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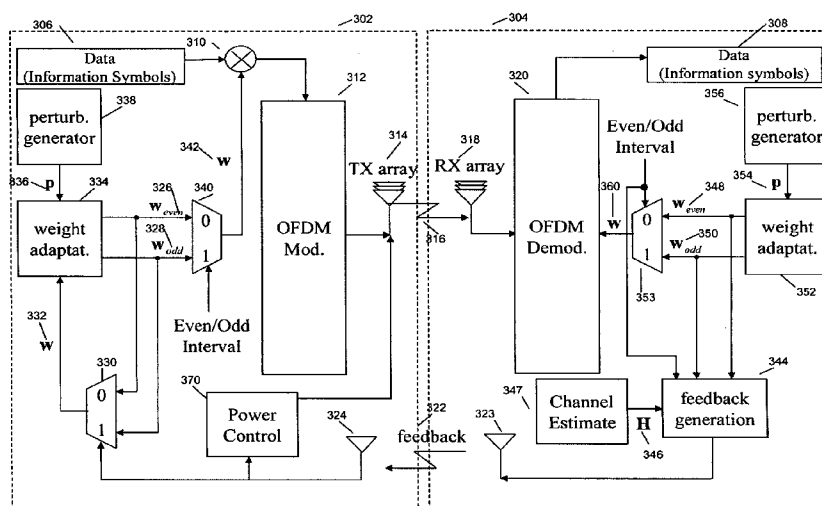


FIG. 3

(57) Abstract: Methods and systems for providing feedback for beamforming and power control are provided. In some embodiments, the methods comprise: calculating a threshold associated with a subcarrier; receiving the subcarrier containing an information symbol at the receiver; determining a channel estimate of the subcarrier and a weighting vector for the information symbol; based at least on the channel estimate and the weighting vector, determining a power level of the subcarrier; comparing the power level to the threshold; generating a feedback signal indicating a first energy level to be used for the subcarrier based on the comparison; subsequent to generating the feedback signal, determining a second power level of the subcarrier; comparing the second power level to the threshold; and generating a second feedback signal to the transmitter indicating a second energy level to be used for the subcarrier.

METHODS AND SYSTEMS FOR PROVIDING FEEDBACK FOR BEAMFORMING AND POWER CONTROL

Cross Reference to Related Application

[0001] This application claims the benefit of United States Provisional Patent Application No. 60/936,340, filed June 19, 2007, which is hereby incorporated by reference herein in its entirety.

Technical Field

[0002] The disclosed subject matter relates to methods and systems for providing feedback for beamforming and power control.

Background

[0003] Digital wireless communication systems have gained widespread adoption in recent years. Common examples of digital wireless communication systems include wireless routers, which are frequently made according to the IEEE 802.11 standards, and mobile telephones.

[0004] A common problem with digital communication systems is multi-path fading as multiple copies of a signal propagate from a transmitter to a receiver via different paths. For example, one copy of a signal can propagate via a straight line between a transmitter and a receiver and another copy can propagate via a reflection off a structure between the transmitter and the receiver. Because the two copies of the signals are taking different paths, the copies will be out of phase when they reach the receiver. This can result in constructive or destructive interference. As a receiver moves relative to a fixed transmitter, the receiver will either pick up a stronger or weaker sum of the copies of the signal. This variation is fading in the signal.

[0005] To address multi-path fading problems, as well as other forms of signal degradation, orthogonal frequency divisional multiplexing (OFDM) has been adopted in many digital wireless systems. OFDM operates by sending digital signals across many different orthogonal subcarriers (or channels). Unlike some other forms of communication which attempt to send a large amount of data over a single carrier at high speed, OFDM

spreads the data across multiple subcarriers at lower speeds. This enables OFDM systems to be more robust to interference problems.

[0006] To further improve the performance of OFDM wireless systems, multiple-input and multiple-output (MIMO) configurations of OFDM systems have been adopted. In a typical configuration, a MIMO system may use two or more transmit antennas and two or more receive antennas. By controlling the signals being output on these transmit antennas, beamforming can be used to control the beam shape of the transmitted signal. By controlling the shape of the beam transmitted by the antennas, various forms of signal degradation, including multi-path fading, can be reduced.

Summary

[0007] Methods and systems for providing feedback for beamforming and power control are provided. In some embodiments, methods for controlling transmit-power between a wireless transmitter and a wireless receiver are provided, the methods comprising: calculating a threshold associated with a subcarrier between the transmitter and the receiver; receiving the subcarrier containing an information symbol at the receiver from the transmitter; determining a channel estimate of the subcarrier and a weighting vector for the information symbol; based at least on the channel estimate and the weighting vector, determining a power level of the subcarrier; comparing the power level to the threshold; generating a feedback signal to the transmitter indicating a first energy level to be used for the subcarrier based on the comparison of the power level to the threshold; subsequent to generating the feedback signal, determining a second power level of the subcarrier based at least on the channel estimate and the weighting vector; comparing the second power level to the threshold; and generating a second feedback signal to the transmitter indicating a second energy level to be used for the subcarrier based on the comparison of the second power level to the threshold.

[0008] In some embodiments, systems for controlling transmit-power from a wireless transmitter are provided, the systems comprising: a receiver that: calculates a threshold associated with a subcarrier between the transmitter and the receiver; receives the subcarrier containing an information symbol from the transmitter; determines a channel estimate of the subcarrier and a weighting vector for the information symbol; based at least on the channel estimate and the weighting vector, determines a power level of the subcarrier; compares the power level to the threshold; generates a feedback signal to the transmitter indicating a first

energy level to be used for the subcarrier based on the comparison of the power level to the threshold; subsequent to generating the feedback signal, determines a second power level of the subcarrier based at least on the channel estimate and the weighting vector; compares the second power level to the threshold; and generates a second feedback signal to the transmitter indicating a second energy level to be used for the subcarrier based on the comparison of the second power level to the threshold.

[0009] In some embodiments, systems for controlling transmit-power from a wireless transmitter are provided, the systems comprising: means for calculating a threshold associated with a subcarrier from the transmitter; means for receiving the subcarrier containing an information symbol from the transmitter; means for determining a channel estimate of the subcarrier and a weighting vector for the information symbol; means for determining a power level of the subcarrier based at least on the channel estimate and the weighting vector; means for comparing the power level to the threshold; means for generating a feedback signal to the transmitter indicating a first energy level to be used for the subcarrier based on the comparison of the power level to the threshold; means for determining a second power level of the subcarrier based at least on the channel estimate and the weighting vector subsequent to generating the feedback signal; means for comparing the second power level to the threshold; and means for generating a second feedback signal to the transmitter indicating a second energy level to be used for the subcarrier based on the comparison of the second power level to the threshold.

Brief Description of the Drawings

[0010] FIG. 1 is a diagram of a system for providing feedback for beamforming and power control in accordance with some embodiments.

[0011] FIG. 2 is a diagram of a mechanism for transmitting a signal in accordance with some embodiments.

[0012] FIG. 3 is a diagram of a system for providing feedback for beamforming in accordance with some embodiments.

[0013] FIG. 4 is a diagram of processes that can be performing in a transmitter and a receiver for providing and using feedback for beamforming in accordance with some embodiments.

[0014] FIG. 5 is a diagram of a process for determining a perturbation vector in accordance with some embodiments.

[0015] FIG. 6 is a graph illustrating a relationship between values of an adoption rate β used in updating weighting vectors and Bit Error Rates in accordance with some embodiments.

[0016] FIG. 7 is a diagram illustrating odd and even intervals containing information symbols and pilot symbols in accordance with some embodiments.

[0017] FIG. 8 is a diagram illustrating weighting vectors being applied to different subcarriers (or channels) during different time intervals in accordance with some embodiments.

[0018] FIG. 9 is a diagram of a process for determining energy levels and thresholds for power control in accordance with some embodiments.

Detailed Description

[0019] In accordance with various embodiments, as described in more detail below, mechanisms for providing feedback for updating beamforming weighting vectors and energy levels are provided. These mechanisms can be used in any suitable digital-wireless-communication application. For example, beamforming weighting vectors and energy levels can be applied to symbols being transmitted in wireless MIMO-OFDM systems to improve the performance of the transmissions, or in any other suitable systems (such as other types of MIMO systems). By updating these vectors and energy levels using feedback, the signal power seen by the receivers can be made to respond to dynamic environmental conditions.

[0020] As a more particular example, in some embodiments, after initializing a base weighting vector, odd and even weighting vectors can be formed. These odd and even weighting vectors can then be multiplexed with information symbols to be transmitted over various OFDM subcarriers during alternating odd and even intervals, and transmitted by a transmitter. At a receiver, channels estimates for each of the subcarriers can be formed (as known in the art) and used, along with the odd and even weighting vectors (which were locally generated), to form a feedback bit indicating which of the weighting vectors results in greater power at the receiver. This feedback bit can then be transmitted to the transmitter, where it can be used to update the base weighting vector. After updating the base weighting vector, the actions above can be repeated.

[0021] As another example, in some embodiments, additionally or alternatively to beamforming, the energy level(s) used to transmit symbols on one or more subcarriers from a transmitter can be controlled for a subcarrier or a group of subcarriers. These energy levels

can be updated using feedback from a receiver. The feedback can be generated by comparing the power seen by the receiver for a subcarrier channel to one or more thresholds. Based on how the power seen compares to the threshold(s), the receiver can instruct the transmitter to modify the power output for the corresponding subcarrier (or a group of subcarriers). When two energy levels and one threshold are used, the feedback signal can be implemented with a single bit.

[0022] For the purpose of illustration, various embodiments that implement a MIMO-OFDM system are described below, although the mechanisms described herein can be used in systems other than MIMO-OFDM systems.

[0023] For example, as illustrated in FIG. 1, a MIMO-OFDM system 100 can employ N_T transmit antennas 106 at a base station 102 and N_R receive antennas 108 at a mobile terminal 104 for down link transmissions. Separate feedback antenna 110 and 112 can be provided at the transmitter and receiver, respectively.

[0024] A block diagram of a transmitter 200 that can be used in some embodiments of such a system is illustrated in FIG. 2. The processing within transmitter 200 can be performed as follows. First, the input data stream 202 can be mapped into a sequence of M Phase-Shift Keying (PSK) or M Quadrature Amplitude Modulation (QAM) symbols by S/P & Mapper 204. Then, this sequence of symbols can be serial-to-parallel converted (also by S/P & Mapper 204), producing a series of non-overlapping blocks; where each block consists of N_u symbols and where N_u represents the number of useful subcarriers. Then, $N_{vc}=N-N_u$ virtual carriers can be inserted in each block by Virtual carrier insertion 206, resulting in an N -dimensional vector:

$$\mathbf{a} \triangleq [a_0, a_1, \dots, a_{N-1}]^T,$$

where a_n represents the channel symbol associated with the n -th subcarrier. These data blocks can then be fed to an adaptive beamforming mechanism 208 operating on a subcarrier-by-subcarrier basis. For the symbol transmitted over the n -th subcarrier, mechanism 208 can generate an N_T -dimensional complex weight vector:

$$\mathbf{w}_n \triangleq [w_{n,1}, w_{n,2}, \dots, w_{n,N_T}]^T,$$

where $w_{n,i}$ is the weight for the i -th transmit antenna 106. The signal transmitted from the N_T antennas 106 over the n -th subcarrier frequency is then $\mathbf{w}_n a_n$. This technique, employed for each subcarrier, can thus produce a parallel stream of N_T vectors (each consisting of N elements), which can then be fed to a bank of N_T OFDM modulators 210 where they can

undergo an N -th order inverse discrete Fourier transform (IDFT) by IDFT 212 followed by cyclic prefix insertion by CP 214, serial to parallel conversion and transmit filtering by P/S & $p(t)$ 216. Finally, the resultant signal can be transmitted by antennas 106.

