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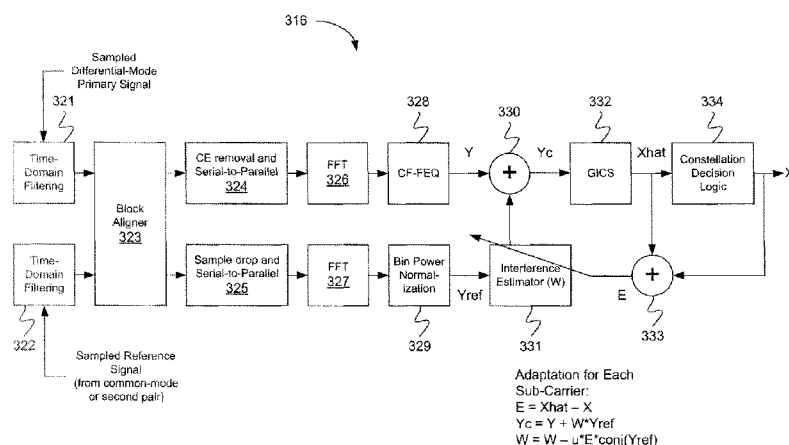


Figure 3

(57) Abstract: A method and apparatus to align data blocks in a data signal and a reference signal to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals and cancel interference in the data signal in the frequency-domain under changing conditions and in the presence of the data signal.

ADAPTIVE FREQUENCY-DOMAIN REFERENCE NOISE CANCELLER FOR MULTICARRIER COMMUNICATIONS SYSTEMS

TECHNICAL FIELD

[0001] This invention relates generally to a multi-carrier communication system and, in particular, to noise cancellation in a multi-carrier communication system.

BACKGROUND

[0002] A multi-carrier communication system, such as a Discrete Multi-Tone (DMT) system in the various types of Digital Subscriber Line (DSL), for example, asymmetric digital subscriber line (ADSL) and very high-speed digital subscriber line (VDSL) systems, carries an information bit stream from a transmitter to a receiver. The information bit stream is typically converted into a sequence of data symbols having a number of tones. Each tone may be a group of one or more frequencies defined by a center frequency and a set bandwidth. The tones are also commonly referred to as sub-carriers or sub-channels. Each tone acts as a separate communication channel to carry information between a local transmitter-receiver (transceiver) device and a remote transceiver device.

[0003] Figure 1 is a block diagram illustrating a conventional DMT receiver. A channel equalizer is used to control the spread of the data symbols after going through the channel. A cyclic prefix (CP) may be employed in such systems to simplify channel equalization to minimize a source of cross channel interference. Generally, if the length of the channel impulse response is equal to or less than the cyclic prefix length plus one sample, then channel equalization is trivial and perfect equalization can be achieved. The channel can be inverted in the frequency domain after a discrete Fourier transform (DFT) by a single complex multiply for each sub-channel. This is usually referred to as frequency-domain equalization (FEQ).

[0004] On transmission lines in DMT communication systems, such as ADSL or VDSL, the data signal is generally transmitted differentially.

Interference such as radio-frequency interference (RFI), crosstalk and impulse noise electromagnetically couples into both the common mode and the differential mode of such transmission lines. In the case of a binder containing multiple transmission lines, such interference may couple into some or all of the transmission line in the binder and such noise may be correlated between lines.

[0005] Conventional techniques for reducing differential noise, thereby improving data rates over the DSL, include use of common-mode information. In a traditional DSL system, the common-mode voltage is measured, an estimate of the differential-mode interference is constructed and the interference estimate is subtracted from the desired signal.

[0006] Traditional cancellation may occur in the time-domain or the frequency domain. For example, frequency bands containing RFI are band-pass filtered and then subtracted from the differential-mode signal in the time domain. In the frequency domain, a small set of frequency bins are used to compute and remove an estimate of RFI on a larger number of data carrying frequency bins. Other conventional systems cancel crosstalk in both the time domain and the frequency domain by solving a specific set of equations.

[0007] However, there are significant drawbacks associated with filtering and subtracting an interference estimate in the time-domain. For example, training and updating the noise estimation unit is difficult, especially in the presence of a data signal. Furthermore, time-domain subtraction tends to result in noise enhancement. A reduction in the power spectral density (PSD) of the interference may be achieved over parts of the frequency band where the interference is strongest, but interference PSD enhancement may occur in other frequency regions, resulting in sub-optimal system performance.

[0008] Known frequency-domain techniques also have significant limitations. Common-mode interference may not be limited to crosstalk or RFI alone, but may be a combination of the two. There may also be wideband noise from sources other than radio transmitters (RFI) or other communications systems (crosstalk) that is correlated between the common and differential modes. Conventional solutions are suited to target only crosstalk or RFI; not

both. Also, the interference sources and their associated coupling transfer functions will, in general, change over time. Known cancellers do not have the ability to adapt to these changing conditions in the presence of the data signal. Furthermore, in a practical implementation, there are complications and difficulties associated with the dynamic range of both the differential-mode and common-mode signals. In implementations in which the multi-carrier communications system is an ADSL or VDSL system, there may be further complications involving interaction of the canceller with On-Line Reconfiguration (OLR), Seamless Rate Adaptation (SRA), and bitswap as defined in the various ADSL and VDSL standards. During such events the transmitted power and/or the constellation size changes for one or more sub-carriers.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings.

[0010] Figure 1 is a block diagram illustrating a conventional DMT receiver.

[0011] Figure 2 is a block diagram illustrating an embodiment of a discrete multi-tone system.

[0012] Figure 3 is a block diagram illustrating one embodiment of a receiver having an adaptive frequency-domain reference noise canceller.

[0013] Figure 4 is a block diagram illustrating an alternative embodiment of a receiver having an adaptive frequency-domain reference noise canceller.

[0014] Figure 5 is a block diagram illustrating a second alternative embodiment of a receiver having an adaptive frequency-domain reference noise canceller.

[0015] Figure 6 is a flow chart illustrating one embodiment of an interference cancellation method.

[0016] Figure 7 is a flow chart illustrating one embodiment of a block alignment adjustment method.

[0017] Figure 8 is a block diagram illustrating one embodiment of a block aligner.

DETAILED DESCRIPTION

[0018] In the following description, numerous specific details are set forth, such as examples of specific commands, named components, connections, number of frames, etc., in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without these specific details. In other instances, well known components or methods have not been described in detail but rather in a block diagram in order to avoid unnecessarily obscuring the present invention. Thus, the specific details set forth are merely exemplary. The specific details may be varied from and still be contemplated to be within the scope of the present invention.

[0019] Some portions of the description that follow are presented in terms of algorithms and symbolic representations of operations on data that may be stored within a memory and operated on by a processor. These algorithmic descriptions and representations are the means used by those skilled in the art to effectively convey their work. An algorithm is generally conceived to be a self-consistent sequence of acts leading to a desired result. The acts are those requiring manipulation of quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, parameters, or the like.

