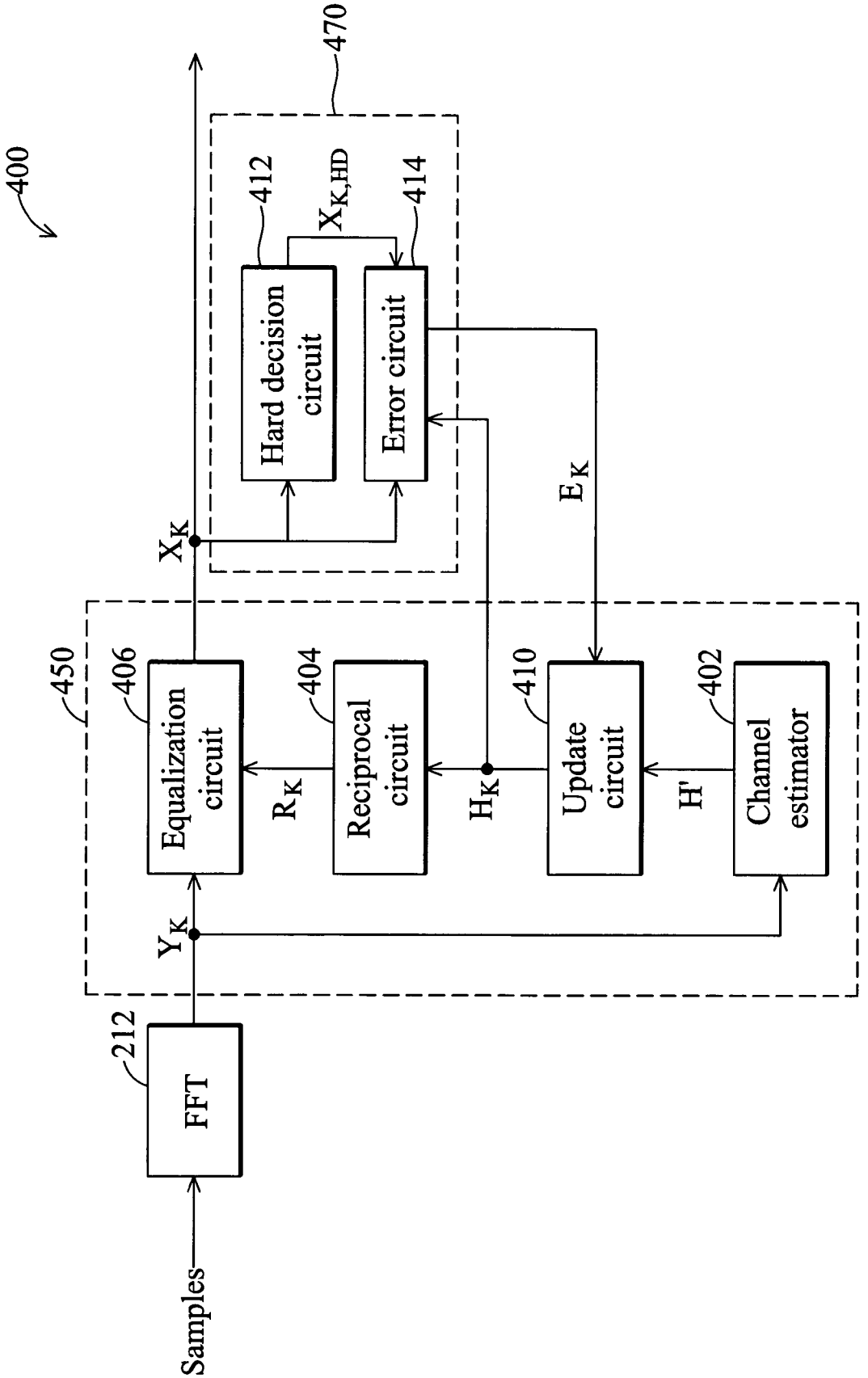

400
470
412
$X_{K,HD}$
414
Hard decision circuit
Error circuit
X_K
E_K
450
406
Equalization circuit
404
Reciprocal circuit
410
Update circuit
402
Channel estimator
R_K
H_K
H'
Y_K
212
FFT
Samples

FIG. 4

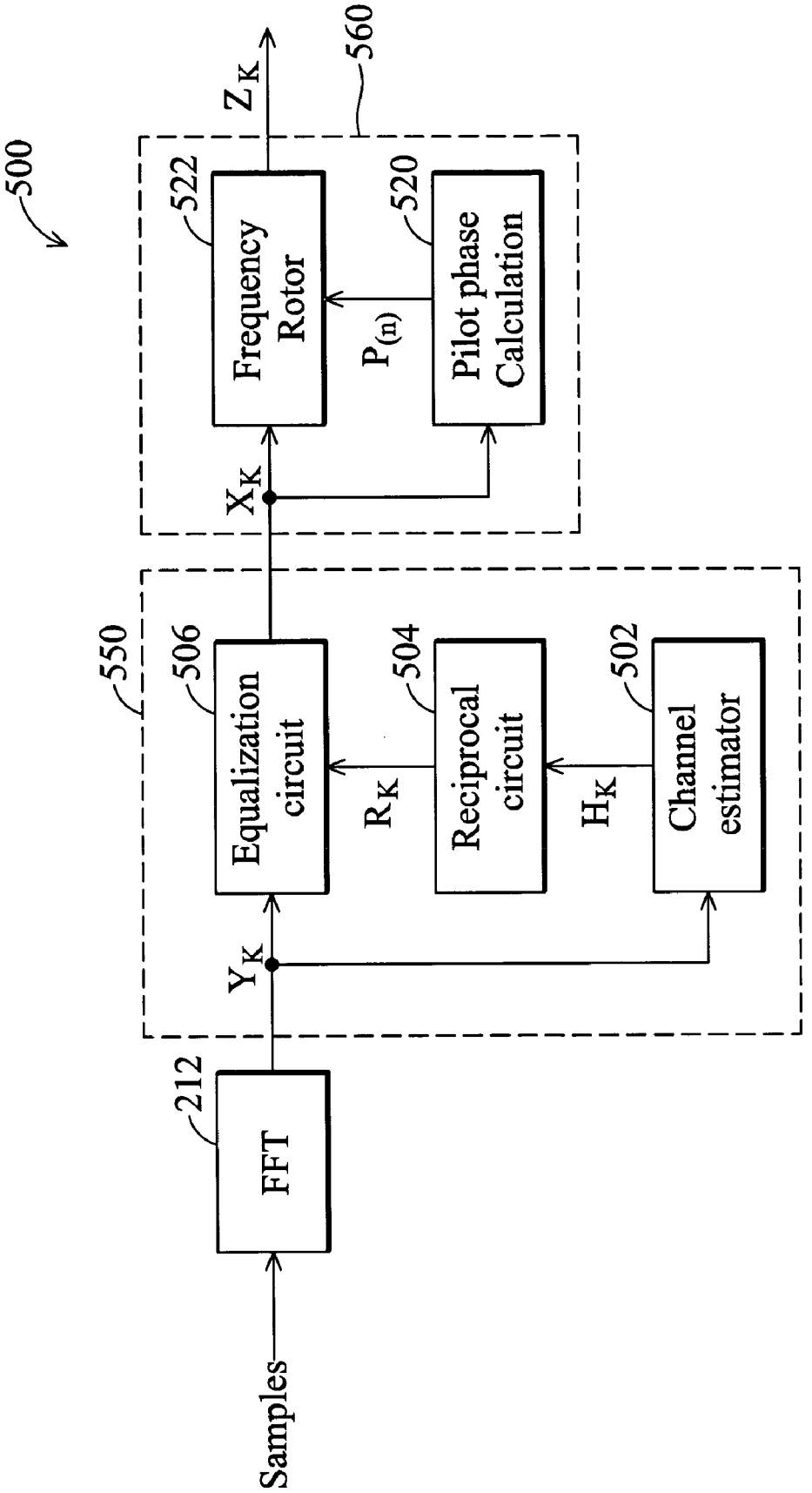

500
560
Z_K
522
Frequency Rotor
520
Pilot phase Calculation
$P_{(n)}$
X_K
550
506
Equalization circuit
504
Reciprocal circuit
502
Channel estimator
R_K
H_K
Y_K
212
FFT
Samples