[0025] In the following, for the purpose of illustration, it is assumed that N_{cp} is the cyclic prefix length, that the impulse response $p(t)$ of the transmit filter in P/S & $p(t)$ 216 is time-limited to the interval $(N_p T_s, N_p T_s)$ (where T_s is the channel symbol interval), and that the Fourier transform $P(f)$ of $p(t)$ is the root of a raised cosine with roll-off α , so that $N_u = \text{int}[N(1 - \alpha)]$.

[0026] The OFDM signal can be transmitted over a wide sense stationary uncorrelated scattering (WSS-US) multipath fading channel. The tapped delay line model:

$$h_{i,j}(t) \triangleq \sum_{l=0}^{L-1} h_{i,j}[l] \delta(t - lT_s) \quad (1)$$

can be adopted for the channel impulse response between the i -th transmit antenna 106 ($i = 1, \dots, N_T$) and the j -th receive antenna 108 ($j = 1, \dots, N_R$). Here, $\delta(t)$ denotes the Dirac delta function, L is the number of channel distinct taps and $h_{i,j}[l]$ is the complex gain of the l -th tap. For the purpose of illustration, it is assumed that: (a) the channel is static over each OFDM symbol interval (quasi static channel) and (b) $N_{cp} \geq 2N_p + L - 1$, so that inter-block interference can be avoided in the detection of each OFDM symbol. At mobile terminal 104, after matched filtering and sampling (wherein the first N_{cp} samples (i.e., the samples associated with the cyclic prefix) can be discarded from each OFDM time interval and ideal timing is assumed), the N samples collected at the j -th receive antenna undergo an N -th order DFT producing the N -dimensional vector:

$$\mathbf{r}_j \triangleq [r_j[0], r_j[1], \dots, r_j[N-1]]^T.$$

It is not difficult to show that this vector can be expressed as:

$$\mathbf{r}_j = \frac{ME_b}{N_T} \sum_{i=1}^{N_T} \mathbf{W}_i \mathbf{A} \mathbf{F}_L \mathbf{h}_{i,j} + \mathbf{n}_j, \quad (2)$$

where:

$\mathbf{A} \triangleq \text{diag}\{a_n, n = 0, 1, \dots, N-1\}$ is an $N \times N$ diagonal matrix containing all the elements of $\mathbf{a}$ along its main diagonal;

$\mathbf{h}_{i,j} \triangleq [h_{i,j}[0], h_{i,j}[1], \dots, h_{i,j}[L-1]]^T$ collects the channel gains of $h_{i,j}(t)$ (see equation (1));

$\mathbf{F}_L$ is an $N \times L$ DFT matrix with $[\mathbf{F}_L]_{p,q} = \exp[-j2\pi pq/N]$;

$p=0, 1, \dots, N-1$;

$q=0, 1, \dots, L-1$;

$\mathbf{W}_i \triangleq \text{diag}\{w_{0,i}, w_{1,i}, \dots, w_{N-1,i}\}$ is an $N \times N$ diagonal matrix collecting the complex weights applied to the OFDM symbol sent by the i -th transmit antenna;

E_b is the total average transmitted energy per information bit over time; and:

$\mathbf{z}_j \triangleq [z_j[0], z_j[1], \dots, z_j[N-1]]^T \sim N_c(\mathbf{0}, \sigma_z^2 \mathbf{I}_N)$; is a noise vector.

[0027] For the purpose of illustration, equation (2) can be converted into a subcarrier-based equation. Specifically, the N_R -dimensional vector:

$$\mathbf{r}[n] \triangleq [r_1[n], \dots, r_{N_R}[n]]^T,$$

containing the samples from all the receive antennas at the n -th subcarrier, can be expressed as:

$$\mathbf{r}[n] = \frac{ME_b}{N_T} \mathbf{H}_n \mathbf{w}_n a_n + \mathbf{z}_n, \quad (3)$$

where:

$\mathbf{z}_n \sim N_c(\mathbf{0}, \sigma_z^2 \mathbf{I}_{N_R})$ is an N_R -dimensional Gaussian noise vector; and

$\mathbf{H}_n = [H_{i,j}[n]]$ (with $i=1, \dots, N_T, j=1, \dots, N_R$) represents an $N_R \times N_T$ matrix collecting the responses of the MIMO channel at the n -th subcarrier frequency.

Note that the N -dimensional vector:

$$\mathbf{H}_{i,j} \triangleq [H_{i,j}[0], H_{i,j}[1], \dots, H_{i,j}[N-1]]^T,$$

collecting the values of the channel frequency response between the i -th transmit and the j -th receive antennas 108, is

$$\mathbf{H}_{i,j} = \mathbf{F}_L \mathbf{h}_{i,j}. \quad (4)$$

[0028] The received signal vectors $\mathbf{r}[n]$, $n=0, 1, \dots, N-1$, in equation (3), at a mobile terminal 104 can be used to generate feedback signals that can be used to (1) update the beamforming vector $\mathbf{w}_n$ and (2) set a proper energy level E_n at the base station.

[0029] Turning to FIGS. 3 and 4, two diagrams illustrating the beamforming of one subcarrier in a MIMO-OFDM system in accordance with some embodiments are shown. Although FIGS. 3 and 4 illustrate the operation of one subcarrier in such a system, any suitable number of subcarriers can be used in systems in accordance with some embodiments, and any one or more of such subcarriers can operate as illustrated in FIGS. 3 and 4.

[0030] As illustrated in FIG. 3, data 306 that is input to a transmitter 302 can be transmitted as a signal 316 and then received and output as data 308 by a receiver 304. Data 306 can be provided from any suitable source, such as a digital processing device that is part of, or coupled to, transmitter 302, and can be for any purpose. Similarly, data 308 can be provided to any suitable destination, such as a digital processing device that is part of, or coupled to, receiver 304, and can be for any purpose. Data 306 and data 308 can be in a modulated form using any suitable technique. For example, this data can be Quadrature Phase-Shift Keying (QPSK) modulated, Quadrature Amplitude Modulation (QAM) modulated, etc. In modulated form, data 306 and data 308 can be referred to as information symbols.

[0031] To provide beamforming in signal 316 during transmission, a weighting vector 342 can be multiplexed with data 306 by a multiplexer 310. This weighted data can then be provided to an OFDM modulator 312, which can modulate the weighted data. The modulated and weighted data can then be transmitted by a transmitter array 314 to receiver 304. The transmission energy level can be under the control of power control mechanism 370 (as described in more detail below). Any suitable multiplexer, OFDM modulator, power control mechanism, and transmitter array can be used to multiplex, modulate and transmit the data signal. Once the transmitted data signal arrives at receiver 304, the data signal can be received by receiver array 318 and then be provided to OFDM demodulator 320, which can then demodulate signal 316 into data 308. Any suitable receiver array and OFDM demodulator can be used to receive and demodulate the data. Because the data received by the OFDM demodulator is weighted, a weighting vector 360 can be provided to OFDM demodulator 320 to facilitate receiving the signal.

[0032] The weighting vectors that are multiplexed with data 306 can be generated and updated in transmitter 302 to take advantage of feedback from receiver 304. More particularly, as illustrated, a feedback signal 322 can be provided by receiver 304 to transmitter 302 using feedback transmitter 323 and feedback receiver 324. Any suitable transmitter and receiver can be used for feedback transmitter 323 and feedback receiver 324. The feedback signal can then be used to select one of two weighting vectors used during a previous interval – an even weighting vector (w_{even}) 326 or an odd weighting vector (w_{odd}) 328 – at multiplexer 330. The selected weighting vector 332 can then be provided to a weighting adaptation mechanism 334, which can produce a new even weighting vector 326 and a new odd weighting vector 328 using a perturbation 336 created by a perturbation

generator 338 (which is described below in connection with FIG. 5). A multiplexer 340 can then select one of the new even weighting vector 326 and new odd weighting vector 328 as the new base weighting vector 342 based on a current even or odd interval slot so that the selected weighting vector can be multiplexed with the data to be transmitted. The application of weighting vectors to data is described further below in connection with FIGS. 7 and 8. Any suitable multiplexers, weighting adaptation mechanisms, and perturbation generators can be used.

[0033] To generate feedback signal 322, receiver 304 can include a feedback generation mechanism 344. In generating the feedback signal, feedback generation mechanism 344 can use one or more channel estimates (**H**) 346, even weighting vector 348, and odd weighting vector 350. The channel estimate(s) can be generated by channel estimate generator 347 using any suitable technique known in the art, such as by using pilot symbols as described in T. Cui, C. Tellambura, "Robust Joint Frequency Offset and Channel Estimation for OFDM Systems," IEEE Veh. Tech. Conf. 2004, vol. 1, pp. 603-607, 26-29 Sept. 2004, which is hereby incorporated by reference herein in its entirety. The odd and even weighting vectors can be produced by weighting adaptation mechanism 352 using perturbation 354 created by perturbation generator 356 (which can operate in the same manner as perturbation generator 338, and which is further described below in connection with FIG. 5). In addition to being used to generate the feedback signal, one of these weighting vectors can be selected by multiplexer 353 to producing weighting vector 360 used by OFDM demodulator 320 to receive signal 316. Any suitable mechanisms can be used to form feedback generation mechanism 344, weight adaptation mechanism 352, perturbation generator 356, and multiplexer 353.

[0034] In some embodiments, a digital processing device (e.g., such as a microprocessor) can be used to control weighting vector formation, feedback, and power control. For example, in transmitter 302, perturbation generator 338, weighting adaptation mechanism 334, multiplexers 310, 330, and 340, and power control mechanism 370 can be implemented in a digital processing device running suitable software. As another example, in receiver 304, perturbation generator 356, weighting adaptation mechanism 352, multiplexer 353, and feedback generation mechanism 344 can be implemented in a digital processing device running suitable software.

[0035] Turning to FIG. 4, mechanisms for weighting, transmitting, and receiving data, generating feedback, and updating weighting vectors in connection with some

embodiments are further illustrated. As mentioned above, FIG. 4 illustrates actions that can be taken in a transmitter 402 and a receiver 404 for one subcarrier of a MIMO-OFDM system, although the same actions can be taken in some embodiments in multiple subcarriers.