[0020] The following detailed description includes several modules, which will be described below. These modules may be implemented by hardware components, such as logic, or may be embodied in machine-executable instructions, which may be used to cause a general-purpose or special-purpose processor programmed with the instructions to perform the operations described herein. Alternatively, the operations may be performed by

a combination of hardware and software.

[0021] Embodiments of a method and apparatus are described to cancel interference in a multi-carrier communications system. In one embodiment, a data signal and a reference signal are received at a receiver. The reference signal is obtained by measuring a common-mode or differential-mode voltage. A block aligner is used to align data blocks in the data and reference signals to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals. The aligned time-domain signals are transformed to the frequency-domain where interference cancellation occurs. A tone-by-tone canceller includes a decision feedback mechanism to adapt the canceller under changing conditions in the presence of the data signal in the frequency-domain.

[0022] Figure 2 is a block diagram illustrating an embodiment of a discrete multi-tone system. The discrete multi-tone system 200, such as a Digital Subscriber Line (DSL) based network, may have two or more transceivers 202 and 204, such as a DSL modem in a set top box. In one embodiment, the set top box may be a stand-alone DSL modem. In one embodiment, for example, the set top box employs a DSL modem along with other media components to combine television (Internet Protocol TV or satellite) with broadband content from the Internet to bring the airwaves and the Internet to an end user's TV set. Multiple carrier communication channels may communicate a signal to a residential home. The home may have a home network, such as an Ethernet. The home network may either use the multiple carrier communication signal directly, or convert the data from the multiple carrier communication signal. The set top box may also include, for example, an integrated Satellite and Digital Television Receiver, High-Definition Digital Video Recorder, Digital Media Server and other components.

[0023] The first transceiver 202, such as a Discrete Multi-Tone transmitter, transmits and receives communication signals from the second transceiver 204 over a transmission medium 206, such as a telephone line. Other devices such as telephone 208 may also connect to this transmission medium 206. An isolating filter 210 generally exists between the telephone

208 and the transmission medium 206. A training period occurs when initially establishing communications between the first transceiver 202 and a second transceiver 204.

[0024] The discrete multi-tone system 200 may include a central office, multiple distribution points, and multiple end users. The central office may contain the first transceiver 202 that communicates with the second transceiver 204 at an end user's location.

[0025] Each transmitter portion 217, 219 of the transceivers 202, 204, respectively, may transmit data over a number of mutually independent sub-channels i.e., tones. In a DMT communication system, data samples on each tone are represented as one of a set of finite number of points in a two-dimensional (2D) Quadrature Amplitude Modulation (QAM) constellation. The transmitted data in a multi-carrier system is usually represented by a point from a constellation of a finite set of possible data points, regularly distributed over a two dimensional space. Each sub-channel carries only a certain portion of data through QAM of the sub-carrier. The number of information bits loaded on each tone and the size of corresponding QAM constellation may potentially vary from one tone to another and depend generally on the relative power of signal and noise at the receiver. When the characteristics of signal and noise are known for all tones, a bit-loading algorithm may determine the optimal distribution of data bits and signal power amongst sub-channels. Thus, a transmitter portion 217, 219 of the transceivers 202, 204 modulates each sub-carrier with a data point in a QAM constellation.

[0026] It should be noted that embodiments of the present invention are described below in reference to receiver 316, which represents one embodiment of receiver 216, for ease of discussion, and that receiver 218 may operate in a similar manner as described below for receiver 316.

[0027] Figure 3 is a block diagram illustrating one embodiment of a receiver having an adaptive frequency-domain reference noise canceller. In this embodiment, receiver 316 includes time domain filtering modules 321, 322, block aligner 323, cyclic extension (CE) removal and serial-to-parallel module 324, sample drop and serial-to-parallel module 325, fast Fourier transform

(FFT) modules 326, 327, channel flattening frequency-domain equalizer (CF-FEQ) module 328, bin power normalization module 329, adders 330, 333, interference estimator module 331, gain inversion and constellation scaling (GICS) module 332, and constellation decision logic module 334. Additional modules and functionality may exist in the receiver 316 that are not illustrated so as not to obscure an understanding of embodiments of the present invention. It should be noted that the operations of one or more modules may be incorporated into or integrated with other modules.

[0028] In one embodiment, receiver 316 is implemented in a DMT communications system operating over a twisted-pair communications channel. N is a variable representing the number of tones used in the multi-carrier communication receiver. The communications system may operate in the presence of RFI, crosstalk and other interference. In this embodiment, received samples of a differential-mode primary data signal sent over the twisted pair are provided to a first time-domain filtering module 321. Additionally, a sampled reference signal is received and provided to a second time-domain filtering module 322. The reference signal is obtained by sampling the common-mode signal of the same twisted-pair as the primary data signal. In an alternative embodiment, the reference signal is obtained by sampling the differential mode interference from a second twisted-pair that is not used for data transmission. In another alternative embodiment, the primary data signal is obtained by sampling the differential voltage of a copper pair in a twisted copper quad and the reference signal is obtained by sampling the differential-mode interference from the other two wires of the twisted quad.

[0029] In this embodiment, receiver 316 is configured to operate independently of the source of the reference signal. A data signal and a reference signal are received and undergo digital time-domain filtering at modules 321 and 322 respectively. Receiver 316 further includes a block aligner module 323. Block aligner module 323 adjusts the relative alignment of the $2N$ -sample blocks of the primary data signal and the reference signal as needed. The block aligner module 323 may be implemented with sample-dropping capability, by programming delay First in, First out (FIFO) buffers, or

by adjusting the group delay of programmable finite impulse response (FIR) filters. The block aligner module 323 aligns the blocks such that the cross correlation of the reference signal and the primary line interference signal is increased as compared to the cross correlation of the unaligned data and reference signals. For example, the increase in cross-correlation may be in a range of approximately 50 percent to over an order of magnitude. In one embodiment, the blocks are aligned such that the cross-correlation is maximized. Block aligner module 323 will be described further below, with respect to Figure 8.

[0030] A first output of block aligner module 323 provides the aligned data signal to cyclic extension (CE) removal and serial-to-parallel module 324. A second output of block aligner module 323 provides the aligned reference signal to sample drop and serial-to-parallel module 325. Modules 324 and 325 serve to remove samples corresponding to any cyclic extension that may have been added to the data stream at the transmitter as well as convert the serial sample stream in to chunks which may be operated on in parallel.

[0031] The data signal and reference signal undergo $2N$ -point discrete Fourier transforms (DFT). In this embodiment, the DFT is computed efficiently by means of a fast Fourier transform (FFT) at FFT modules 326 and 327. The time-domain samples of both the data signal and the reference signal are provided to FFT modules 326 and 327 which convert the samples into frequency-domain symbols to be used by the canceller.