FIG. 5

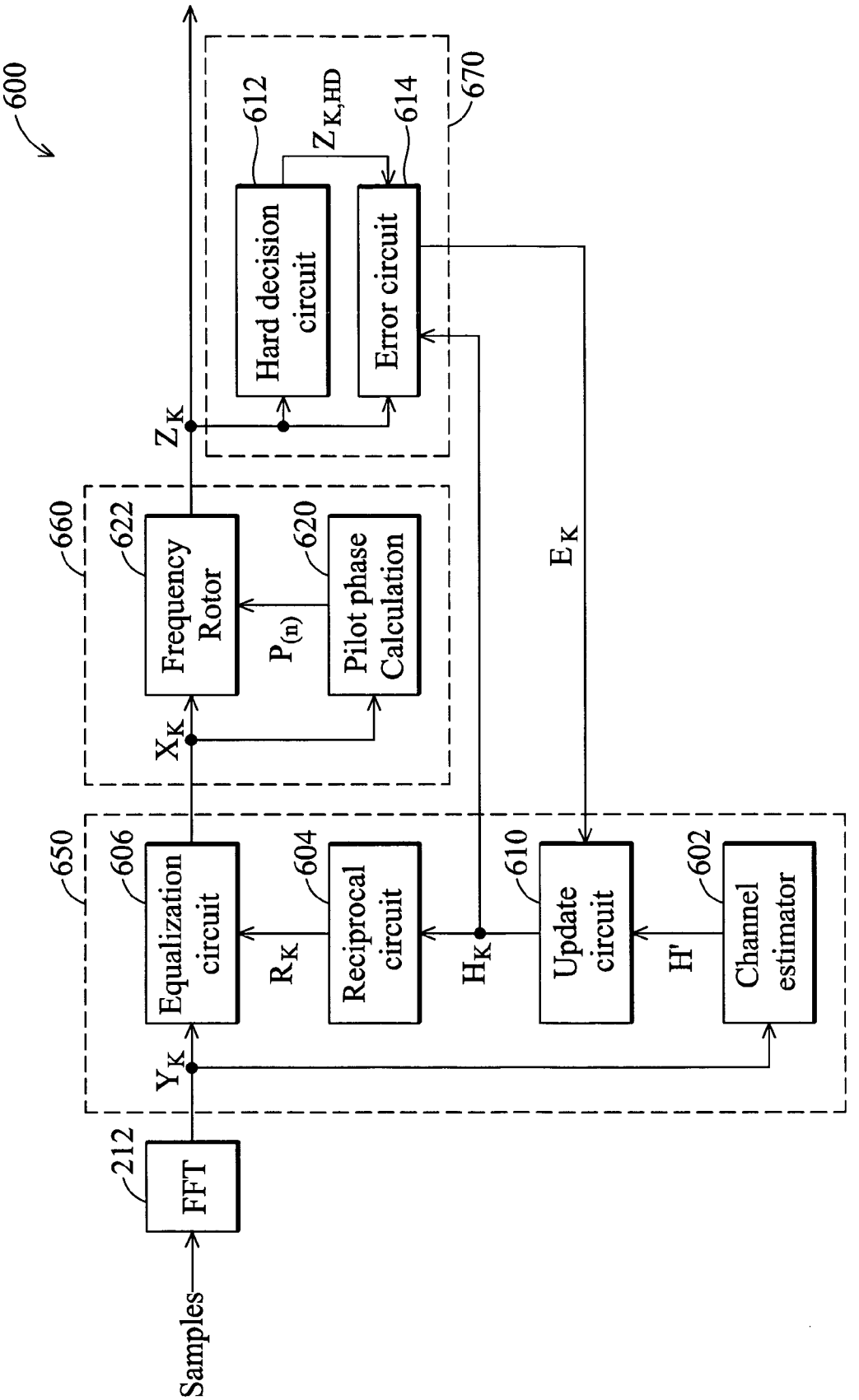

600
670
612
$Z_{K,HD}$
614
Hard decision circuit
Error circuit
Z_K
660
622
620
Frequency Rotor
$P_{(n)}$
Pilot phase Calculation
X_K
E_K
650
606
604
610
602
Equalization circuit
R_K
Reciprocal circuit
H_K
Update circuit
H'
Channel estimator
Y_K
212
FFT
Samples