[0036] As shown at 406, the weighting vector ($\mathbf{w}$) for the subcarrier can be initialized. Any suitable process for initializing the weighting vector can be used. For example, in some embodiments, the initial value for the weighting vector can be calculated randomly. As another example, in some embodiments, a code book can be used to calculate the initial value of $\mathbf{w}$. More particularly, using the values from the codebook of Table 1, γ_k^{LMMSE} can be calculated for each entry in the table using the following equation (5):

$$\gamma_k^{LMMSE} = \frac{1}{\sigma^2 [\mathbf{w}^H \mathbf{H}^H \mathbf{H} \mathbf{w} + \sigma^2 I]_{k,k}^{-1}} - 1 \quad (5)$$

[0037] This equation assumes that receiver 404 is a least-minimum-mean-square-error (LMMSE) receiver. When $\mathbf{w}$ possesses a Householder structure, further simplification in equation (5) can be attained. Particularly for the case of a $4 \times N_R \times 2$ system (i.e., four transmitter antennas and two transmission ranks, and any number of receiver antennas), the product term inside the inverse can be written as follows in equation (6):

$$\begin{aligned} \mathbf{W}^H \mathbf{H}^H \mathbf{H} \mathbf{W} = & \begin{bmatrix} \|\mathbf{h}_1\|^2 & \mathbf{h}_1^H \mathbf{h}_2 \\ \mathbf{h}_2^H \mathbf{h}_1 & \|\mathbf{h}_2\|^2 \end{bmatrix} - 2 \begin{bmatrix} u_1 \mathbf{u}^H \mathbf{H}^H \mathbf{h}_1 & u_1 \mathbf{u}^H \mathbf{H}^H \mathbf{h}_2 \\ u_2 \mathbf{u}^H \mathbf{H}^H \mathbf{h}_1 & u_2 \mathbf{u}^H \mathbf{H}^H \mathbf{h}_2 \end{bmatrix} \\ & - 2 \begin{bmatrix} u_1^* \mathbf{h}_1^H \mathbf{H} \mathbf{u} & u_2^* \mathbf{h}_1^H \mathbf{H} \mathbf{u} \\ u_1^* \mathbf{h}_2^H \mathbf{H} \mathbf{u} & u_2^* \mathbf{h}_2^H \mathbf{H} \mathbf{u} \end{bmatrix} + 4 \begin{bmatrix} |u_1|^2 \mathbf{u}^H \mathbf{H}^H \mathbf{H} \mathbf{u} & u_1 u_2^* \mathbf{u}^H \mathbf{H}^H \mathbf{H} \mathbf{u} \\ u_2 u_1^* \mathbf{u}^H \mathbf{H}^H \mathbf{H} \mathbf{u} & |u_2|^2 \mathbf{u}^H \mathbf{H}^H \mathbf{H} \mathbf{u} \end{bmatrix} \end{aligned} \quad (6)$$

Here, $\mathbf{h}_i$ denotes the i -th column vector of the channel matrix (or channel estimate) $\mathbf{H}$ and u_j is the j -th element of the vector $\mathbf{u}$. Notice that the above expression only involves matrix-vector operations of three different terms: $\mathbf{u}^H \mathbf{H}^H \mathbf{h}_1$, $\mathbf{u}^H \mathbf{H}^H \mathbf{h}_2$, and $\mathbf{u}^H \mathbf{H}^H \mathbf{H} \mathbf{u}$. The rest are simply scalar complex multiplications and additions. This allows significant complexity reduction. A similar technique can be applied to $4 \times N_R \times 3$ scenario or any other configuration.

[0038] The value of $\mathbf{u}$ that produces the largest value of γ_k^{LMMSE} can then be used as the initial value for $\mathbf{w}$.

Table 1. $4 \times N_R \times 2$ Householder codebook: 4 bits

#	u	Rows	#	u	Rows
1	0.2927 0.1298 + 0.6512i -0.0335 - 0.5622i 0.1662 + 0.3586i	1, 2	9	0.4326 -0.4304 + 0.0481i 0.6963 - 0.1860i 0.1500 + 0.2888i	1, 2
2	0.5754 0.0530 + 0.2187i -0.7569 + 0.1852i 0.0209 + 0.1035i	1, 2	10	0.4225 -0.0582 - 0.3111i -0.4713 - 0.1316i -0.5823 - 0.3779i	1, 2
3	0.4379 0.4527 - 0.0588i -0.3630 - 0.3639i -0.3692 + 0.4465i	1, 2	11	0.6569 0.1485 - 0.0776i -0.0998 - 0.4801i 0.5359 + 0.1125i	1, 2
4	0.5062 -0.1806 - 0.1003i 0.6056 + 0.0988i 0.2603 - 0.5068i	1, 2	12	0.7509 -0.4061 - 0.1814i 0.0274 + 0.2670i 0.0993 - 0.3954i	1, 2
5	0.0774 -0.3019 - 0.1046i -0.2880 + 0.8634i 0.2237 + 0.1160i	1, 2	13	0.3816 0.5020 + 0.1775i 0.3039 - 0.5125i 0.4323 - 0.1702i	1, 2
6	0.1056 -0.5156 + 0.2733i -0.5343 - 0.2538i -0.5021 + 0.2152i	1, 2	14	0.6961 0.1961 + 0.5260i -0.0002 - 0.0892i -0.3517 + 0.2622i	1, 2
7	0.3474 0.1465 - 0.4442i 0.6611 - 0.4650i -0.0535 + 0.0662i	1, 2	15	0.1991 0.0523 - 0.4184i 0.0165 + 0.4263i 0.1029 - 0.7681i	1, 2
8	0.3585 0.0138 + 0.3114i -0.0018 + 0.1268i -0.7014 + 0.5160i	1, 2	16	0.1471 -0.2071 - 0.4459i 0.2385 - 0.1701i 0.6400 + 0.4912i	1, 2

[0039] In order to facilitate demodulation of data and updating of weighting vectors, the weighting vectors used in the transmitter and the receiver can be synchronized. To do so, for example, as illustrated at 414, receiver 404 can also initialize a weighting vector in the receiver in the same manner as performed at 406. In some embodiments, the weighting vector can be determined as described only at receiver 404 and then provided to transmitter 402 through a feedback channel.

[0040] Next, at 408, the odd and even weighting vectors can be calculated using the following equations (7) and (8):

$$\mathbf{w}_n^e = \frac{\mathbf{w}_n^b + \beta \mathbf{p}_n}{\|\mathbf{w}_n^b + \beta \mathbf{p}_n\|} \quad (7)$$

$$\mathbf{w}_n^o = \frac{\mathbf{w}_n^b - \beta \mathbf{p}_n}{\|\mathbf{w}_n^b - \beta \mathbf{p}_n\|} \quad (8)$$

where:

n indicates the subcarrier corresponding to this weighting vector.

$\mathbf{p}_n$ is a perturbation for the subcarrier.

β is the adaptation rate, which determines how fast the weighting matrices change.

$\mathbf{w}_n^b$ is the preferred weight vector (or base weighting vector) previously selected

based on feedback, or is the initial value of $\mathbf{w}$, for the subcarrier.

$\mathbf{w}_n^e$ is the even weighting vector for the subcarrier.

$\mathbf{w}_n^o$ is the odd weighting vector for the subcarrier.

[0041] The perturbation vector ($\mathbf{p}_n$) can be calculated using any suitable technique. For example, the perturbation vector can be calculated using a Quasi Monte Carlo technique 500 illustrated in FIG. 5. As shown at 502, a first set of B prime numbers can be determined. B can be any suitable number and is based on the number of transmission antennas reflected in the dimensions of the weighting vectors. For example, for B equal to 4 for four transmission antennas, the set of prime numbers can be {3, 5, 7, 11}. Next, at 504, a random number n_0 can be generated and the first N natural numbers beginning at n_0 identified. Any suitable value for N can be selected, and can be based on the accuracy of tracking the channel modes. For example, for n_0 equal to 15 and N equal to 1000, the N identified numbers can be {15, 16, 17, ..., 1014}. Then, at 506 through 514, for each of the N identified numbers, a set of B elements can be created using respective ones, b, of the B prime numbers. Particularly, for each one, n, of the N identified numbers (looping between 506 and 514), each one of the B elements (looping between 508 and 512) can then be determined by taking the sequence of digits of n when expressed in base b (where b is a respective one of the B prime numbers) and using those digits to form a base 10 number. For example, with $n=15$ and $b=2$, the digits of n when expressed in base b are "1111." These digits can then be used to form the number 1,111 (in base 10). This formation of numbers can be performed for each combination of n and b to form a set of N x B numbers ($u(N,B)$). As illustrated in the figure, this can be

represented in pseudo-code as $u(n,b)=\text{val}(\text{itoa}(n(\text{base } b)))$, where $n(\text{base } b)$ is the number n in base b , $\text{itoa}()$ converts an integer number to a string, and $\text{val}()$ converts a string to a base 10 number. This set of $N \times B$ numbers can be referred to as a Halton Sequence. Next at 516, for each one, n , of the values N in the Halton Sequence, $\mathbf{p}_n$ can be calculated using the following equation (9):

$$\mathbf{p}_n = \frac{1}{B} \sum_{b=1}^B \phi^{-1}(u(n,b)) \quad (9)$$

where:

ϕ^{-1} is an inverse mapping of the Gaussian distribution; and

$u(n,b)$ are the B numbers corresponding to each of the N values in the Halton Sequence.

$\mathbf{p}_n$ is a gaussian random vector with zero mean and covariance Matrix $\mathbf{I}$ (identity matrix).

This process is further described in D. Guo and X. Wang, "Quasi-Monte Carlo filtering in nonlinear dynamic systems", IEEE Trans. Sign. Proc., vol. 54, no. 6, pp. 2087-2098, Jun. 2006, which is hereby incorporated by reference herein in its entirety.

[0042] Additionally or alternatively, the perturbation can be calculated using normal Monte-Carlo techniques or randomly. As stated above, any other suitable technique for determining the perturbation vector can be used.

[0043] As mentioned above, β is the adaptation rate of the perturbation $\mathbf{p}_n$ into the even and odd weighting vectors. In fast changing environments, it can be desirable for the even and odd weighting vectors to change rapidly, and, thus, to use a large value of β . Example values for β versus resultant Bit Error Ratios (BER) are illustrated in FIG. 6 for different normalized Doppler bandwidths (B_{DNT_s}) for motion of the receiver and/or transmitter. Any suitable values for β can be used. For example, β equal to 0.2 can be used.

[0044] Returning to FIG. 4, once again, to maintain synchronization between the weighting vectors in the transmitter and receiver, at 416, the odd and even weighting vectors can also be calculated in the same manner as performed at 408

[0045] Next, at 410, the data can be multiplexed with the odd and even weighting vectors in any suitable manner. For example, FIGS. 7 and 8 illustrate ways in which odd and

even weighting vectors can be multiplexed with data. As shown in FIG. 7, for different subcarriers of a MIMO-OFDM system (which are represented at different points on f-axis 706), pilot symbols 702 and information symbols 704 can be transmitted at different time intervals 710 and 712 (which are represented at different points on t-axis 708). As indicated in legend 714, pilot symbols 702 can be not-weighted and used for channel estimation (as known in the art), information symbols 704 can be weighted using the even weighting vector during even intervals 710, and information symbols 704 can be weighted using the odd weighting vector during odd intervals 712.

[0046] Although pilot symbols are illustrated as being transmitted in every third interval in FIG. 7, and at an even spacing across subcarriers, any suitable approach to transmitting pilot symbols can be used. For example, in some embodiments, pilot symbols can be transmitted more or less frequently and/or on more or less subcarriers. In some embodiments, pilot symbols can be omitted.

[0047] As also shown, multiple intervals 710 and 712 can form perturbation probing periods (PPP) 716 and 718. During a PPP, a feedback signal can be generated. This feedback signal can then be used to determine the odd and even weight vectors to be used during the next PPP.