[0032] The output of FFT module 326 for the data signal is sent to a channel flattening frequency-domain equalizer (CF-FEQ) module 328. The CF-FEQ module normalizes the phase and power on each frequency bin of the data signal. In a traditional DMT system, at the output of the FFT, each frequency bin of the data signal undergoes an FEQ multiply that inverts the channel attenuation and phase rotation, inverts the fine gain adjustment value assigned to the bin, and adjusts for the constellation size. The result is such that the FEQ output is scaled to an integer grid for decoding. In this embodiment of the present invention, the traditional FEQ is split into a CF-FEQ module 328 and a gain inversion and constellation scaling (GICS) module

332. The two stage approach allows the data signal from the output of FFT module 326 to be normalized for computationally efficient removal of interference using integer arithmetic. It also decouples on-line reconfiguration (OLR), seamless rate adaptation (SRA) and bitswap from the reference noise canceller. That is, the reference noise canceller taps do not need to change during or after such an event.

[0033] The output of FFT module 327 for the reference signal undergoes a scaling stage in which the power on each frequency bin of the reference signal is normalized. The bin-power normalization module 329 receives the output of FFT module 327 and corrects amplitude and phase distortion in the reference signal. The bin-power normalization module 329 produces a normalized reference channel output signal Y_{ref} .

[0034] The normalized reference channel output signal Y_{ref} is provided to an interference estimator module 331. Interference estimator module 331 multiplies the reference signal Y_{ref} by a single complex tap for each frequency bin thus forming an estimate of the interference in the differential-mode signal for each bin. This estimate is subtracted from the normalized primary channel output signal Y provided by the CF-FEQ module 328. The subtraction is performed by adder 330 and results in a canceller output signal Y_c . The canceller output signal Y_c is provided to an input of the GICS module 332.

[0035] GICS module 332 adjusts the signal for per-bin gain and constellation size. The GICS module 332 produces an output signal X_{hat} which is provided to an input of a constellation decision logic module 334. In the constellation decision logic module 334, the signal X_{hat} undergoes constellation decoding where constellation decisions are formed. The constellation decision logic module 334 may include a trellis decoder or a simple un-coded constellation decoder or slicer. Constellation decision logic module 334 produces a constellation decision signal X . The constellation decision signal X is subtracted from the GICS module output signal X_{hat} to form a decision error estimate E . The subtraction is performed by adder 333. The decision error estimate E is used to adaptively update the canceller taps in the interference estimator module 331. In one embodiment, a least-mean-

square (LMS) algorithm is used to update the taps. In alternative embodiments, other algorithms may be used to update the taps such as a recursive least square (RLS) algorithm, a gradient computation, or other algorithm. The structure of receiver 316 allows the canceller to adapt under changing conditions, such as interference sources and their associated coupling transfer functions, and effectively cancel interference in the presence of the actual data signal.

[0036] Figure 4 is a block diagram illustrating an alternative embodiment of a receiver 416 having an adaptive frequency-domain reference noise canceller. In this embodiment, the CF-FEQ module 328 of Figure 3 is removed and the GICS module 332 of Figure 3 is replaced with FEQ module 435. FEQ module 435 receives the canceller output signal Y_c at an input and provides the decoder input signal X_{hat} to constellation decision logic module 334. The canceller output signal Y_c is obtained by subtracting the interference estimate directly from the primary channel output Y of FFT module 326. The reference signal is processed in the same manner as described above with respect to Figure 3.

[0037] Figure 5 is a block diagram illustrating a second alternative embodiment of a receiver having an adaptive frequency-domain reference noise canceller. In this embodiment, the CF-FEQ module 328 of Figure 3 is replaced with FEQ module 536 and GICS module 332 of Figure 3 is removed. FEQ module 536 receives the output of FFT module 326 at an input and provides an FEQ output signal Y to adder 330. Bin power normalization module 329 of Figure 3 has also been removed in this embodiment. The reference channel output Y_{ref} of the FFT module 327 is directly multiplied by a single complex tap to form an interference estimate at interference estimator module 331. The interference estimate is subtracted from the FEQ output signal Y at adder 330 and the canceller output Y is provided directly to the constellation decision logic module 334.

[0038] Figure 6 is a flow chart illustrating one embodiment of an interference cancellation method 600. The process 600 may be performed by processing logic that comprises hardware, firmware, software, or a combination

thereof. In one embodiment, process 600 is performed by the receiver 316 of Figure 3.

[0039] Referring to Figure 6, interference cancellation method 600 reduces the interference in a data signal in a multi-carrier communications system. At block 610, method 600 aligns data blocks from a received data signal and a reference signal to increase cross correlation between the data signal and the reference signal as compared to the unaligned data and reference signals. The block alignment process will be discussed further below with respect to Figure 7.

[0040] At block 620, method 600 drops unneeded samples corresponding to the cyclic extension of the data signal from the aligned data and reference signals. Method 600 also removes any cyclic extension that may have been added to the data stream at the transmitter as well as converts the serial sample stream in to chunks which may be operated on in parallel. At block 630, method 600 transforms the data and reference signals from the time-domain to the frequency-domain. The transformation may be accomplished with the use of a discrete Fourier transform (DFT). In one embodiment, the DFT is performed by FFT modules 326 and 327 of Figure 3.

[0041] At block 640, method 600 normalizes the power on each frequency bin of the data and reference signals. Method 600 corrects any amplitude and phase distortion in the signal to enable efficient noise cancellation. At block 650, the data signal undergoes a constellation decision logic stage where constellation decisions are formed. The output of the constellation decision logic is subtracted from the input to form an error estimate. The error estimate is used to adaptively update canceller taps at block 660. In one embodiment, a least-mean-square (LMS) algorithm is used to update the taps. In alternative embodiments, other algorithms may be used to update the taps such as a recursive least square (RLS) algorithm, a gradient computation, or other algorithm.

[0042] At block 670, method 600 multiplies the transformed reference signal by a single complex tap for each of one or more frequency bins of the reference signal. The multiplication results in an estimate of the interference in

the data signal. At block 680, method 600 subtracts the interference estimate from the data signal. The subtraction results in a canceller output signal which is then applied to an input the constellation decision logic and method 600 continues at block 650 with the new input. In this manner, method 600 is able to adaptively update the interference canceller with an interference estimate to cancel changing sources of interference during data transmission.

[0043] Figure 7 is a flow chart illustrating one embodiment of a block alignment adjustment method 700. The process 700 may be performed by processing logic that comprises hardware, firmware, software, or a combination thereof. In one embodiment, process 700 is performed by the block aligner 323 of Figure 3.

[0044] Referring to Figure 7, block alignment adjustment method 700 enables alignment of data blocks from at least a received data signal and a reference signal to increase cross correlation between the data signal and the reference signal as compared to the unaligned data and reference signals. Alignment of the data blocks allows for the canceller to achieve optimal noise cancellation. At block 710, method 700 sets the block alignment to a default value. In one embodiment, the default value may be zero offset in both the data signal and the reference signal.