FIG. 6

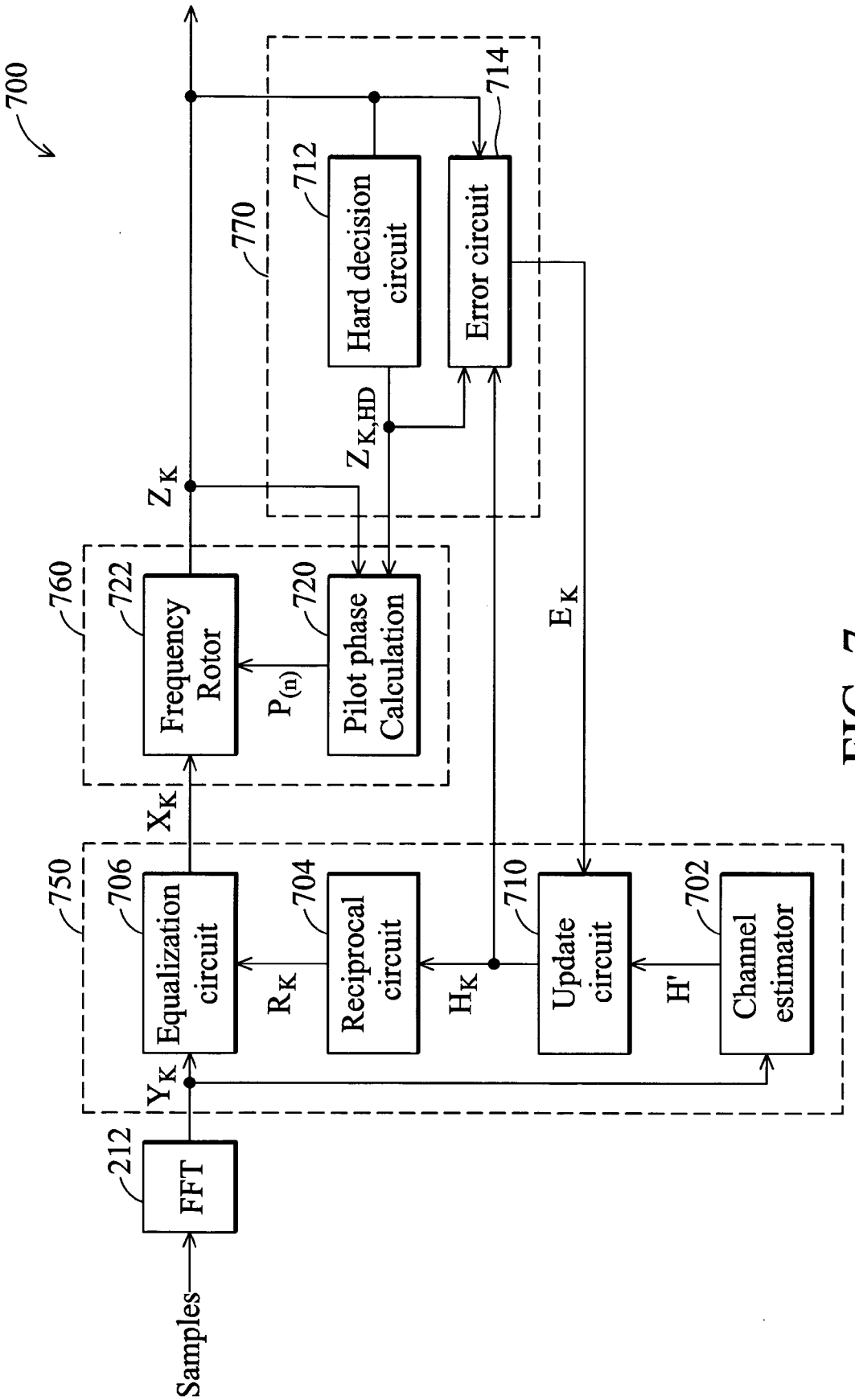

700
770
712
Hard decision circuit
714
Error circuit
$Z_{K,HD}$
Z_K
760
722
Frequency Rotor
720
Pilot phase Calculation
$P_{(n)}$
E_K
X_K
750
706
Equalization circuit
704
Reciprocal circuit
710
Update circuit
702
Channel estimator
R_K
H_K
H'
Y_K
212
FFT
Samples

FIG. 7

CIRCUIT FOR IMPROVING CHANNEL IMPULSE RESPONSE ESTIMATION AND COMPENSATING FOR REMNANT FREQUENCY OFFSET IN THE ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING BASEBAND RECEIVER FOR IEEE 802.11A/G WIRELESS LAN STANDARD STANDARD

BACKGROUND

[0001] The present invention relates to a baseband processor of an orthogonal frequency division multiplexing (OFDM) receiver, and more particularly, to an OFDM baseband processor for wireless LAN (WLAN) IEEE 802.11a or IEEE 802.11g standards.

[0002] Orthogonal frequency division multiplexing (OFDM) is a modulation technique for wireless LAN standards such as IEEE 802.11a or 802.11g. OFDM distributes the data over a large number of carriers (or sub-carriers) that are spaced apart at precise frequencies. This spacing provides the "orthogonality" that prevents the demodulators from seeing frequencies other than their own. Because the data is split for transmission on several sub-carriers, the duration of every transmitted symbol on each sub-carrier is increased, and the amount of crosstalk between symbols or inter-symbol interference (ISI) is reduced. This is the reason why OFDM is so popular among applications for high bit rate communication systems nowadays.

[0003] In IEEE 802.11a, the carrier frequency is 5 GHz. There are 64 implied subcarrier frequencies with a spacing of 312.5 kHz(=20 MHz/64, wherein 20 MHz is the channel bandwidth). Among the 64 implied subcarriers, there are 52 nonzero subcarriers, which includes 48 data subcarriers carrying data and four pilot subcarriors used as pilot tones. Each subcarrier hums away at 312.5 k symbols/second. Data is blocked into 3.2-microsecond frames with an additional 0.8 microsecond of cyclic prefix tacked on for mitigation of intersymbol interference, and the data frame and the cyclic prefix thereof forms a data symbol lasting for 4 μs. A 64-point fast Fourier transform is performed over 3.2 microseconds to extract the 48 data symbols on the 48 QAM signals. For binary phase-shift keying (BPSK), with 1 bit per symbol, that is 48 bits in 4 microseconds, for an aggregate data rate of 12 Mbits/s. Half-rate convolutional coding brings the net rate down to 6 Mbits/s. For 64 QAM, the aggregate data rate is six times higher, or 72 Mbits/s.

[0004] FIG. **1** illustrates the main function blocks of the transmitter end **100** of the OFDM baseband processor according to the IEEE 802.11a standard. The main function blocks of the transmitter end include a signal mapper **102**, a serial to parallel converter **104**, an inverse fast Fourier transform (IFFT) block **106**, a parallel to serial converter **108**, a cyclic prefix (CP) adding block **110**, a digital to analog converter (DAC) **112**, and a radio frequency (RF) transmitter **114**. OFDM is a multi-carrier modulation technique. First, the data stream is modulated with signal mapper **102** using modulation techniques such as Quadrature Amplitude Modulation (QAM) or Binary Phase Shift keying (BPSK). The next step in OFDM modulation is to convert the serial data into parallel data streams with the serial to parallel converter **104**. The Inverse Fast Fourier transform (IFFT) is then performed on the modulated data with the IFFT block **106**. The IFFT is at the heart of the OFDM modulation, because it provides a simple way to modulate data streams onto orthogonal subcarriers. The data streams before and after IFFT are designated as X[n] and x[n] to represent frequency domain data and time domain data respectively, wherein n represents the order number of the subcarriers. After the IFFT, the parallel data streams are concatenated into a single data stream by the parallel to serial converter **108**. Finally a characteristic cyclic prefix (CP) is added to each OFDM symbol being transmitted in the single data stream with the cyclic prefix adding block **110**. The OFDM symbol is now ready, and after being converted from digital to analog form with the DAC **112** and modulated by the RF transmitter with a carrier frequency fc, it is sent over the channel **150** as RF signals to the receiver end.

[0005] FIG. **2** illustrates the main function blocks of receiver end **200** of the OFDM baseband processor according to the IEEE 802.11a standard. The main function blocks of the receiver end **200** include a RF receiver **202**, a sampler **204**, a synchronization block **206**, a cyclic prefix remover **208**, a serial to parallel converter **210**, a fast Fourier transform (FFT) block **212**, a channel estimation and equalization block **214**, a parallel to serial converter **216**, and a signal demapper **218**. The receiver end **200** performs the inverse of the transmitter end **100**. After transmitting through channel **150**, the signal is received by the RF receiver **202** with carrier frequency fc'. The received signal is then passed to the sampler **204** and sampled. Then the data samples are compensated for carrier frequency offset (CFO) with the CFO correction block **226** inside the synchronization block **206** wherein the CFO is caused from the difference between carrier frequency of transmitter end **100** and receiver end **200** (fc and fc'). The other function blocks inside the synchronization block **206** are frame detection block **220** and timing synchronization block **224**. Frame detection is to detect the symbol frame of the data samples, and timing synchronization is to detect the symbol boundary of the data samples inside data frame. The receiver end **200** has to determine the symbol boundary to assure that only the signal part of every OFDM symbol is written into the FFT and no part of the cyclic prefix. Implementing timing synchronization can also avoid Inter Symbol Interference (ISI) caused by sampling timing errors. After the cyclic prefix of symbols are removed with the CP removal block **208**, the data samples are converted from serial to parallel, and applied to the FFT block **212**. The Fast Fourier Transform (FFT) converts the time domain samples back into a frequency domain. Because the signal through channel **150** has suffered from frequency selective attenuation, the data samples are passed to the channel estimation and equalization block **214** for equalizing the attenuation. The parallel to serial converter block **216** converts the parallel data samples into a serial data stream. Finally, the data stream is demodulated with a QAM or BPSK scheme by signal demapper **218** to recover the original input data.