[0048] Turning to FIG. 8, the weighting vectors 804, 806, 808, and 810 that can be used over even intervals 710 and odd intervals 712 are illustrated. As shown, a weighting vector w_1^e 804 can be used to weight subcarrier 1 during even interval 710. A weighting vector w_2^e 806 can be used to weight subcarrier 2 during even interval 710. A weighting vector w_1^o 808 can be used to weight subcarrier 1 during interval 712. And, a weighting vector w_2^o 810 can be used to weight subcarrier 2 during interval 712. Although two subcarriers are specifically identified in connection with FIG. 8, any suitable number of the subcarriers can have weighting applied.

[0049] Although odd and even intervals are illustrated in FIGS. 7 and 8 as occurring every other interval, any suitable approach for designating intervals as odd or even can be used. For example, a first pair (or any other suitable number) of intervals can be even, and the next pair (or any other suitable number) of intervals can be odd.

[0050] Referring back to FIG. 4, after the data is weighted at 410, the weighted data can be transmitted to receiver 404 at 412. This weighted data can then be received at 418. Any suitable technique can be used to transmit and receive the weighted data/information

symbols. For example, the data/information symbols can be transmitted using MIMO-OFDM transmitters and receivers.

[0051] Next, at 420, the receiver can generate the feedback signal. For example, the feedback signal can be generated as a feedback bit using the following equation (10):

$$b_n = \text{sign} \left(\left\| \mathbf{H}_n^e \mathbf{w}_n^e \right\|_F^2 - \left\| \mathbf{H}_n^o \mathbf{w}_n^o \right\|_F^2 \right) \quad (10)$$

where:

$\mathbf{H}_n^e$ is the channel gain matrix (or channel estimate) for the even OFDM intervals of a given PPP; and

$\mathbf{H}_n^o$ is the channel gain matrix (or channel estimate) for the odd OFDM intervals of a given PPP.

Equation (10) results in b_n being equal to +1 if the even weighting vector results in greater power for a given subcarrier n , and being equal to -1 if the odd weighting vector results in greater power for a given subcarrier n . In some embodiments, rather than using different channel gain matrices for the odd and even intervals, a single channel gain matrix can be used.

[0052] This feedback bit can then be transmitted from receiver 404 to transmitter 402 at 422 and 424. Any suitable technique for transmitting the feedback bit from the receiver to the transmitter can be used.

[0053] Next, at 426 and 428, the weighting vector in each of the receiver and the transmitter can be updated. For example, using the feedback bit, the weighting vector can be updated using the following equation:

$$\mathbf{w}_n^b = \begin{cases} \mathbf{w}_n^e, & \text{if } b_n = +1 \\ \mathbf{w}_n^o, & \text{if } b_n = -1 \end{cases} \quad (11)$$

That is, if the feedback bit is +1, then the weighting vector is set to the even weighting vector. Otherwise, if the feedback bit is -1, then the weighting vector is set to the odd weighting vector.

[0054] After updating the weighting vectors in the receiver and the transmitter, the processes shown loop back to 416 and 408, respectively.

[0055] As mentioned above, feedback can also be used to control transmit power on subcarriers of MIMO systems (such as MIMO-OFDM systems having beamformed channels

as described above) in some embodiments: Controlling of the energy level E_n for each subcarrier n can be performed according to the following rule:

$$E_n = \begin{cases} E_1, & \text{if } \lambda_n < \tau \\ E_2, & \text{if } \lambda_n > \tau \end{cases}, n = 0, \dots, N-1 \quad (12)$$

where:

E_1 is a first energy level;

E_2 is a second energy level;

τ represents a threshold level; and

λ_n represents the main power of a beamformed channel seen by a mobile terminal at an n -th subcarrier.

More particularly, λ_n can be used to represent the main power of a beamformed channel by the following equation (see also equation (6)):

$$\lambda_n \triangleq \mathbf{w}_n^H \mathbf{H}_n^H \mathbf{H}_n \mathbf{w}_n \quad (13)$$

where:

$\mathbf{w}_n^H$ represents the Hermetian operation on $\mathbf{w}_n$;

$\mathbf{H}_n^H$ represents the Hermetian operation on $\mathbf{H}_n$;

$\mathbf{H}_n$ represents the channel estimate of subcarrier n ; and

$\mathbf{w}_n$ represents the beamforming weight applied to subcarrier n .

[0056] In some embodiments, where beamforming is not used, the power determined in equation (13) can be represented as:

$$\lambda_n \triangleq \mathbf{H}_n^H \mathbf{H}_n.$$

[0057] Referring to FIG. 3, feedback generation mechanism 344 in receiver 304 can be used to determine whether the energy level E_n for a subcarrier n should be set to E_1 or E_2 based on current values E_1 , E_2 , λ_n , and τ using equations (12) and (13), and return any suitable feedback (such as a bit set to 0 for E_1 or to 1 for E_2) to transmitter 302. Within transmitter 302, a power control mechanism 370 can be used to receive this feedback and control the energy level on the subcarrier generated by transmit array 314. This determination, feedback, and control can be performed for every symbol transmitted on a subcarrier, or periodically (e.g., every m symbols or t time increments), and can be performed at the same and/or different times from the updating of the beamforming weights.

[0058] In order to provide this feedback and set E_n , the receiver needs to have values for E_1 , E_2 , and τ , and the transmitter needs to have values for E_1 and E_2 . In some

embodiments, E_1 , E_2 , and $\mathcal{T}$ can be calculated in receiver 304 (as described below, for example) and E_1 and E_2 provided to transmitter 302 through the feedback channel. In some embodiments, the transmitter can perform separate and similar calculations as being performed in the receiver to determine E_1 and E_2 .

[0059] The energy levels E_1 and E_2 , and the threshold $\mathcal{T}$, can be selected to minimize the bit error rate (BER) on each subcarrier n . BER expressions depend on the constellation (e.g., QAM or QPSK) of symbols that is adopted in a transmitter. Formulas for some common constellations can be found in J.G. Proakis, "Digital Communications," 4th ed., McGraw-Hill, New York, NY, 2001, which is hereby incorporated by reference herein in its entirety.

[0060] Using QPSK as an example (although any other suitable constellation can also be used), the signal-to-noise ratio per bit for the n -th subcarrier in a MIMO-OFDM system can be given by:

$$[SNR]_n = \frac{2E_b}{\sigma_z^2} \lambda_n, \quad (14)$$

and the corresponding average bit error probability can be given by:

$$P_n = \int_0^\infty Q\left(\sqrt{SNR_n(\lambda_n)}\right) p(\lambda_n) d\lambda_n, \quad (15)$$

where:

σ_z^2 represents the noise variance of the subcarrier signal;

Q represents the probabilistic function related to the subcarrier signal, and is described in J.G. Proakis, "Digital Communications," 4th ed., McGraw-Hill, New York, NY, 2001; and

$p(\lambda_n)$ represents the probability density function of λ_n .

Substituting equation (14) into equation (15) and taking into account rule (12) yields the bit error probability:

$$P_n = \int_0^\tau Q\left(\sqrt{2E_1\lambda_n/\sigma_z^2}\right) p(\lambda_n) d\lambda_n + \int_\tau^\infty Q\left(\sqrt{2E_2\lambda_n/\sigma_z^2}\right) p(\lambda_n) d\lambda_n \quad (16)$$

Energy levels E_1 and E_2 , and threshold $\mathcal{T}$ can then be selected while attempting to minimize this bit error probability P_n under the following time-based energy constraint:

$$q_1 E_1 + q_2 E_2 = E_b, \quad (17)$$

where:

$$q_1 \triangleq \int_0^\tau p(\lambda_n) d\lambda_n;$$

$$q_2 \triangleq \int_\tau^\infty p(\lambda_n) d\lambda_n; \text{ and}$$

E_b is the total average transmitted energy per information bit over time.

The time-based energy constraint attempts to control the energy level over time so that the average energy level is E_b .

[0061] This selection can be performed in some embodiments using Lagrange multipliers. For example, to do so, the following Lagrangian function can be defined:

$$L = \int_0^\tau Q\left(\sqrt{2E_1\lambda_n/\sigma_z^2}\right) p(\lambda_n) d\lambda_n + \int_\tau^\infty Q\left(\sqrt{2E_2\lambda_n/\sigma_z^2}\right) p(\lambda_n) d\lambda_n + \mu q_1 E_1 + \mu q_2 E_2 - \mu E_b, \quad (18)$$

and the following system solved:

$$\begin{cases} \frac{dL}{dE_1} = \int_0^\tau E_1^{-1/2} \exp(-E_1\lambda_n) \lambda_n^{-1/2} p(\lambda_n) d\lambda_n + \mu q_1 = 0 \\ \frac{dL}{dE_2} = \int_\tau^\infty E_2^{-1/2} \exp(-E_2\lambda_n) \lambda_n^{-1/2} p(\lambda_n) d\lambda_n + \mu q_2 = 0 \\ \frac{dL}{d\tau} = Q\left(\sqrt{2E_1\tau/\sigma_z^2}\right) + \mu E_1 - Q\left(\sqrt{2E_2\tau/\sigma_z^2}\right) - \mu E_2 = 0 \\ \frac{dL}{d\mu} = q_1 E_1 + q_2 E_2 - E_b = 0 \end{cases} \quad (19)$$

From the third equation of system (19) it can be inferred that:

$$\mu = \frac{Q\left(\sqrt{2E_2\tau/\sigma_z^2}\right) - Q\left(\sqrt{2E_1\tau/\sigma_z^2}\right)}{E_1 - E_2} \quad (20)$$

and from the fourth equation of system (19) that:

$$E_2 = \frac{E_b - q_1 E_1}{q_2} \quad (21)$$

Substituting equations (20) and (21) into the second equation of system (19) yields the following system based on E_1 and τ :

$$\begin{cases} f(E_1, \tau) = 0 \\ g(E_1, \tau) = 0 \end{cases}$$

This system can be solved iteratively using the Newton-Raphson method. Given an initial point $(E_1^{(i)}, \tau^{(i)})$, to simplify the problem $f(E_1, \tau)$ and $g(E_1, \tau)$ can be replaced with the first order Taylor approximation around $(E_1^{(i)}, \tau^{(i)})$:

$$\begin{cases} f(E_1, \tau) \approx f(E_1^{(i)}, \tau^{(i)}) + f_{E_1}(E_1^{(i)}, \tau^{(i)})(E_1 - E_1^{(i)}) + f_{\tau}(E_1^{(i)}, \tau^{(i)})(\tau - \tau^{(i)}) \\ g(E_1, \tau) \approx g(E_1^{(i)}, \tau^{(i)}) + g_{E_1}(E_1^{(i)}, \tau^{(i)})(E_1 - E_1^{(i)}) + g_{\tau}(E_1^{(i)}, \tau^{(i)})(\tau - \tau^{(i)}) \end{cases} \quad (22)$$

An iterative algorithm for the joint estimation of E_1 and τ is given by:

$$E_1^{(i+1)} = E_1^{(i)} + \delta_{E_1} \quad \tau^{(i+1)} = \tau^{(i)} + \delta_{\tau} \quad (23)$$

where the vector $\delta = [\delta_{E_1}, \delta_{\tau}]^T$ is the solution of the following system:

$$\mathbf{J}(E_1^{(i)}, \tau^{(i)})\delta = -\mathbf{F}(E_1^{(i)}, \tau^{(i)}) \quad (24)$$

where

$$\mathbf{J}(E_1^{(i)}, \tau^{(i)}) = \begin{pmatrix} f_{E_1}(E_1^{(i)}, \tau^{(i)}) & f_{\tau}(E_1^{(i)}, \tau^{(i)}) \\ g_{E_1}(E_1^{(i)}, \tau^{(i)}) & g_{\tau}(E_1^{(i)}, \tau^{(i)}) \end{pmatrix} \quad (25)$$

and

$$\mathbf{F}(E_1^{(i)}, \tau^{(i)}) = \begin{pmatrix} f(E_1^{(i)}, \tau^{(i)}) \\ g(E_1^{(i)}, \tau^{(i)}) \end{pmatrix} \quad (26)$$