[0045] At block 720, method 700 collects $2N$ time-domain samples from each of the time domain signal and the reference signal. In one embodiment, the collection of each of the two sets of $2N$ samples begins at the same absolute time. This results in the $2N$ -sample blocks of the data signal and reference signal being roughly-aligned.

[0046] At block 730, method 700 performs cross-correlation of the data and reference signals and computes a peak offset value. Block alignment fine tuning is performed by using the cross-correlation of the interference on the data and reference signals. The measurement occurs when the data signal is not present, such as before modem training commences or at a time during modem training when the far-end transmitter is quiet. After dual $2N$ -sample blocks are captured at block 720, the cross correlation is computed as

$$(y*y_{ref})[n]=\sum_j y[j]*y_{ref}*[n+j]$$

(1)

j

where y is a block of $2N$ samples from the data signal in the time-domain during a quiet period, y_{ref} is the corresponding block of $2N$ samples from the reference signal in the time-domain during the same time period, n is the peak offset between the data and reference signals and j is a counting index. The offset is found by determining the values of n for which the cross correlation $(y*y_{ref})[n]$ is greater than when there is no offset (i.e. $n=0$). In one embodiment method 700 may determine the value of n for which the cross correlation is a maximum. A range of values for n may result in increased cross correlation, however as the values become nearer the value which results in maximum cross-correlation, the efficiency of the interference cancelling increases.

Method 700 selects one value of n to use as the offset in the block aligner.

[0047] At block 740, method 700 makes a determination as to whether the selected value of n is greater or less than zero. If n is greater than zero, method 700 proceeds to block 750. At block 750, method 700 adjusts the block alignment by the offset n samples. In one embodiment, method 700 increases the delay in the data signal by n samples and in an alternative embodiment, method 700 decreases the delay in the reference signal by n samples. If n is less than zero, method 700 proceeds to block 760. At block 760, method 700 adjusts the block alignment by the offset, n samples. In one embodiment, method 700 increases the delay in the reference signal by $(-n)$ samples and in an alternative embodiment, method 700 decreases the delay in the data signal by $(-n)$ samples. After the block alignment has been adjusted at either block 750 or 760, method 600 ends.

[0048] Figure 8 is a block diagram illustrating one embodiment of a block aligner 823. The block aligner 823 includes two D-sample delay FIFO buffers 883, 893. A first FIFO buffer 883 is in the primary data signal path and a second FIFO buffer 893 is in the reference signal path. If the delay through both time-domain filtering blocks 321, 322 is equivalent, and the Serial-to-Parallel blocks 324, 325 are synchronized such that sample collection for each

block begins at the same time on both channels, then the block aligner 823 in this form allows for a plus or minus D-sample fine-tuning delay adjustment between the primary and reference paths. In an alternative embodiment, finite impulse response (FIR) filters are used in place of FIFO buffers 883, 893. Block aligner 823 aligns the blocks of the data and reference signals such that there is an increase in the cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals.

[0049] In one embodiment, the methods described above may be embodied onto a machine-readable medium. A machine-readable medium includes any mechanism that provides (e.g., stores and/or transmits) information in a form readable by a machine (e.g., a computer). For example, a machine-readable medium includes read only memory (ROM); random access memory (RAM); magnetic disk storage media; optical storage media; flash memory devices; DVD's, or any type of media suitable for storing electronic instructions. The information representing the apparatuses and/or methods stored on the machine-readable medium may be used in the process of creating the apparatuses and/or methods described herein.

[0050] While some specific embodiments of the invention have been shown the invention is not to be limited to these embodiments. The invention is to be understood as not limited by the specific embodiments described herein, but only by the scope of the appended claims.

CLAIMS

What is claimed is:

1. A method comprising:
receiving a data signal and a reference signal; and
aligning data blocks in the data signal with data blocks in the reference signal to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals.
2. The method of claim 1, wherein aligning the data blocks comprises introducing a first delay into the data signal and introducing a second delay into the reference signal.
3. The method of claim 2, wherein introducing a first delay comprises programming a first programmable delay First in, First out (FIFO) buffer and introducing a second delay comprises programming second programmable delay FIFO buffer.
4. The method of claim 2, wherein introducing a first delay and a second delay comprises adjusting the group delay of a first programmable finite impulse response (FIR) filter and a second programmable FIR filter.
5. The method of claim 3 further comprising:
generating an interference estimate by multiplying the aligned reference signal by a single complex tap for each of one or more frequency bins of the reference signal; and
subtracting the interference estimate from the aligned data signal.
6. An apparatus comprising:
a block aligner configured to align data blocks in a data signal received from a data line with data blocks in a reference signal received from a reference

line to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals.

7. The apparatus of claim 6, wherein the block aligner comprises a first delay module coupled to the data line and configured to introduce a first delay into the data signal and a second delay module coupled to the reference line and configured to introduce a second delay into the reference signal.

8. The apparatus of claim 7, wherein the first and second delay modules comprise programmable delay First in, First out (FIFO) buffers.

9. The apparatus of claim 7, wherein the first and second delay modules comprise programmable finite impulse response (FIR) filters.

10. The apparatus of claim 7, further comprising:
a tone-by-tone canceller coupled to the block aligner and configured to operate in the frequency domain and cancel interference in the data signal.

11. A method comprising:
generating an interference estimate for a received data signal; and
adaptively updating an interference canceller with the interference estimate to cancel changing sources of interference during data transmission.

12. The method of claim 11, wherein generating an interference estimate comprises:
generating an error estimate in the data signal;
adaptively updating canceller taps with the error estimate; and
multiplying a reference signal by a single complex canceller tap for each of one or more frequency bins of the reference signal.

13. The method of claim 12, wherein generating an error estimate comprises subtracting an output of a constellation decision logic module from an input of the constellation decision logic module.
14. The method of claim 12, wherein adaptively updating the canceller tap comprises using the error estimate in a least-mean-square algorithm.
15. The method of claim 12, wherein adaptively updating the canceller tap comprises using the error estimate in a recursive least square algorithm.
16. The method of claim 11, wherein adaptively updating the interference canceller comprises subtracting the interference estimate from the data signal.
17. The method of claim 16, further comprising:
 - aligning blocks of the data signal with blocks of a reference signal to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals.
18. An apparatus comprising:
 - a tone-by-tone canceller operating in the frequency domain, configured to reduce interference in a data signal.
19. The apparatus of claim 18, wherein the tone-by-tone canceller comprises:
 - a constellation decision logic module to perform constellation decoding;
 - a first adder coupled to the constellation decision logic module and configured to subtract an output of the constellation decision logic module from an input of the constellation decision logic module to form an error estimate.;
 - an interference estimator module coupled to the first adder and configured to receive the error estimate; and

a second adder coupled to the interference estimator module and configured to subtract the interference estimate from the data signal.