[0006] There are many sources of the frequency offset in wireless systems. The main sources are the difference between local oscillators at the transmitter and the receiver and the Doppler shift. Frequency offset destroys the orthogonality between the OFDM symbol subcarriers and introduces inter-channel interference (ICI) at the output of the OFDM demodulator. Therefore, the CFO correction block **226** shown in FIG. **2** is required to compensate the samples for CFO. The preamble of an OFDM packet specified by the

IEEE standard consists of 10 identical short training symbols (each containing 16 data samples) and two identical long training symbols (each containing 64 data samples). These symbols can be used for the CFO estimation in the conventional method. The CFO is estimated based on some repeated training symbols with structures that are different due to CFO from ideal structures. The conventional method of the frequency offset estimation uses equations based on maximum likelihood (ML) criterion. These equations perform the search for the maximum of the correlation between the received training symbols or their functions to derive CFO. However, there is still some remnant CFO not compensated for in the conventional method. Because the OFDM system is far more vulnerable to the carrier frequency offset than single-carrier systems, even the remnant CFO of a small fraction of the subcarrier spacing can cause serious performance degradation if not properly compensated.

[0007] FIG. **3** shows an equalizer **300** for implementing channel equalization in the conventional method. The equalizer **300** is one embodiment of the channel estimation and equalization block **214** shown in FIG. **2**. Channel equalization compensates for channel distortion caused from multipath fading channels, which introduce inter-symbol interference (ISI) in the received signal. To remove ISI from the signal, the equalizer **300** require knowledge about the channel impulse response H_k, which can be provided by a channel estimator **302**. The suffix k represents the order of the sub-carriers, and channel estimation in OFDM is typically done by using a simple estimation technique in the frequency domain independently in all the sub-carriers. The reciprocal circuit **304** then generates the reciprocal R_k of the channel impulse response H_k. Assume the equalizer **300** receives signal Y_k from FFT block **212**, the equalization circuit **306** can then use the reciprocal R_k of the channel impulse response H_k to compensate the signal Y_k for channel distortion to generate a signal X_k. However, if the estimate of channel impulse response H_k is not accurate enough, the signal X_k will not reflect the original signal in the transmitter end. Thus there is a need for a method to obtain more accurate estimation of the channel impulse response H_k.

SUMMARY

[0008] It is therefore an object of the present invention to provide a circuit for improving accuracy of channel impulse response estimation and compensating for remnant frequency offset in a receiver of an orthogonal frequency division multiplexing (OFDM) system.

[0009] An embodiment of a circuit for improving accuracy of channel impulse response estimation and compensating for remnant frequency offset is provided. The circuit comprises an equalizer, for compensating a first signal for channel distortion with the channel impulse response estimate to generate a second signal. The circuit also comprises a remnant frequency compensation module, coupled to the equalizer, for rotating a phase of the second signal with a phase angle of phase offset coefficient calculated according to a plurality of pilot signals of the second signal to generate a third signal. The circuit further comprises a error estimation module, coupled to the remnant frequency compensation module, for generating an error estimate according to the third signal and its hard decision estimate, and the error estimate is further fed back to the equalizer to refine the channel impulse response estimate.

[0010] In another provided embodiment of a circuit for improving accuracy of channel impulse response estimation, the circuit comprises an equalizer, for compensating a first signal for channel distortion with the channel impulse response estimate to generate a second signal. The circuit also comprises an error estimation module, coupled to the equalizer, for generating an error estimate according to a hard decision estimate of the second signal and the first signal. Then the error estimate is further fed back to the equalizer to refine the channel impulse response estimate.

[0011] In another provided embodiment of a circuit for compensating for remnant frequency offset, the circuit comprises an equalizer, for compensating a first signal for channel distortion with the channel impulse response estimate to generate a second signal. The circuit also comprises a remnant frequency compensation module, coupled to the equalizer, for rotating a phase of the second signal with a phase angle of an phase offset coefficient calculated according to a plurality of pilot signals of the second signal to generate a third signal.

DESCRIPTION OF THE DRAWINGS

[0012] The invention can be more fully understood by reading the subsequent detailed description in conjunction with the examples and references made to the accompanying drawings, wherein:

[0013] FIG. **1** illustrates the main function blocks of the transmitter end of the OFDM baseband processor according to the IEEE 802.11a standard;

[0014] FIG. **2** illustrates the main function blocks of receiver end of the OFDM baseband processor according to the IEEE 802.11a standard;

[0015] FIG. **3** shows an equalizer to implement channel equalization in the conventional method;

[0016] FIG. **4** illustrates the main function blocks of a circuit for channel equalization with improved channel impulse response estimation accuracy according to an embodiment of the present disclosure;

[0017] FIG. **5** illustrates the main function blocks of a circuit for channel equalization with remnant frequency offset compensation according to an embodiment of the present disclosure;

[0018] FIG. **6** illustrates the main function blocks of a circuit for channel equalization with improved channel frequency response accuracy and remnant frequency offset compensation according to an embodiment of the present disclosure;

[0019] FIG. **7** illustrates the main function blocks of a circuit for channel equalization with improved channel frequency response accuracy and remnant frequency offset compensation according to another embodiment of the present disclosure.

DETAILED DESCRIPTION

[0020] FIG. **4** illustrates the main function blocks of a circuit **400** for channel equalization with improved channel impulse response estimation accuracy according to an embodiment of the present disclosure, and the circuit **400** comprises an equalizer **450** and an error estimation module

470. Equalizer **450** resembles the equalizer **300** shown in FIG. **3**, but the error estimation module **470** is provided for improving the channel impuse response estimation accuracy. The error estimation module **470** uses a hard-decision equation to generate a hard-decision estimate of the equalized signal, which is fed back to the next iteration of the estimation of channel impulse response on the next sub-carrier to improve its accuracy.

[**0021**] Because the equalizer **450** processes frequency domain data, samples of the received signal are delivered to a FFT block **212** to perform fast Fourier transformation and convert the samples on the k-th sub-carrier to frequency domain signal Y_k, wherein the suffix k represents the order of sub-carrier. The equalizer **450** includes a channel estimator **402**, an update circuit **410**, a reciprocal circuit **404**, and an equalization circuit **406**. First, channel estimator **402** generates an estimate H' of the channel impulse response. An update circuit **410** then generates a revised estimate $H_{k(n)}$ of channel impulse response of the k-th sub-carrier at current time index n according to an error estimate $E_{k(n-1)}$ and a channel impulse response estimate $H_{k(n-1)}$ of the k-th sub-carrier at the last time index n−1 with the following equation:

$$H_{k(n)}=H_{k(n-1)}+u\times E_{k(n-1)}\times \mathrm{conj}(X_{k,HD(n-1)}),$$

wherein the parameter n in the parentheses represents the time index of the OFDM symbols. The estimate H' of the channel impulse response from the channel estimator **402** is used as the initial value $H_{k(0)}$ of the channel impulse response of of the k-th sub-carrier to generate the $H_{k(1)}$ and the estimates at the following time index by iteration. u is a predetermined constant, $E_{k(n-1)}$ is an error estimate at the last time index generated from an error circuit **414**, and conj $(X_{k(n-1)})$ is the conjugate of a signal $X_{k(n-1)}$ at the last time index generated from the equalization circuit **406**. The error estimate $E_{k(n-1)}$ and signal $Z_{k(n-1)}$ is further described in the following. The reciprocal circuit **404** can then generate the reciprocal R_k of the revised channel impulse response estimate H_k.