The partial derivatives in equations (25) and (26) are given by equations (27), (28), (29), and (30):

$$\begin{aligned} f_{E_1}(E_1, \tau) = & - \int_0^{\tau} E_1^{-3/2} \exp(-E_1 \lambda_n) \left[\lambda_n^{1/2} + 2E_1 \lambda_n^{3/2} \right] p(\lambda_n) d\lambda_n + \\ & q_1 \left[\left(\frac{q_1 \tau \exp\left(-\tau \frac{E_b - q_1 E_1}{q_2}\right)}{2\sqrt{\pi \tau q_2 (E_b - q_1 E_1)}} + \frac{\tau \exp(-E_1 \tau)}{2\sqrt{\pi \tau E_1}} \right) (E_1 - E_b) \right. \\ & \left. - \frac{1}{q_2} \left(Q\left(\sqrt{2\tau \frac{E_b - q_1 E_1}{q_2}}\right) - Q(\sqrt{2\tau E_1}) \right) \right] \quad ; \quad (27) \end{aligned}$$

$$\begin{aligned} f_{\tau}(E_1^{(i)}, \tau^{(i)}) = & E_1^{-1/2} \exp(-E_1 \tau) \tau^{-1/2} p(\tau) + \\ & \frac{q_1}{E_1 - \frac{E_b - q_1 E_1}{q_2}} \left[\frac{(E_b - q_1 E_1) \exp\left(-\frac{E_b - q_1 E_1}{q_2} \tau\right)}{2q_2 \sqrt{\pi q_2 (E_b - q_1 E_1)} \tau} - \frac{E_1 \exp(-E_1 \tau)}{2\sqrt{\pi E_1 \tau}} \right] \quad ; \quad (28) \end{aligned}$$

$$\begin{aligned} g_{E_1}(E_1, \tau) = & \int_{\tau}^{\infty} \left(-\frac{q_1}{q_2} + \frac{q_1 (E_b - q_1 E_1)}{q_2^2} \lambda_n \right) \exp\left(-\frac{E_b - q_1 E_1}{q_2} \lambda_n\right) \lambda_n^{-1/2} p(\lambda_n) d\lambda_n + \\ & q_2 \left[\left(\frac{q_1 \tau \exp\left(-\tau \frac{E_b - q_1 E_1}{q_2}\right)}{2\sqrt{\pi \tau q_2 (E_b - q_1 E_1)}} + \frac{\tau \exp(-E_1 \tau)}{2\sqrt{\pi \tau E_1}} \right) (E_1 - E_b) \right. \\ & \left. - \frac{1}{q_2} \left(Q\left(\sqrt{2\tau \frac{E_b - q_1 E_1}{q_2}}\right) - Q(\sqrt{2\tau E_1}) \right) \right] \quad ; \text{ and} \quad (29) \end{aligned}$$

$$g_{\tau}(E_1^{(i)}, \tau^{(i)}) = - \left(\frac{E_b - q_1 E_1}{q_2} \right)^{-1/2} \exp \left(- \frac{E_b - q_1 E_1}{q_2} \tau \right) \tau^{-1/2} p(\tau) + \frac{q_2}{E_1 - \frac{E_b - q_1 E_1}{q_2}} \left[\frac{(E_b - q_1 E_1) \exp \left(- \frac{E_b - q_1 E_1}{q_2} \tau \right)}{2 q_2 \sqrt{\pi q_2 (E_b - q_1 E_1) \tau}} - \frac{E_1 \exp(-E_1 \tau)}{2 \sqrt{\pi E_1 \tau}} \right] \quad (30)$$

[0062] The probability density function $p(\lambda_n)$ in equations (28) and (30) can be estimated using standard numerical techniques and the integrals in equations (27) and (29) can be solved using Monte Carlo techniques, as known in the art.

[0063] Then, if N_{it} represents the maximum number of the iterations in the Newton-Raphson method and $E_1^{(0)} = E_b$, $\tau^{(0)} = \text{median}(\lambda_n)$ are selected at the first iteration, E_1 and τ can be iteratively estimated, and then E_2 computed as illustrated in process 900 of FIG. 9. As shown, this can be performed by setting $i=1$ at 902, and then computing $J(E_1^{(i)}, \tau^{(i)})$ from equation (25) at 904, $F(E_1^{(i)}, \tau^{(i)})$ from equation (26) at 906, and a new estimate $E_1^{(i+1)}$ for E_1 and $\tau^{(i+1)}$ for τ from equations (23) and (24) at 908. Next, at 910, it can be determined whether $i=N_{it}$. If not, i can be incremented at 912. Otherwise, E_2 can be computed from equation (21) at 914 using the final estimate of E_1 and τ .

[0064] In some embodiments, rather than initializing the weighting vectors in the transmitter and the receiver only once, these vectors are initialized periodically (e.g., every 100 intervals, every 30 PPP, etc.). Similarly, the energy levels E_1 and E_2 and threshold τ can be initialized periodically. This can be advantageous in fast changing environments where conditions can rapidly move back to preferring the initial weighting, or something close to it.

[0065] As mentioned above, techniques for updating beamforming and power control are illustrated for a single subcarrier. These techniques can be used across multiple subcarriers in some embodiments. For example, rather than performing these techniques for each subcarrier, in some embodiments, multiple subcarriers can be grouped and these techniques can be performed on a subset of the subcarriers – e.g., the center subcarrier. The weighting vector, energy levels, and/or threshold determined for the center subcarrier can then be used for all subcarriers in the group.

[0066] While single-bit feedback approaches to updating beamforming and power control have been described above, any suitable number of bits for feedback can be used in accordance with some embodiments. For example, in a two bit approach, rather than generating odd and even weighting vectors, four weighting vectors, labeled 1 through 4, can be generated. These weighting vectors can then each be applied to information symbols

across every four intervals. As another example, rather than using two energy levels and one threshold, three energy levels and two thresholds, four energy levels and three thresholds, etc., can be used. Obviously, any other suitable approach can be used.

[0067] As described above, beamforming and power control can be used separately or together to improve the performance of wireless digital communication systems, such as MIMO (or more particularly, MIMO-OFDM) systems. Because these techniques can increase processing requirements at a transmitter and receiver, and thus increase power usage and decrease battery life of portable devices, in some embodiments the usage of the techniques can be controlled automatically or manually. In an automatic approach, a mobile terminal can automatically determine if it is in a dynamic environment by monitoring whether the channel estimate for a subcarrier changes or by detecting whether the mobile terminal is moving (e.g., based on an attached GPS device). In a manual approach, a mobile terminal can receive a setting from a user selecting whether the device is moving or not, or specifically selecting whether beamforming and/or power control are to be used, and if so at what frequency the beamforming and power control are to be updated. When selections are based on movement (e.g., whether detected automatically or in response to user input), any suitable selection of beamforming and/or power control can automatically be configured. For example, if a mobile terminal is determined to be moving, beamforming can be selected to be active, while power control can be selected to be disabled in order to decrease power demands and increase battery life of the mobile terminal.

[0068] Although the invention has been described and illustrated in the foregoing illustrative embodiments, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the details of implementation of the invention can be made without departing from the spirit and scope of the invention, which is only limited by the claims which follow. Features of the disclosed embodiments can be combined and rearranged in various ways.

What is claimed is:

1. A method for controlling transmit-power between a wireless transmitter and a wireless receiver, comprising:
 - calculating a threshold associated with a subcarrier between the transmitter and the receiver;
 - receiving the subcarrier containing an information symbol at the receiver from the transmitter;
 - determining a channel estimate of the subcarrier and a weighting vector for the information symbol;
 - based at least on the channel estimate and the weighting vector, determining a power level of the subcarrier;
 - comparing the power level to the threshold;
 - generating a feedback signal to the transmitter indicating a first energy level to be used for the subcarrier based on the comparison of the power level to the threshold;
 - subsequent to generating the feedback signal, determining a second power level of the subcarrier based at least on the channel estimate and the weighting vector;
 - comparing the second power level to the threshold; and
 - generating a second feedback signal to the transmitter indicating a second energy level to be used for the subcarrier based on the comparison of the second power level to the threshold.
2. The method of claim 1, wherein the subcarrier is a MIMO signal.
3. The method of claim 1, wherein the subcarrier is a MIMO-OFDM signal.
4. The method of claim 1, wherein the channel estimate is determined from one or more pilot symbols.
5. The method of claim 1, further comprising calculating the first energy level and the second energy level at the receiver based on a time-based energy constraint.
6. The method of claim 1, wherein the feedback signal is a single bit.

7. The method of claim 1, further comprising:
 - determining a perturbation vector;
 - determining a plurality of weighting vectors to be applied to the subcarrier based on a base weighting vector and the perturbation vector;
 - generating a third feedback signal based on at least one of the plurality of weighting vectors; and
 - transmitting the third feedback signal to the transmitter.
8. A system for controlling transmit-power from a wireless transmitter, comprising:
 - a receiver that:
 - calculates a threshold associated with a subcarrier between the transmitter and the receiver;
 - receives the subcarrier containing an information symbol from the transmitter;
 - determines a channel estimate of the subcarrier and a weighting vector for the information symbol;
 - based at least on the channel estimate and the weighting vector, determines a power level of the subcarrier;
 - compares the power level to the threshold;
 - generates a feedback signal to the transmitter indicating a first energy level to be used for the subcarrier based on the comparison of the power level to the threshold;
 - subsequent to generating the feedback signal, determines a second power level of the subcarrier based at least on the channel estimate and the weighting vector;
 - compares the second power level to the threshold; and
 - generates a second feedback signal to the transmitter indicating a second energy level to be used for the subcarrier based on the comparison of the second power level to the threshold.
9. The system of claim 8, wherein the subcarrier is a MIMO signal.
10. The system of claim 8, wherein the subcarrier is a MIMO-OFDM signal.

11. The system of claim 8, wherein the channel estimate is determined from one or more pilot symbols.

12. The system of claim 8, wherein the receiver also calculates the first energy level and the second energy level at the receiver based on a time-based energy constraint.