20. The apparatus of claim 19, wherein the constellation decision logic module comprises a trellis decoder.

21. The apparatus of claim 19, wherein the constellation decision logic module comprises an un-coded constellation decoder.

22. The apparatus of claim 19, further comprising:
a block aligner coupled to the tone-by-tone canceller, wherein the block aligner is configured to align data blocks in the data signal and a reference signal to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals.

23. A method comprising:
aligning blocks of a received data signal with blocks of a received reference signal to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals; and
canceling interference in the data signal in the frequency domain.

24. The method of claim 23, further comprising:
dropping unneeded samples corresponding to a cyclic extension of the data signal from the aligned data and reference signals.

25. The method of claim 24, further comprising:
transforming the aligned data and reference signals from the time-domain to the frequency-domain.

26. The method of claim 25, further comprising:

normalizing a power of one or more frequency bins of both the transformed data signal and the transformed reference signal.

27. The method of claim 26, further comprising:

generating an interference estimate by multiplying the transformed reference signal by a single complex tap for each of the one or more frequency bins of the reference signal.

28. The method of claim 27, wherein canceling interference in the data signal comprises subtracting the interference estimate from the transformed data signal.

29. An apparatus comprising:

a block aligner configured to align data blocks in a data signal and a reference signal to increase cross-correlation between the data signal and the reference signal as compared to the unaligned data and reference signals; and

a tone-by-tone canceller coupled to the block aligner, the canceller operating in the frequency domain to cancel interference in the data signal.

30. The apparatus of claim 29, wherein the block aligner comprises a first delay module configured to introduce a first delay into the data signal and a second delay module configured to introduce a second delay into the reference signal.

31. The apparatus of claim 30, wherein the tone-by-tone canceller comprises:

a constellation decision logic module to perform constellation decoding;

a first adder coupled to the constellation decision logic module and configured to subtract an output of the constellation decision logic module from an input of the constellation decision logic module to form an error estimate.;

a interference estimator module coupled to the first adder and configured to receive the error estimate; and

a second adder coupled to the interference estimator module and configured to subtract the interference estimate from the data signal.

32. The apparatus of claim 31, further comprising:

a cyclic extension removal and serial-to-parallel module coupled to the block aligner and configured to remove a number of redundant samples from the data signal; and

a sample drop and serial-to-parallel module coupled to the block aligner and configured to remove a same number of samples from the reference signal as were removed from the data signal.

33. The apparatus of claim 32, further comprising:

a first fast Fourier transform (FFT) module coupled to the cyclic extension and serial-to-parallel module to transform the data signal from the time-domain to the frequency-domain; and

a second FFT module coupled to the sample drop and serial-to-parallel module to transform the reference signal from the time-domain to the frequency-domain.

34. The apparatus of claim 33, further comprising:

a channel flattening frequency domain equalizer (CF-FEQ) module coupled to the first FFT module and configured to receive an output of the first FFT module and provide an output to an adder;

a gain inversion and constellation scaling (GICS) module coupled to the second adder and configured to receive an output of the adder; and

a bin power normalization module coupled to the second FFT module and configured to receive an output of the second FFT module.

35. The apparatus of claim 34, wherein the GICS module is further configured to decouple on-line reconfiguration (OLR), seamless rate adaptation (SRA) and bitswap from the tone-by-tone canceller.

36. An apparatus, comprising:
means for receiving a data signal and a reference signal; and
means for aligning data blocks in the data signal with data blocks in the reference signal to maximize cross-correlation between the data signal and the reference signal.
37. The apparatus of claim 36, wherein the means for receiving comprises means for performing time-domain filtering of the data signal and the reference signal.
38. The apparatus of claim 36, further comprising:
means for collecting $2N$ time-domain samples of the data signal and the reference signal.
39. The apparatus of claim 38, further comprising:
means for performing cross-correlation of the data signal and the reference signal and computing a peak offset value of the samples.
40. The apparatus of claim 39, further comprising:
means for introducing a first delay into the data signal and a second delay into the reference signal.
41. The apparatus of claim 40, further comprising:
means for generating an interference estimate for the data signal; and
means for adaptively updating an interference canceller with the interference estimate during data transmission.