[**0022**] Equalization circuit **406** compensates the signal Y_k for channel distortion with the reciprocal R_k to generate a signal X_k. Signal X_k is then fed to the error estimation module **470**, which includes a hard decision module **412** and an error circuit **414**. The hard decision circuit **412** use a hard decision equation to generate a hard decision estimate $X_{k,HD}$ of the signal X_k. Thus, the error circuit **414** can calculate an error estimate Ek between signal X_k and its hard decision estimate $X_{k,HD}$ according the following equation:

$$E_{k(n)}=(X_{k(n)}-X_{k,HD(n)})\times H_{k(n)},$$

wherein the parameter n in the parentheses represents the time index of the OFDM symbols. The error estimate $E_{k(n)}$ is delivered to the update circuit **410** for improving the precision of the channel impulse response estimate $H_{k(n+1)}$ of the next time index of the OFDM symbols. In equalizer **400** the hard decision block **412**, error circuit **414**, and update circuit **410** are added to refine the estimate of channel impulse response, and the hard decision estimate is fed back to the update circuit **410** to generate a more precise channel impulse response estimate through iteration. Thus, performance of circuit **400** is better than that of circuit **300** shown in FIG. **3**.

[**0023**] FIG. **5** illustrates the main function blocks of a circuit **500** for channel equalization with the remnant frequency offset compensation according to another embodiment of the present disclosure. The circuit **500** includes an equalizer **550** and a remnant frequency compensation module **560**. Equalizer **550** resembles the equalizer **300** shown in FIG. **3**, but a remnant frequency compensation module **560** is provided for remnant frequency offset compensation in frequency domain. The remnant frequency compensation module **560** uses a frequency rotor circuit for remnant frequency offset compensation by means of utilizing the phase of the pilot signals.

[**0024**] Because the equalizer **550** processes frequency domain data, samples of received signals are delivered to an FFT block **212** to perform fast Fourier transformation and convert the samples on the k-th sub-carrier to frequency domain signal Y_k, wherein the suffix k represents the order of sub-carriers. The equalizer **550** includes a channel estimator **502**, a reciprocal circuit **504**, and an equalization circuit **506**. First, channel estimator **502** generates an estimate H_k of the channel impulse response of the k-th sub-carrier. The reciprocal circuit **504** can then generate the reciprocal R_k of the revised channel impulse response estimate H_k'. Equalization circuit **506** then compensates the signal Y_k for channel distortion with the reciprocal R_k to generate a signal X_k.

[**0025**] Signal X_k is then fed to the remnant frequency compensation module **560**, which includes a pilot phase calculation circuit **520** and a frequency rotor circuit **522**.The pilot phase calculation circuit **520** can calculate phase offset coefficient $P_{(n)}$ with the prior symbol of the pilot signal $X_{pilot,j}$, which is actually the signal X_k on the pilot sub-carriers with specific suffix k, and suffix j ranges from 1 to 4 because there are four pilot sub-carriers in the OFDM system. The phase offset coefficient $P_{(n)}$ is calculated according to the following equation:

$$P_{(n)}=\mathrm{angle}\left(\sum_{j=1}^{4}[|H_{pilot,j(n)}|^2\times(X_{pilot,j(n)}-X_{pilot,j(n-1)})]\right),$$

wherein $X_{pilot,j(n)}$ is the sample of j-th pilot signal of the signal X at the current time index n, $X_{pilot,j(n-1)}$ is the sample of the j-th pilot signal of the signal X at the last time index n−1, and $H_{pilot,j(n)}$ is the estimate of the channel impulse response of the j-th pilot sub-carrier at current time index n.

[**0026**] The frequency rotor circuit **522** rotates the phase of the signal X_k with the phase angle of the phase offset coefficient $P_{(n)}$ calculated from samples of pilot signals to generate a signal Z_k. The frequency rotor circuit **522** generates signal Z_k according to the following equation:

$$Z_{k(n)}=X_{k(n)}\times\exp(j\times P_{(n)}),$$

wherein the parameter n in the parentheses represents the time index of the OFDM symbols, exp( ) is the exponential function, and the signal Z_k is the signal compensated for remnant frequency offset.

[**0027**] FIG. **6** illustrates the main function blocks of a circuit **600** for channel equalization with improved channel frequency response accuracy and remnant frequency offset compensation according to another embodiment of the present disclosure. The circuit **600** includes an equalizer **650**, a remnant frequency compensation module **660** and an error estimation module **670**.

[0028] Equalizer **650** resembles the equalizer **300** shown in FIG. **3**, but the circuit **400** is combined with the circuit **500** by introducing both a remnant frequency compensation module **660** and an error estimation module **670** for improving the accuracy of channel impulse response and compensating for remnant frequency offset, respectively.

[0029] Because the equalizer **650** processes frequency domain data, samples of received signal are delivered to a FFT block **212** to perform fast Fourier transformation and convert the samples on the k-th sub-carrier to frequency domain signal Y_k, wherein the suffix k represents the order of sub-carrier. The equalizer **650** includes a channel estimator **602**, an update circuit **610**, a reciprocal circuit **604**, and an equalization circuit **606**. First, channel estimator **602** generates an estimate H' of the channel impulse response. An update circuit **610** then generates a revised estimate $H_{k(n)}$ of channel impulse response of the k-th sub-carrier at current time index n according to an error estimate $E_{k(n-1)}$ and a channel impulse response estimate $H_{k(n-1)}$ of the k-th sub-carrier at the last time index n−1 with the following equation:

$$H_{k(n)}=H_{k(n-1)}+u\times E_{k(n-)}\times \mathrm{conj}(Z_{k,HD(n-1)}),$$

[0030] wherein the parameter n in the parentheses represents the time index of the OFDM symbols. The estimate H' of the channel impulse response from the channel estimator **602** is used as the initial value $H_{k(0)}$ of the channel impulse response of of the k-th sub-carrier to generate the $H_{k(1)}$ and the estimates at the following time index by iteration. u is a predetermined constant, $E_{k(n-1)}$ is an error estimate at the last time index generated from an error circuit **614**, and conj $(Z_{k(n-1)})$ is the conjugate of a signal $Z_{k(n-1)}$ at the last time index generated from the equalization circuit **606**. The error estimate $E_{k(n-1)}$ and signal $Z_{k(n-1)}$ is further described in the following. The reciprocal circuit **604** can then generate the reciprocal R_k Of the revised channel impulse response estimate H_k. Equalization circuit **606** then compensates the signal Y_k for channel distortion with the reciprocal R_k to generate a signal X_k.