13. The system of claim 8, wherein the feedback signal is a single bit.

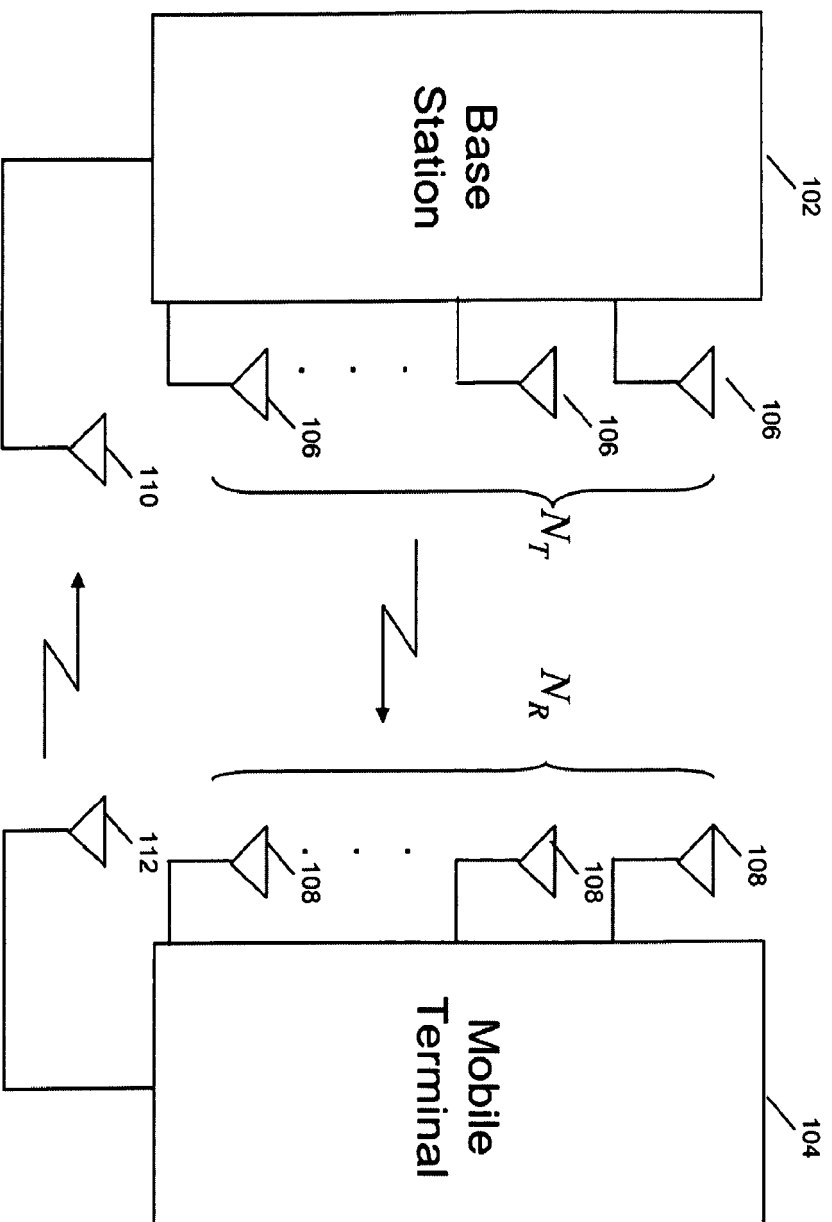
14. The system of claim 8, wherein the receiver also:
determines a perturbation vector;
determines a plurality of weighting vectors to be applied to the subcarrier based on a base weighting vector and the perturbation vector;
generates a third feedback signal based on at least one of the plurality of weighting vectors; and
transmits the third feedback signal to the transmitter.

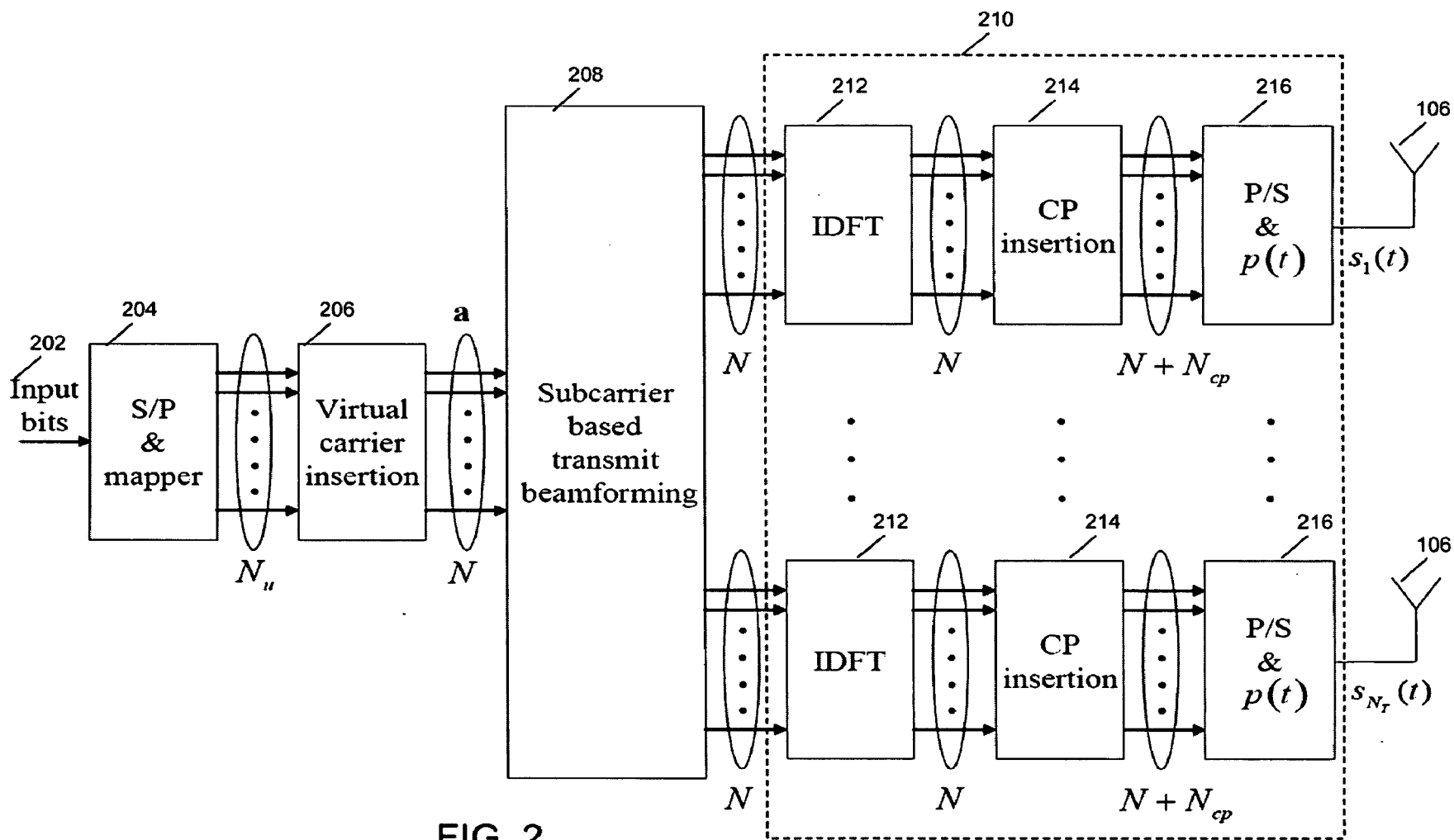
15. A system for controlling transmit-power from a wireless transmitter, comprising:
means for calculating a threshold associated with a subcarrier from the transmitter;
means for receiving the subcarrier containing an information symbol from the transmitter;
means for determining a channel estimate of the subcarrier and a weighting vector for the information symbol;
means for determining a power level of the subcarrier based at least on the channel estimate and the weighting vector;
means for comparing the power level to the threshold;
means for generating a feedback signal to the transmitter indicating a first energy level to be used for the subcarrier based on the comparison of the power level to the threshold;
means for determining a second power level of the subcarrier based at least on the channel estimate and the weighting vector subsequent to generating the feedback signal;

means for comparing the second power level to the threshold; and
means for generating a second feedback signal to the transmitter indicating a second energy level to be used for the subcarrier based on the comparison of the second power level to the threshold.

16. The system of claim 15, wherein the subcarrier is a MIMO signal.
17. The system of claim 15, wherein the subcarrier is a MIMO-OFDM signal.
18. The system of claim 15, wherein the channel estimate is determined from one or more pilot symbols.
19. The system of claim 15, further comprising means for calculating the first energy level and the second energy level at the receiver based on a time-based energy constraint.
20. The system of claim 15, wherein the feedback signal is a single bit.
21. The system of claim 15, further comprising:
 - means for determining a perturbation vector;
 - means for determining a plurality of weighting vectors to be applied to the subcarrier based on a base weighting vector and the perturbation vector;
 - means for generating a third feedback signal based on at least one of the plurality of weighting vectors; and
 - means for transmitting the third feedback signal to the transmitter.