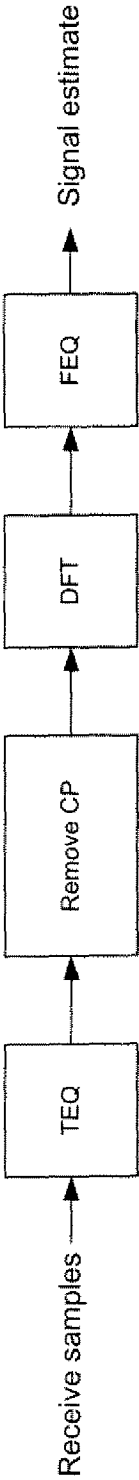


Figure 1

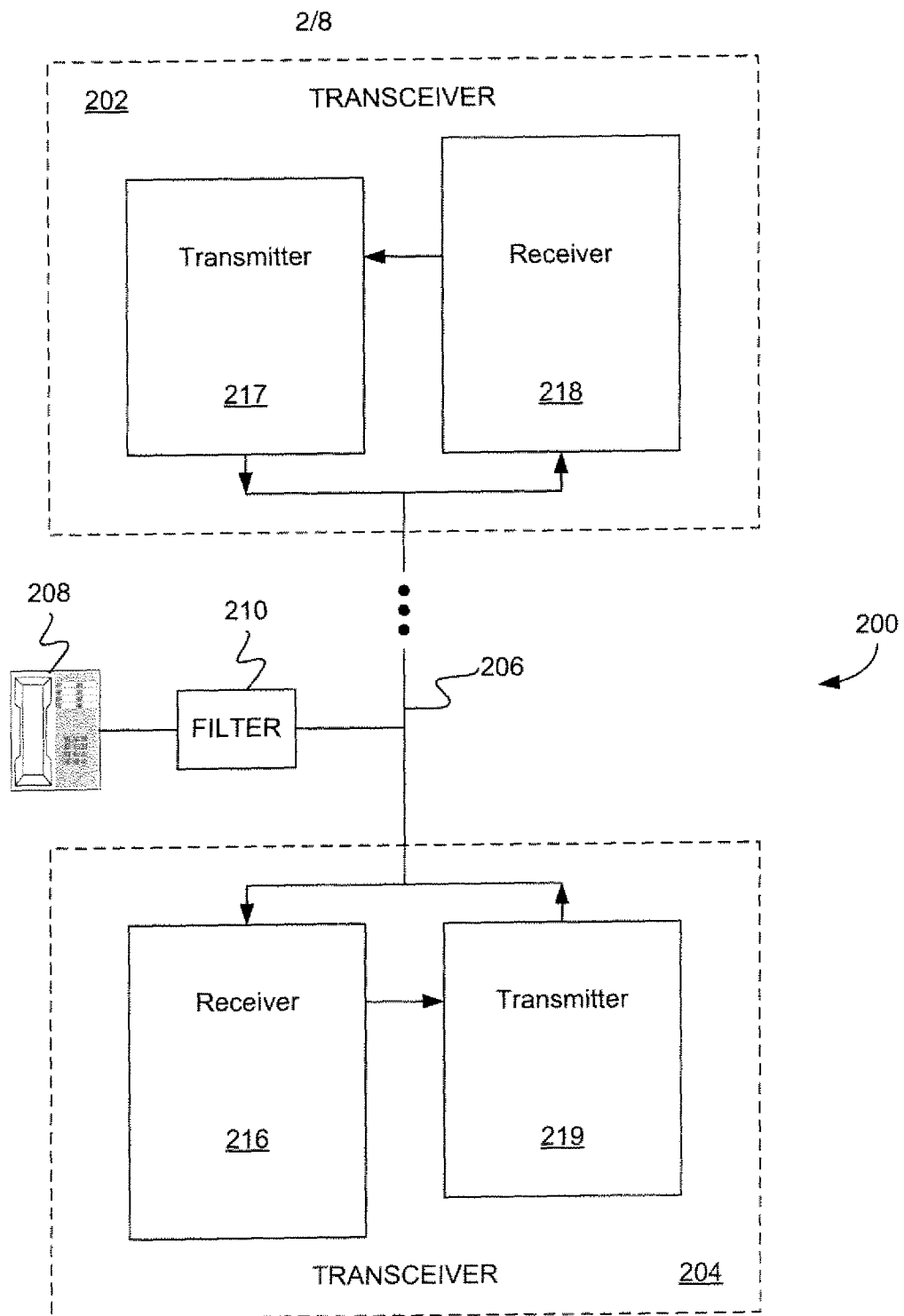


Figure 2

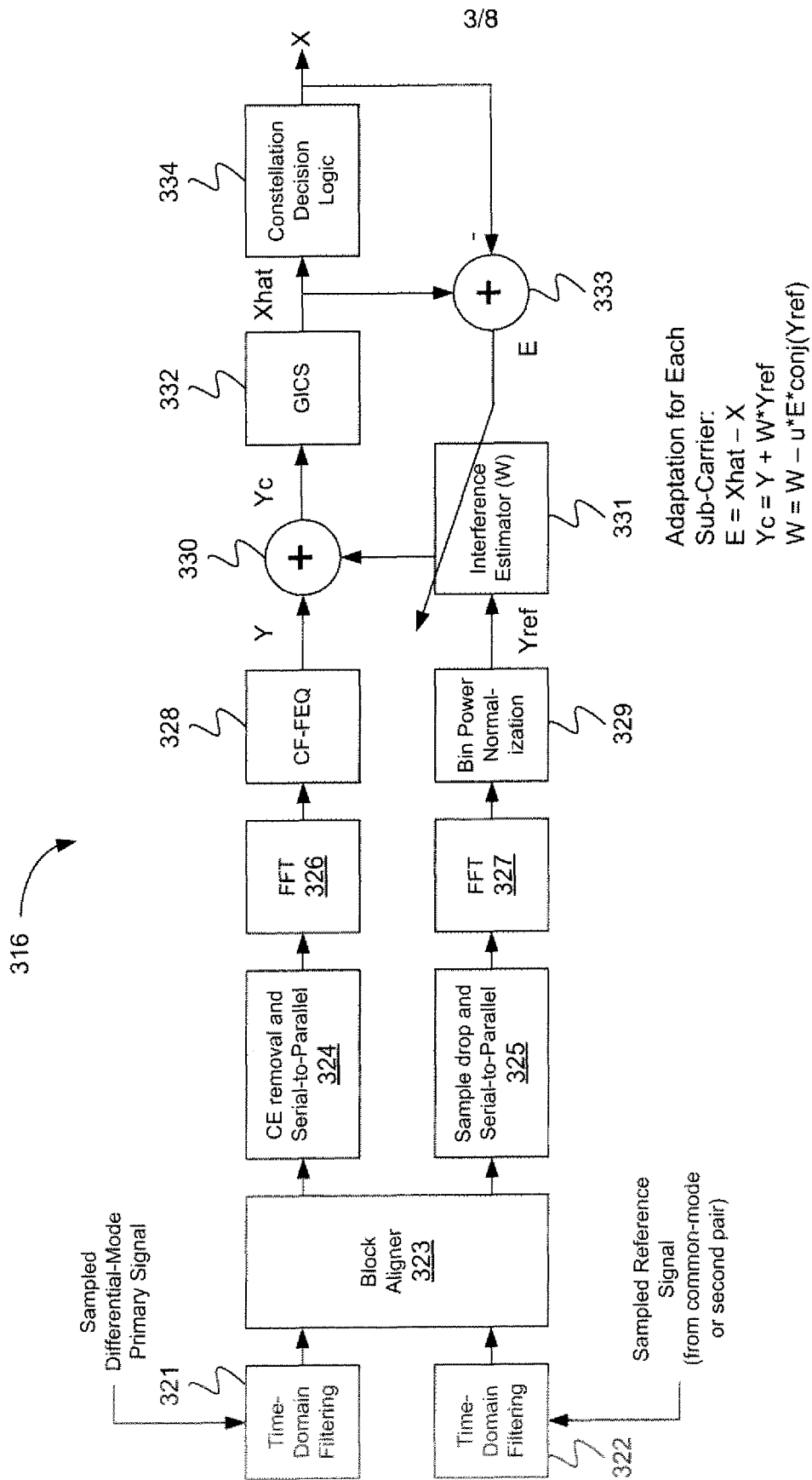