[0031] Signal X_k is then fed to the remnant frequency compensation module **660**, which includes a pilot phase calculation circuit **620** and a frequency rotor circuit **622**. The pilot phase calculation circuit **620** can calculate phase offset coefficient $P_{(n)}$ with the prior symbol of the pilot signal $X_{pilot,j}$, which is actually the signal X_k on the pilot sub-carriers with specific suffix k, and suffix j ranges from 1 to 4 because there are four pilot sub-carriers in the OFDM system. The phase offset coefficient $P_{(n)}$ is calculated according to the following equation:

$$P_{(n)} = \mathrm{angle}\left(\sum_{j=1}^{4}\left[|H_{pilot,j(n)}|^2\times(X_{pilot,j(n)}-X_{pilot,j(n-1)})\right]\right),$$

wherein $X_{pilot,j(n)}$ is the sample of j-th pilot signal of the signal X at the current time index n, $X_{pilot,j(n-1)}$ is the sample of the j-th pilot signal of the signal X at the last time index n−1, and $H_{pilot,j(n)}$ is the estimate of the channel impulse response of the j-th pilot sub-carrier at current time index n.

[0032] The frequency rotor circuit **622** rotates the phase of the signal X_k with the phase angle of the phase offset coefficient $P_{(n)}$ calculated from samples of pilot signals to generate a signal Z_k. The frequency rotor circuit **622** generates signal Z_k according to the following equation:

$$Z_{k(n)}=X_{k(n)}\times\exp(j\times P_{(n)}),$$

wherein the parameter n in the parentheses represents the time index of the samples, exp( ) is the exponential function, and the signal Z_k is the signal compensated for remnant frequency offset.

[0033] Signal Z_k is then fed to the error estimation module **670**, which includes a hard decision module **612** and an error circuit **614**. The hard decision circuit **612** adopts a hard decision equation to generate a hard decision estimate $Z_{k,HD}$ of the signal Z_k. Thus, the error circuit **614** can calculate an error estimate E_k between signal Z_k and its hard decision estimate $Z_{k,HD}$ according the following equation:

$$E_{k(n)}=(Z_{k(n)}-Z_{k,HD(n)})\times H_{k(n)},$$

wherein the parameter n in the parentheses represents the time index of the samples. The error estimate E_k is delivered to the update circuit **610** for improving the precision of the channel impulse response estimate $H_{k(n+1)}$ at the next time index. In equalizer **600** the pilot phase calculation circuit **620** and frequency rotor circuit **622** are added to compensate for remnant frequency offset by means of utilizing the phase of the pilot signals. The hard decision block **612**, error circuit **614**, and update circuit **610** are also added to refine the estimate of channel impulse response, and the hard decision estimate is fed back to the update circuit **610** to generate a more precise channel impulse response estimate through iterations. Thus, the performance of circuit **600** is better than that of circuit **300** shown in FIG. **3**.

[0034] Refer now to FIG. **7**, which illustrates the main function blocks of a circuit **700** for channel equalization with improved channel frequency response accuracy and remnant frequency offset compensation according to another embodiment of the present disclosure. The circuit **700** includes an equalizer **750**, a remnant frequency compensation module **760** and an error estimation module **770**. Circuit **700** resembles the circuit **600** shown in FIG. **6**, because it combines the circuit **400** with the circuit **500** by introducing both a remnant frequency compensation module **760** and an error estimation module **770** for improving the accuracy of channel impulse response and compensating for remnant frequency offset, respectively. It differs from the circuit **600** slightly in that the function performed by the pilot phase calculation circuit **720**.

[0035] Because the equalizer **750** processes frequency domain data, samples of received signal are delivered to a FFT block **212** to perform fast Fourier transformation and convert the samples on the k-th sub-carrier to frequency domain signal Y_k, wherein the suffix k represents the order of sub-carrier. The equalizer **750** includes a channel estimator **702**, an update circuit **710**, a reciprocal circuit **704**, and an equalization circuit **706**. First, channel estimator **702** generates an estimate H' of the channel impulse response. An update circuit **710** then generates a revised estimate $H_{k(n)}$ of channel impulse response of the k-th sub-carrier at current time index n according to an error estimate $E_{k(n-1)}$ and a channel impulse response estimate $H_{k(n-1)}$ of the k-th sub-carrier at the last time index n−1 with the following equation:

$$H_{k(n)}=H_{k(n-1)}+u\times E_{k(n-1)}\times \mathrm{conj}(Z_{k,HD(n-1)}),$$

[0036] wherein the parameter n in the parentheses represents the time index of the OFDM symbols. The estimate H' of the channel impulse response from the channel estimator **702** is used as the initial value $H_{k(0)}$ of the channel impulse response of of the k-th sub-carrier to generate the $H_{k(1)}$ and the estimates at the following time index by iteration. u is a predetermined constant, $E_{k(n-1)}$ is an error estimate at the last time index generated from an error circuit **714**, and conj $(Z_{k(n-1)})$ is the conjugate of a signal $Z_{k(n-1)}$ at the last time index generated from the equalization circuit **706**. The error estimate $E_{k(n-1)}$ and signal $Z_{k(n-1)}$ is further described in the following. Then, the reciprocal circuit **704** can generate the reciprocal R_k of the revised channel impulse response estimate H_k. Equalization circuit **706** then compensates the signal Y_k for channel distortion with the reciprocal R_k to generate a signal X_k.

[0037] Signal X_k is then fed to the remnant frequency compensation module **760**, which includes a pilot phase calculation circuit **720** and a frequency rotor circuit **722**. The pilot phase calculation circuit **720** can calculate a phase offset coefficient $P_{(n-1)}$ with the pilot signal $Z_{pilot,j}$ and a hard decision estimate of the pilot signal $Z_{pilotHD,j}$. The pilot signal $Z_{pilot,j}$ is actually the signal Z_k on the pilot sub-carriers with specific suffix k, and suffix j ranges from 1 to 4 because there are four pilot sub-carriers in the OFDM system. The phase offset coefficient $P_{(n)}$ is calculated according to the following equation:

$$P_{(n)} = \text{angle}\left(\sum_{j=1}^{4} Z_{pilot,j(n-1)} \times conj(Z_{pilotHD,j(n-1)}) \times |H_{pilot,j(n)}|^2\right),$$

wherein $Z_{pilot,j(n-1)}$ is the sample of the j-th pilot signal of the signal Z at time index n−1, $Z_{pilotHD,j(n-1)}$ is a hard decision estimate of the sample of the j-th pilot signal of the signal Z at time index n−1, conj( ) is the conjugate function, and $H_{pilot,j(n)}$ is the channel impulse response estimate of the j-th pilot sub-carrier.

[0038] The frequency rotor circuit **722** rotates the phase of the signal X_k with the phase angle of the phase offset coefficient $P_{(n)}$ calculated from samples of pilot signals at last time index to generate a signal Z_k. The frequency rotor circuit **722** generates signal Z_k according to the following equation:

$$Z_{k(n)}=X_{k(n)}\times\exp(j\times P_{(n)}),$$

wherein the parameter n in the parentheses represents the time index of the samples, exp( ) is the exponential function, and the signal Z_k is the signal compensated for remnant frequency offset.