FIG. 1





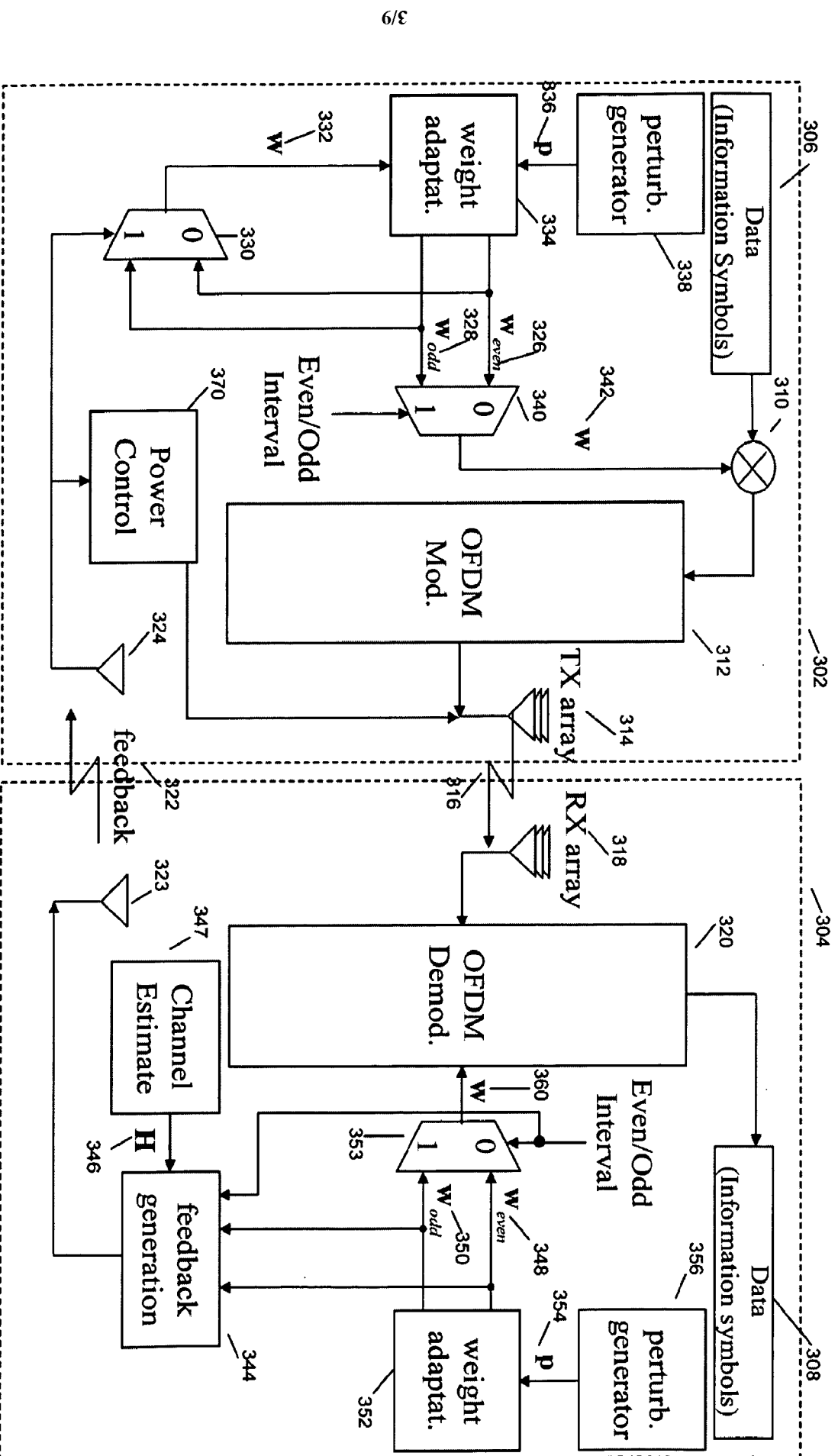
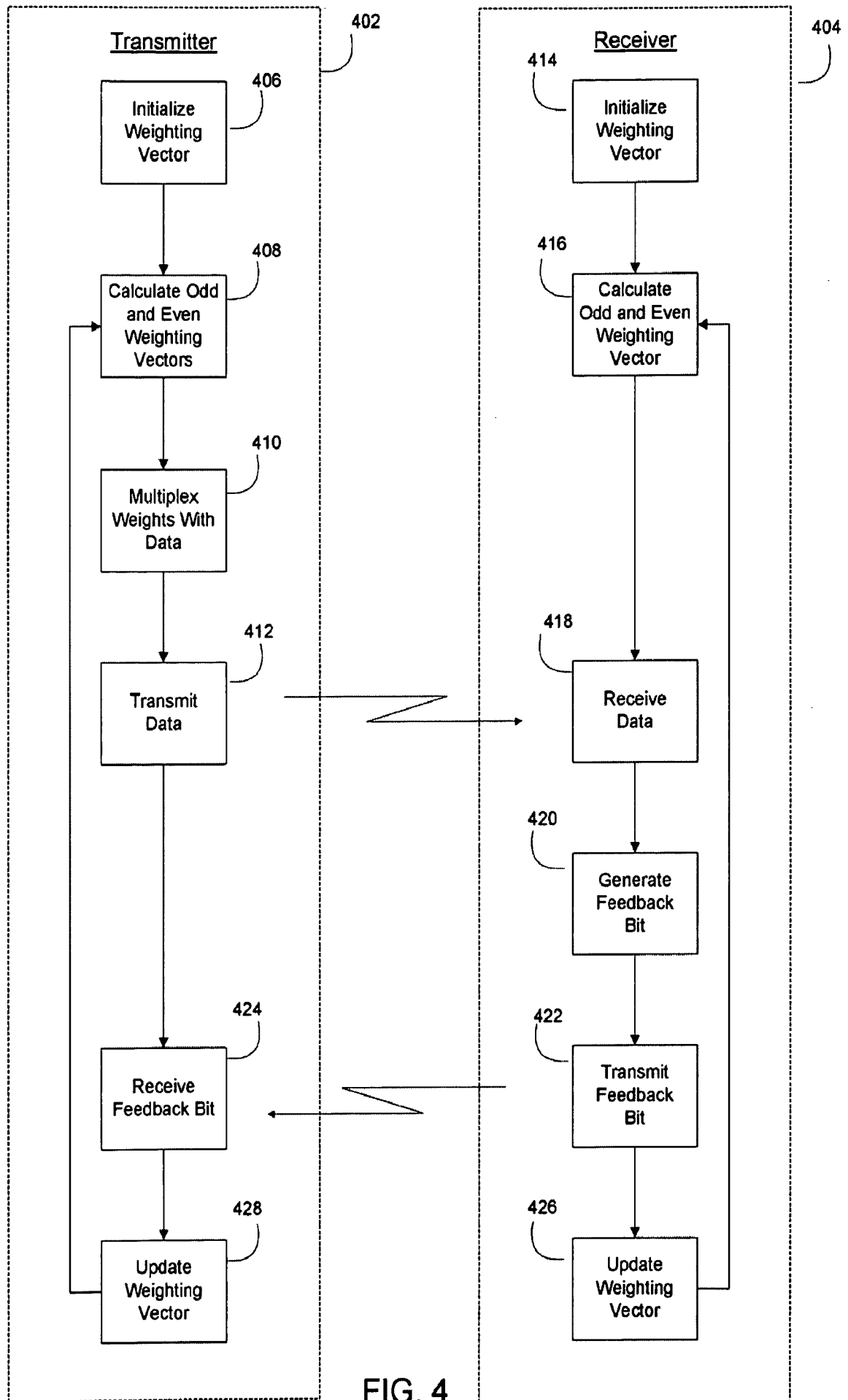