Figure 3

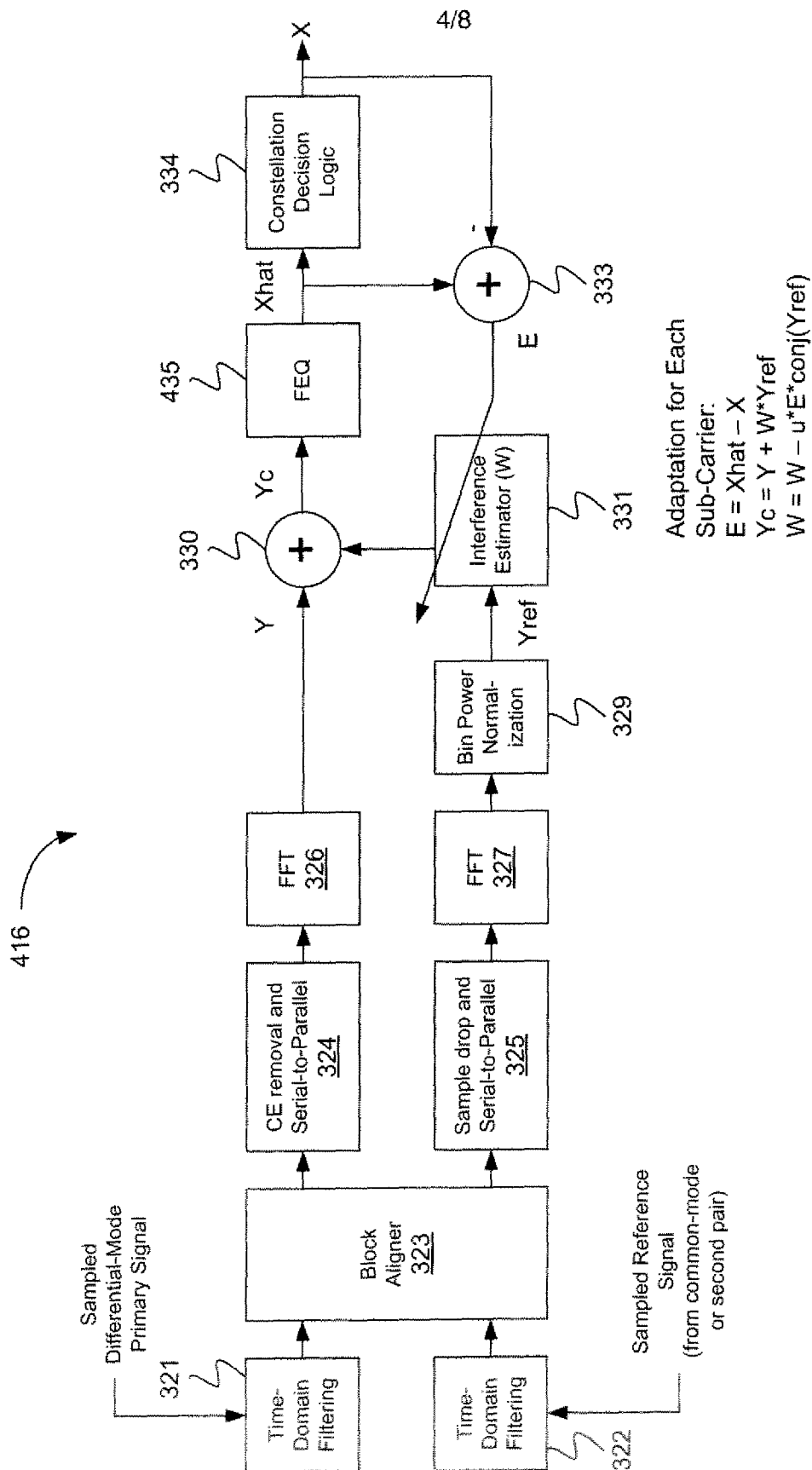


Figure 4

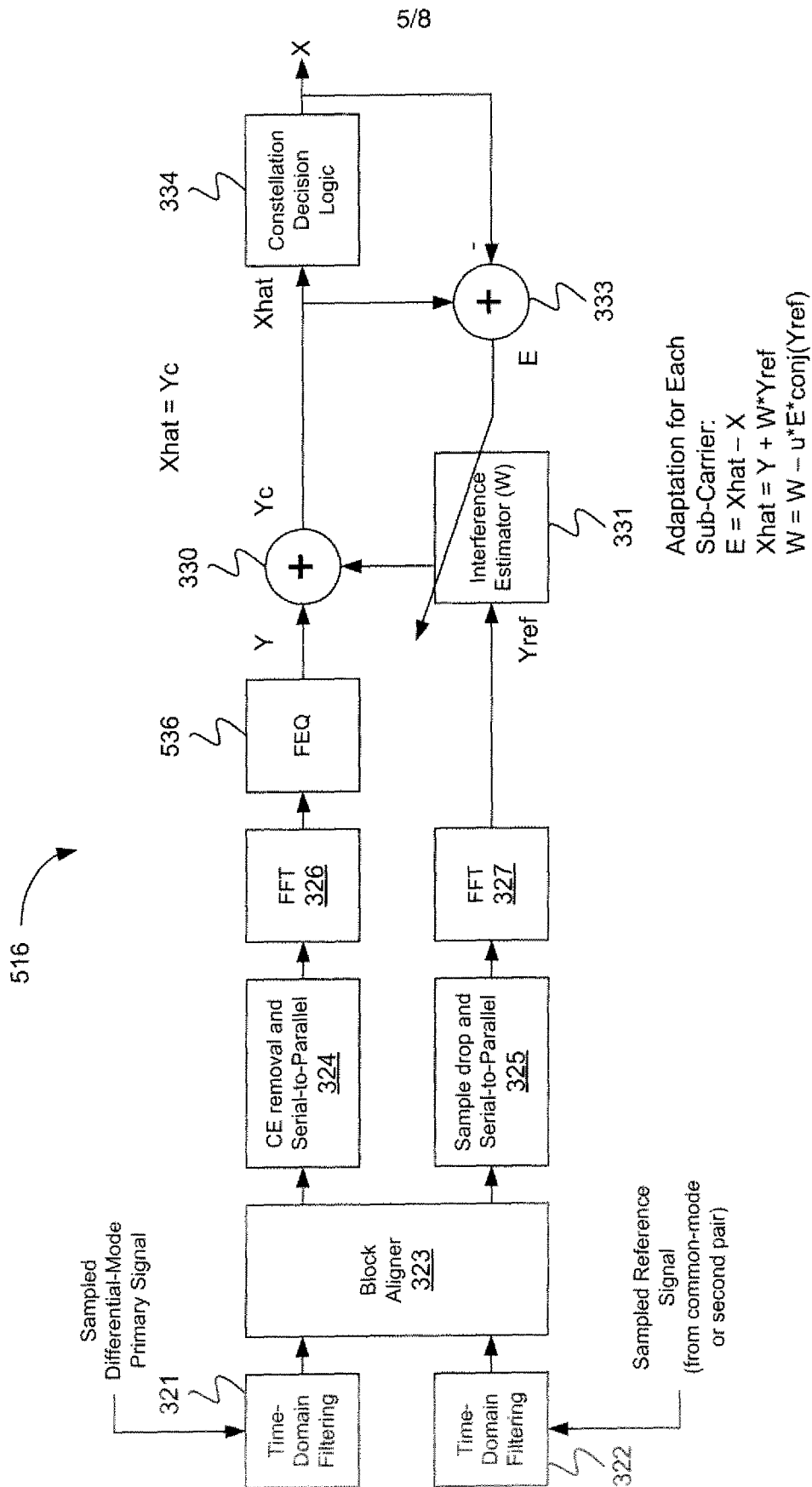


Figure 5