[0039] Then, signal Z_k is fed to the error estimation module **770**, which includes a hard decision module **712** and an error circuit **714**. The hard decision circuit **712** adopts a hard decision equation to generate a hard decision estimate $Z_{k,HD}$ of the signal Z_k. Thus, the error circuit **714** can calculate an error estimate E_k between signal Z_k and its hard decision estimate $Z_{k,HD}$ according the following equation:

$$E_{k(n)}=(Z_{k(n)-Zk,HD(n)})\times H_{k(n)},$$

wherein the parameter n in the parentheses represents the time index of the samples. The error estimate E_k is delivered to the update circuit **710** for improving the precision of the channel impulse response estimate $H_{k(n+1)}$ at the next time index. In equalizer **700** the pilot phase calculation circuit **720** and frequency rotor circuit **722** are added to compensate for remnant frequency offset by means of utilizing the phase of the pilot signals. The hard decision block **712**, error circuit **714**, and update circuit **710** are also added to refine the estimate of channel impulse response, and the hard decision estimate is fed back to the update circuit **710** to generate a more precise channel impulse response estimate through iterations. Thus, performance of circuit **700** is better than that of circuit **300** shown in FIG. **3**.

[0040] In this disclosure, we provide a simple method for estimating channel impulse response accurately and canceling the remnant effects of frequency offset in the wireless LAN environment. Because the equalization is more precise, the overall performance of the OFDM baseband receiver can be improved.

[0041] Finally, while the invention has been described by way of example and in terms of the above, it is to be understood that the invention is not limited to the disclosed embodiment. On the contrary, it is intended to cover various modifications and similar arrangements as would be apparent to those skilled in the art. Therefore, the scope of the appended claims should be accorded the broadest interpretation so as to encompass all such modifications and similar arrangements.

What is claimed is:

1. A circuit for improving accuracy of channel impulse response estimation and compensating for remnant frequency offset in a receiver of an orthogonal frequency division multiplexing (OFDM) system, the circuit comprising:

an equalizer, for compensating a first signal for channel distortion with the channel impulse response estimate to generate a second signal;

a remnant frequency compensation module, coupled to the equalizer, for rotating a phase of the second signal with a phase angle of an phase offset coefficient calculated according to a plurality of pilot signals of the second signal to generate a third signal;

a error estimation module, coupled to the remnant frequency compensation module, for generating an error estimate according to the third signal and a hard decision estimate of the third signal, and the error estimate is further fed back to the equalizer to refine the channel impulse response estimate.

2. The circuit according to claim 1, wherein the remnant frequency compensation module includes:

a pilot phase calculation circuit, coupled to the equalizer, for calculating the phase offset coefficient according to the plurality of pilot signals of the second signal;

a frequency rotor circuit, coupled to the equalizer and the pilot phase calculation circuit, for rotating the phase of the second signal by the angle of the phase offset coefficient to generate the third signal.

3. The circuit according to claim 2, wherein the pilot phase calculation circuit calculates the phase offset coefficient according to a following equation:

$$P_{(n)} = \text{angle}\left(\sum_{j=1}^{4} [|H_{pilot,j(n)}|^2 \times (X_{pilot,j(n)} - X_{pilot,j(n-1)})]\right)$$

wherein the suffix j represents an order of a plurality of pilot subcarriers, and the parameter n represents an OFDM symbol time index, $P_{(n)}$ is the phase offset coefficient at a current time index n, $X_{pilot,j(n)}$ is a j-th pilot signal of the second signal X at the current time index n, $X_{pilot,j(n-1)}$ is the j-th pilot signal of the second signal X at a last time index n−1, and $H_{pilot,j(n)}$ is the channel impulse response estimate of the j-th pilot sub-carrier at the current time index n.

4. The circuit according to claim 2, wherein the pilot phase calculation circuit is further coupled to the frequency rotor circuit and an error estimation module which generates the hard decision estimate of the third signal, and the pilot phase calculation circuit generates the phase offset coefficient according to a following equation:

$$P_{(n)} = \text{angle}\left(\sum_{j=1}^{4} Z_{pilot,j(n-1)} \times conj(Z_{pilotHD,j(n-1)}) \times |H_{pilot,j(n)}|^2\right)$$

wherein the suffix j represents an order of a plurality of pilot subcarriers, and the parameter n represents an OFDM symbol time index, $P_{(n)}$ is the phase offset coefficient at a current time index n, $Z_{pilot,j(n-1)}$ is a j-th pilot signal of the third signal at a last time index n−1, $Z_{HDpilot,j(n-1)}$ is a hard decision estimate of the j-th pilot signal of the third signal at the last time

index n−1, conj( ) is a conjugate function, and $H_{pilot,j(n)}$ is a channel impulse response estimate of a j-th pilot subcarrier.

5. The circuit according to claim 2, wherein the frequency rotor circuit generates the third signal according to the following equation:

$$Z_{k(n)}=X_{k(n)}\times X \exp(j\times P_{(n)});$$

wherein the parameter n represents an OFDM symbol time index, Z(n) is the third signal at a time index n, $X_{(n)}$ is the second signal at the time index n, exp( ) is an exponential function, and $P_{(n)}$ is the phase offset coefficient at a time index n.

6. The circuit according to claim 1, wherein the error estimation module includes:

a hard decision circuit, coupled to the equalizer, for estimating the hard decision estimate of the third signal;

an error circuit, coupled to the hard decision circuit and the equalizer, for calculating the error estimate according to the hard decision estimate and the third signal.

7. The circuit according to claim 6, wherein the error circuit calculates the error estimate according to a following equation:

$$E_{k(n)}=(Z_{k(n)}-Z_{HD,k(n)})\times H_{k(n)},$$

wherein the suffix k represents an order of a plurality of subcarriers, and the parameter n represents an OFDM symbol time index, E is the error estimate, Z is the third signal, Z_{HD} is the hard decision estimate, and H is the channel impulse response estimate.

8. The circuit according to claim 1, wherein the equalizer includes:

a channel estimator, for estimating an initial channel impulse response estimate;

an update circuit, coupled to the channel estimator and the error estimation module, for adjusting the initial channel impulse response estimate with the error estimate to generate the channel impulse response estimate;

an equalization circuit, coupled to the update circuit, for compensating the first signal for channel distortion with the channel impulse response estimate to generate the second signal.

9. The circuit according to claim 8, wherein the update circuit generates the channel impulse response estimate according to a following equation:

$$H_{k(n)}=H_{k(n-1)}+u\times E_{k(n-1)}\times \text{conj}(Z_{k,HD(n-1)})$$

wherein the suffix-k represents an order of a plurality of subcarriers, $H_{k(n)}$ is the channel impulse response estimate of a k-th subcarrier at a current time index n, $H_{k(n-1)}$ is the channel impulse response estimate of a k-th subcarrier at a last time index n-1, u is a constant, $E_{k(n-1)}$ is an error estimate of the k-th subcarrier at the last time index n−1, conj ($Z_{k,HD(n-1)}$) is a conjugate of a hard decision estimate $Z_{k,HD}$ of the third signal Z_k on the k-th subcarrier at the last time index n−1, and the initial channel impulse response estimate generated from the channel estimator is used as an initial value $H_{k(0)}$ of the channel impulse response of of the k-th sub-carrier to generate the the channel impulse response estimate $H_{k(1)}$ at a first time index.