FIG. 3



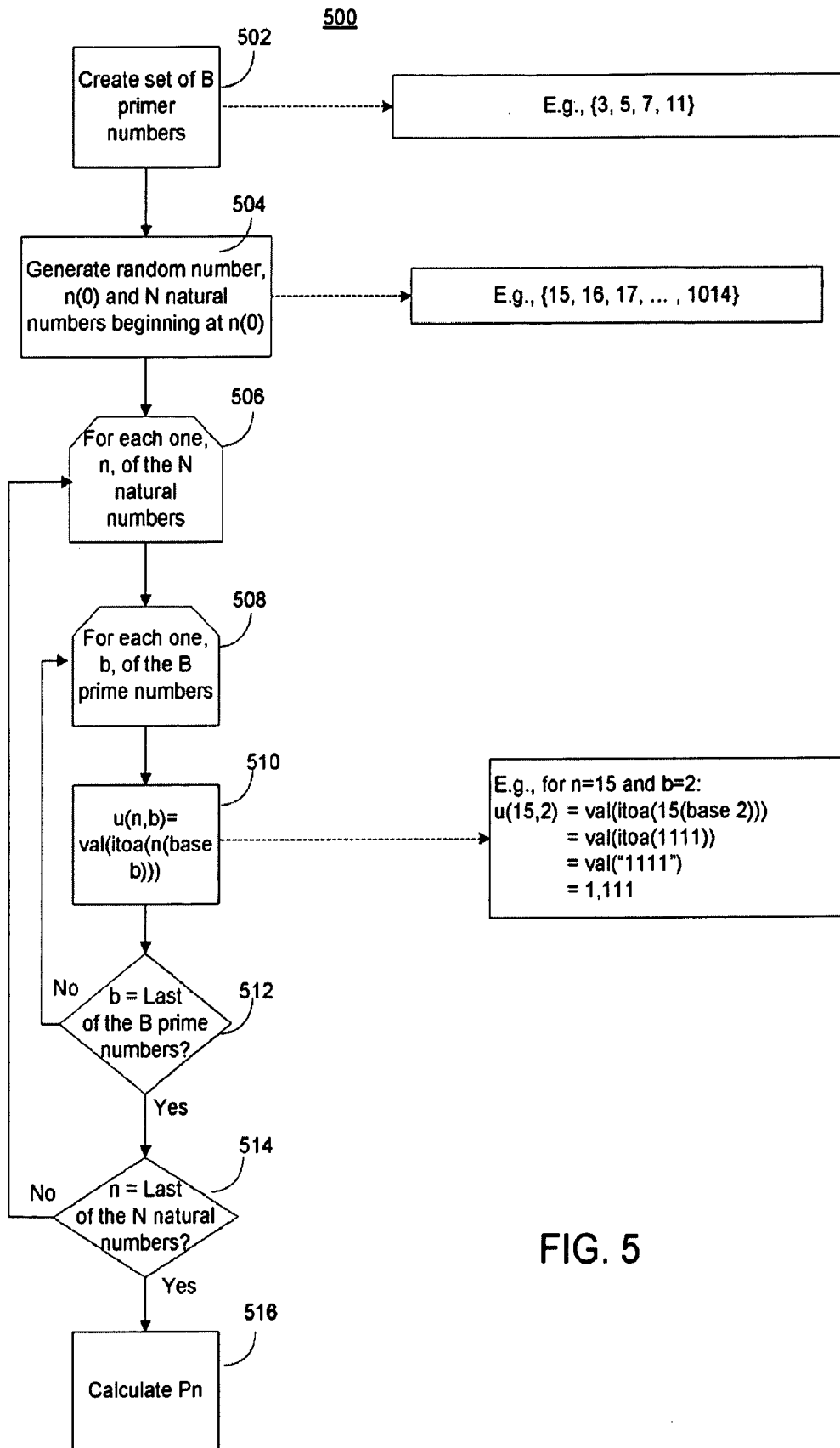


FIG. 5

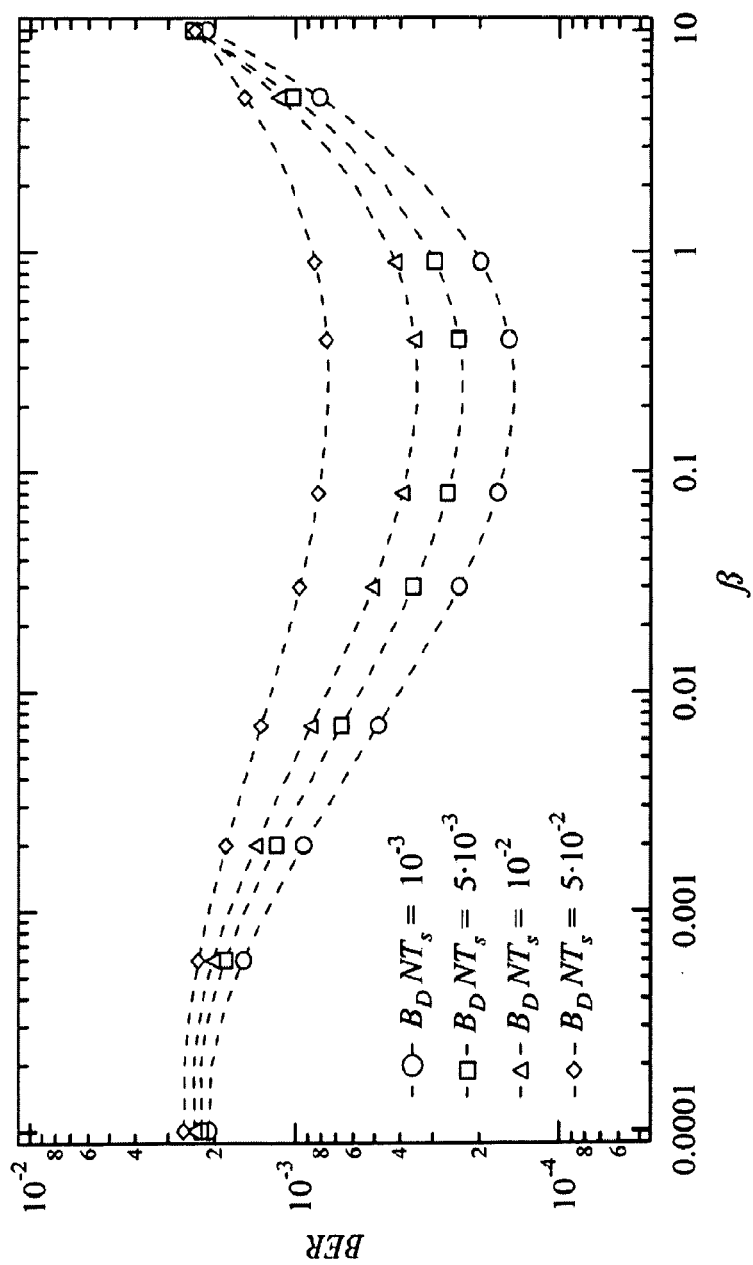


FIG. 6

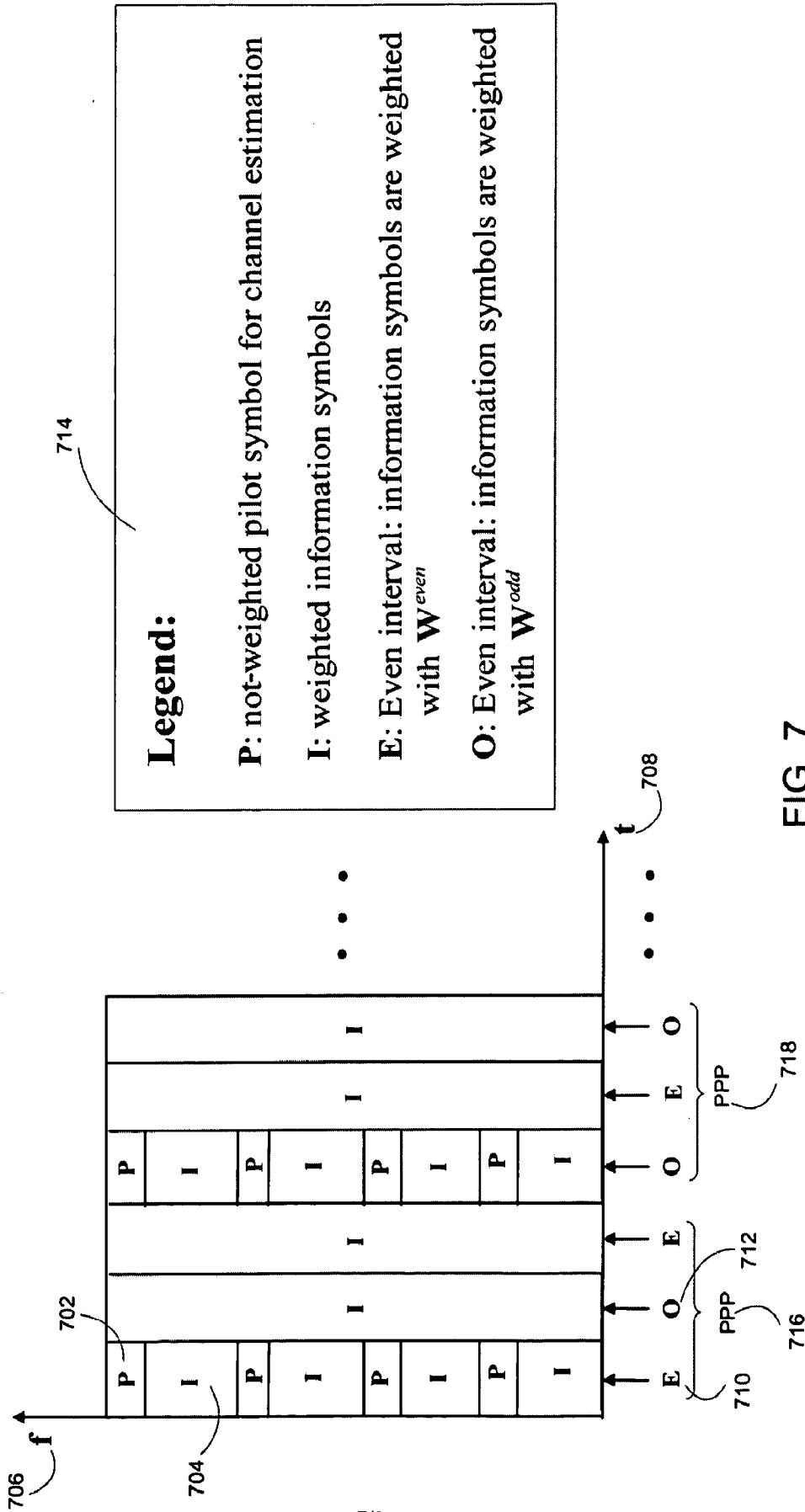


FIG. 7

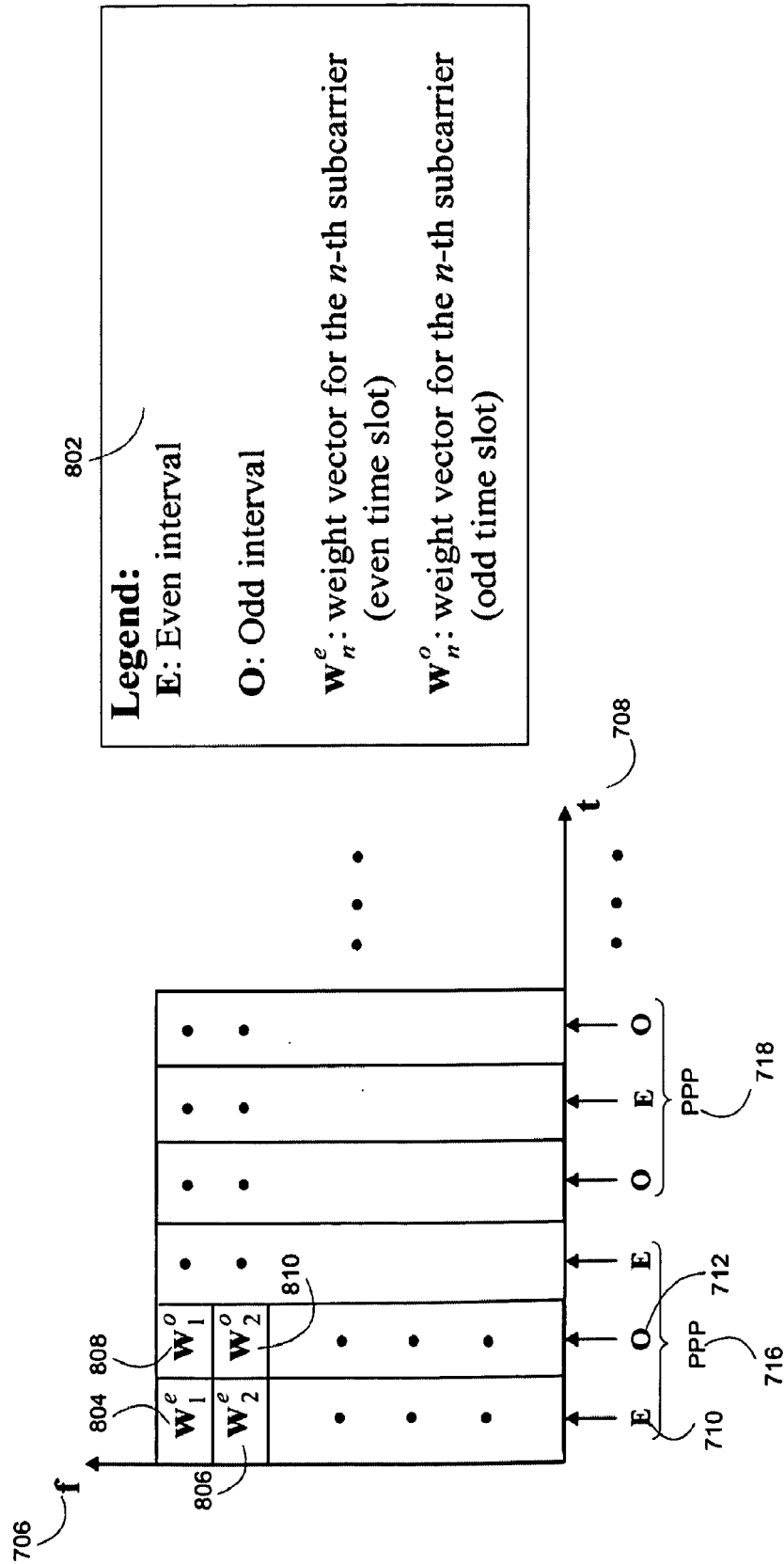


FIG. 8

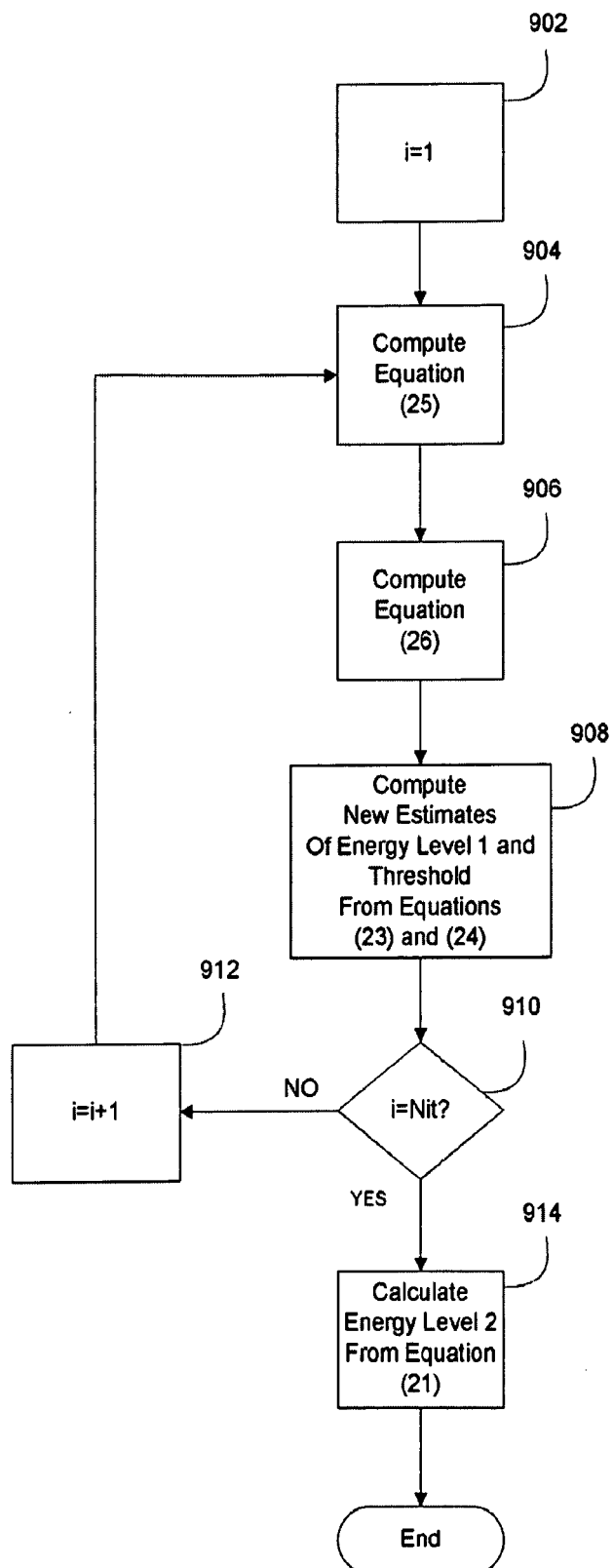
900

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2008/067546

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04J 11/00 (2008.04)

USPC - 370/203

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - H04J 11/00; H04L 7/00 (2008.04)

USPC - 370/203; 375/354

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

MicroPatent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0076582 A1 (TANAKA et al) 05 April 2007 (05.04.2007) entire document	1-21
Y	US 2007/0098094 A1 (YUE et al) 03 May 2007 (03.05.2007) entire document	1-21
Y	US 2003/0215006 A1 (RAGHOTHAMAN) 20 November 2003 (20.11.2003) entire document	5, 7, 12, 14, 19, 21

☐ Further documents are listed in the continuation of Box C.


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"&" document member of the same patent family

Date of the actual completion of the international search

07 October 2008

Date of mailing of the international search report

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