10. The circuit according to claim 8, wherein the equalization circuit compensates the first signal for channel distortion according to the following equation:

$$X_{k(n)}=Y_{k(n)}/H_{k(n)};$$

wherein the suffix j represents an order of a plurality of pilot subcarriers, and the parameter n represents an OFDM symbol time index, $X_{k(n)}$ is the second signal, $Y_{k(n)}$ is the first signal, and $H_{k(n)}$ is the channel impulse response estimate.

11. A circuit for improving accuracy of channel impulse response estimation in a receiver of an orthogonal frequency division multiplexing (OFDM) system, the circuit comprising:

an equalizer, for compensating a first signal for channel distortion with the channel impulse response estimate to generate a second signal;

an error estimation module, coupled to the equalizer, for generating an error estimate according to the second signal and a hard decision estimate of the the second signal, and the error estimate is further fed back to the equalizer to refine the channel impulse response estimate.

12. The circuit according to claim 11, wherein the error estimation module includes:

a hard decision circuit, coupled to the equalizer, for estimating the hard decision estimate of the second signal;

an error circuit, coupled to the hard decision circuit and the equalizer, for calculating the error estimate

according to the hard decision estimate and the second signal.

13. The circuit according to claim 12, wherein the error circuit calculates the error estimate according to a following equation:

$$E_{k(n)}=(X_{k(n)}-X_{HD,k(n)})\times H_{k(n)},$$

wherein the suffix k represents an order of a plurality of subcarriers, and the parameter n represents an OFDM symbol time index, E is the error estimate, X is the second signal, X_{HD} is the hard decision estimate, and H is the channel impulse response estimate.

14. The circuit according to claim 11, wherein the equalizer includes:

a channel estimator, for estimating an initial channel impulse response estimate;

an update circuit, coupled to the channel estimator and the error estimation module, for adjusting the initial channel impulse response estimate with the error estimate to generate the channel impulse response estimate;

an equalization circuit, coupled to the update circuit, for compensating the first signal for channel distortion with the channel impulse response estimate to generate the second signal.

15. The circuit according to claim 14, wherein the update circuit generates the channel impulse response estimate according to a following equation:

$$H_{k(n)}=H_{k(n-)}+u\times E_{k(n-1)}\times \mathrm{conj}(X_{k,HD(n-1)})$$

wherein the suffix k represents an order of a plurality of subcarriers, $H_{k(n)}$ is the channel impulse response estimate of a k-th subcarrier at a current time index n, $H_{k(n-1)}$ is the channel impulse response estimate of a k-th subcarrier at a last time index n−1, u is a constant, $E_{k(n-1)}$ is an error estimate of the k-th subcarrier at the last time index n−1, conj ($X_{k,HD(n-1)}$) is a conjugate of a hard decision estimate $X_{k,HD}$ of the second signal X_k on the k-th subcarrier at the last time index n−1, and the initial channel impulse response estimate generated from the channel estimator is used as an initial value $H_{k(0)}$ of the channel impulse response of of the k-th sub-carrier to generate the the channel impulse response estimate $H_{k(1)}$ at a first time index.

16. The circuit according to claim 14, wherein the equalization circuit compensates the first signal for channel distortion according to the following equation:

$$X_{k(n)}=Y_{k(n)}/H_{k(n)};$$

wherein the suffix j represents an order of a plurality of pilot subcarriers, and the parameter n represents an OFDM symbol time index, $X_{k(n)}$ is the second signal, $Y_{k(n)}$ is the first signal, and $H_{k(n)}$ is the channel impulse response estimate.

17. A circuit for compensating for remnant frequency offset in a receiver of an orthogonal frequency division multiplexing (OFDM) system, the circuit comprising:

an equalizer, for compensating a first signal for channel distortion with a channel impulse response estimate to generate a second signal;

a remnant frequency compensation module, coupled to the equalizer, for rotating a phase of the second signal with a phase angle of an phase offset coefficient calculated according to a plurality of pilot signals of the second signal to generate a third signal.

18. The circuit according to claim 17, wherein the remnant frequency compensation module includes:

a pilot phase calculation circuit, coupled to the equalizer, for calculating the phase offset coefficient according to the plurality of pilot signals of the second signal; and

a frequency rotor circuit, coupled to the equalizer and the pilot phase calculation circuit, for rotating the phase of the second signal by the angle of the phase offset coefficient to generate the third signal.

19. The circuit according to claim 18, wherein the pilot phase calculation circuit calculates the phase offset coefficient according to a following equation:

$$P_{(n)}=\mathrm{angle}\left(\sum_{j=1}^{4}[|H_{pilot,j(n)}|^2\times(X_{pilot,j(n)}-X_{pilot,j(n-1)})]\right)$$

wherein the suffix j represents an order of a plurality of pilot subcarriers, and the parameter n represents an OFDM symbol time index, $P_{(n)}$ is the phase offset coefficient at a current time index n, $X_{pilot,j(n)}$ is a j-th pilot signal of the second signal X at the current time index n, $X_{pilot,j(n-1)}$ is the j-th pilot signal of the second signal X at a last time index n−1, and $H_{pilot,j(n)}$ is the channel impulse response estimate of the j-th pilot sub-carrier at the current time index n.

20. The circuit according to claim 18, wherein the pilot phase calculation circuit is further coupled to the frequency rotor circuit and an error estimation module which generates a hard decision estimate of the third signal, and the pilot phase calculation circuit generates the phase offset coefficient according to a following equation:

$$P_{(n)}=\mathrm{angle}\left(\sum_{j=1}^{4}Z_{pilot,j(n-1)}\times conj(Z_{pilotHD,j(n-1)})\times|H_{pilot,j(n)}|^2\right)$$

wherein the suffix j represents an order of a plurality of pilot subcarriers, and the parameter n represents an OFDM symbol time index, $P_{(n)}$ is the phase offset coefficient at a current time index n, $Z_{pilot,j(n-1)}$ is a j-th pilot signal of the third signal at a last time index n−1, $Z_{HDpilot,j(n-1)}$ is a hard decision estimate of the j-th pilot signal of the third signal at the last time index n−1, conj( ) is a conjugate function, and $H_{pilot,j(n)}$ is a channel impulse response estimate of a j-th pilot subcarrier.

21. The circuit according to claim 18, wherein the frequency rotor circuit generates the third signal according to the following equation:

$$Z_{k(n)}=X_{k(n)}\times\exp(j\times P_{(n)});$$

wherein the parameter n represents an OFDM symbol time index, Z(n) is the third signal at a current time index n, $X_{(n)}$ is the second signal at the current time

index n, exp( ) is an exponential function, and $P_{(n)}$ is the phase offset coefficient at the current time index n.

22. The circuit according to claim 17, wherein the equalizer includes:

a channel estimator, for estimating an initial channel impulse response estimate;

an equalization circuit, coupled to the channel estimator, for compensating the first signal for channel distortion with the initial channel impulse response estimate to generate the second signal.

23. The circuit according to claim 22, wherein the equalization circuit compensates the first signal for channel distortion according to the following equation:

$$X_{k(n)}=Y_{k(n)}/H_{k(n)};$$

wherein the suffix j represents an order of a plurality of pilot subcarriers, and the parameter n represents an OFDM symbol time index, $X_{k(n)}$ is the second signal, $Y_{k(n)}$ is the first signal, and $H_{k(n)}$ is the channel impulse response estimate.

* * * * *