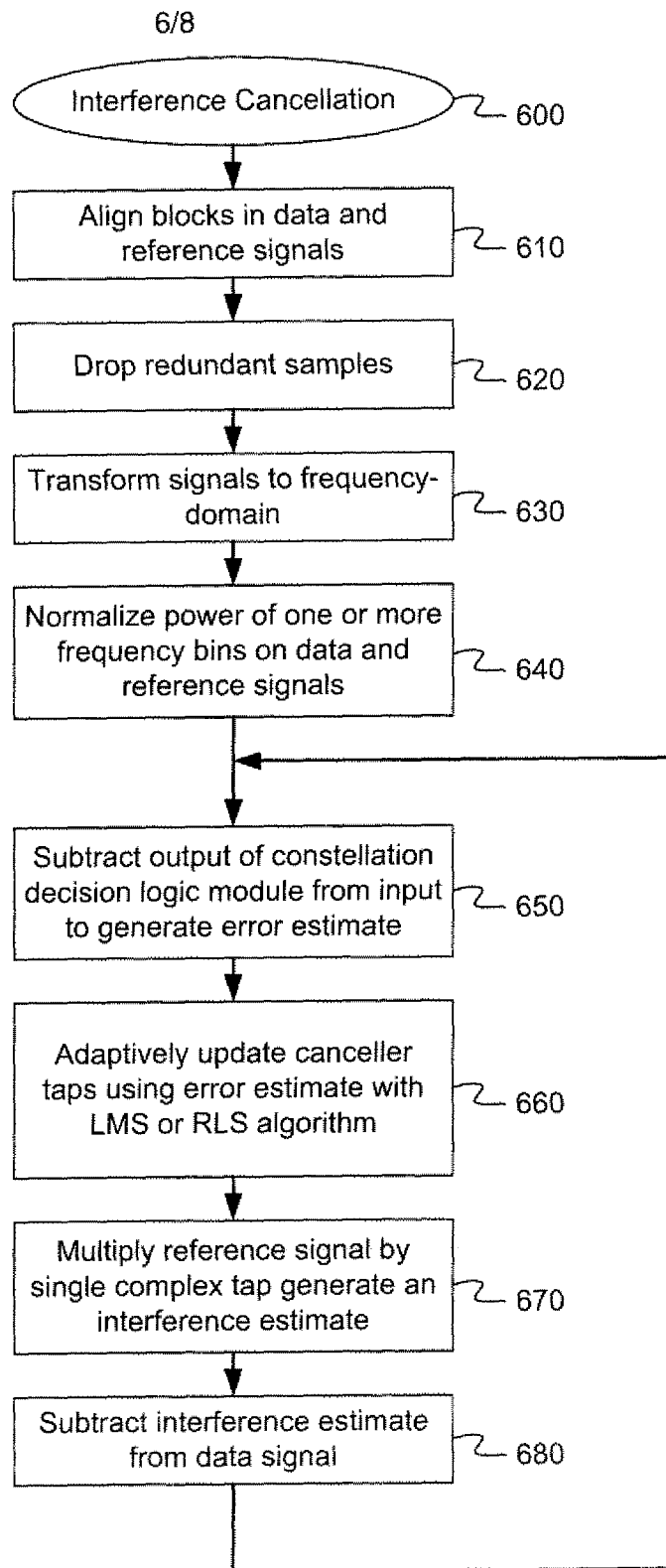


Figure 6

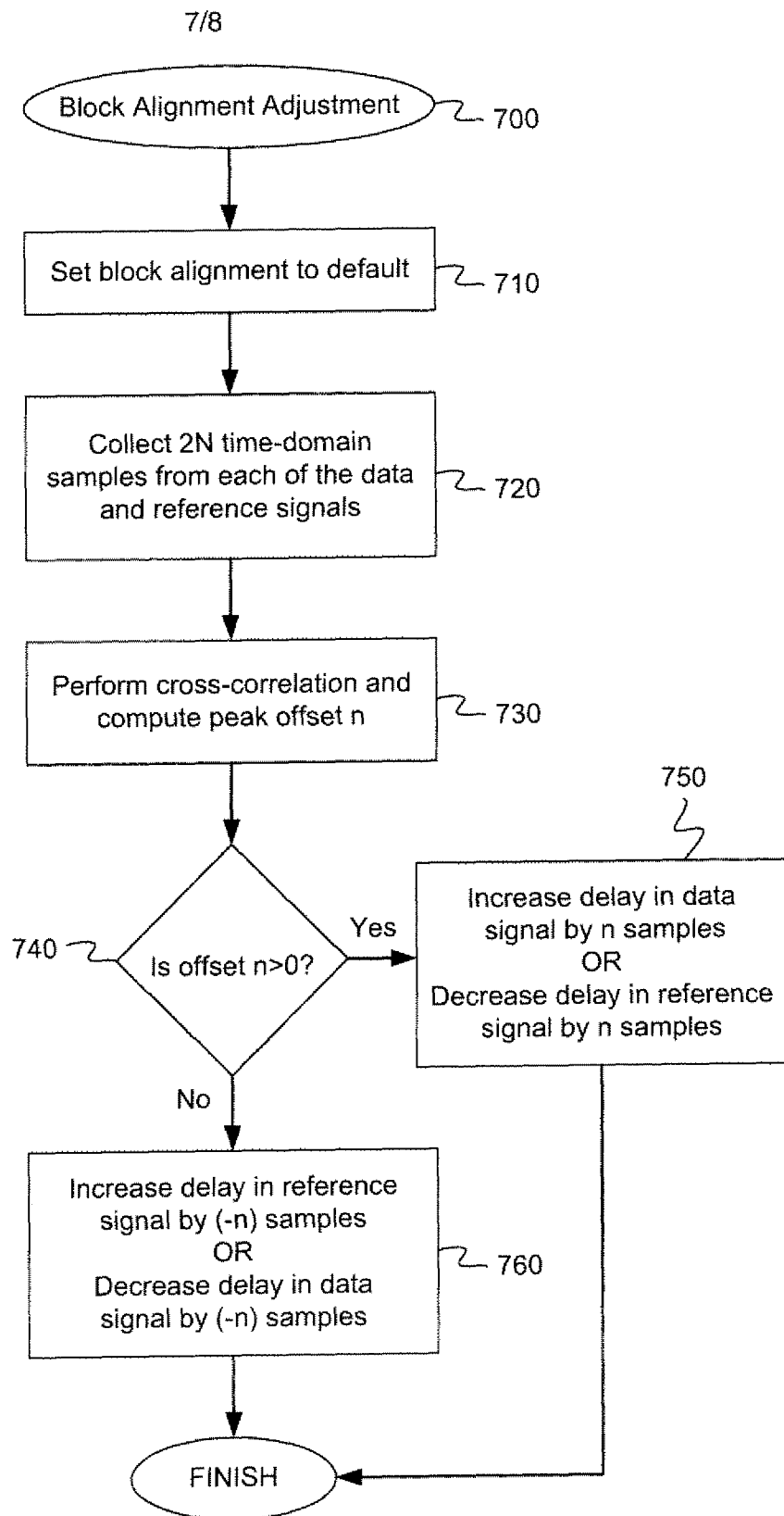


Figure 7

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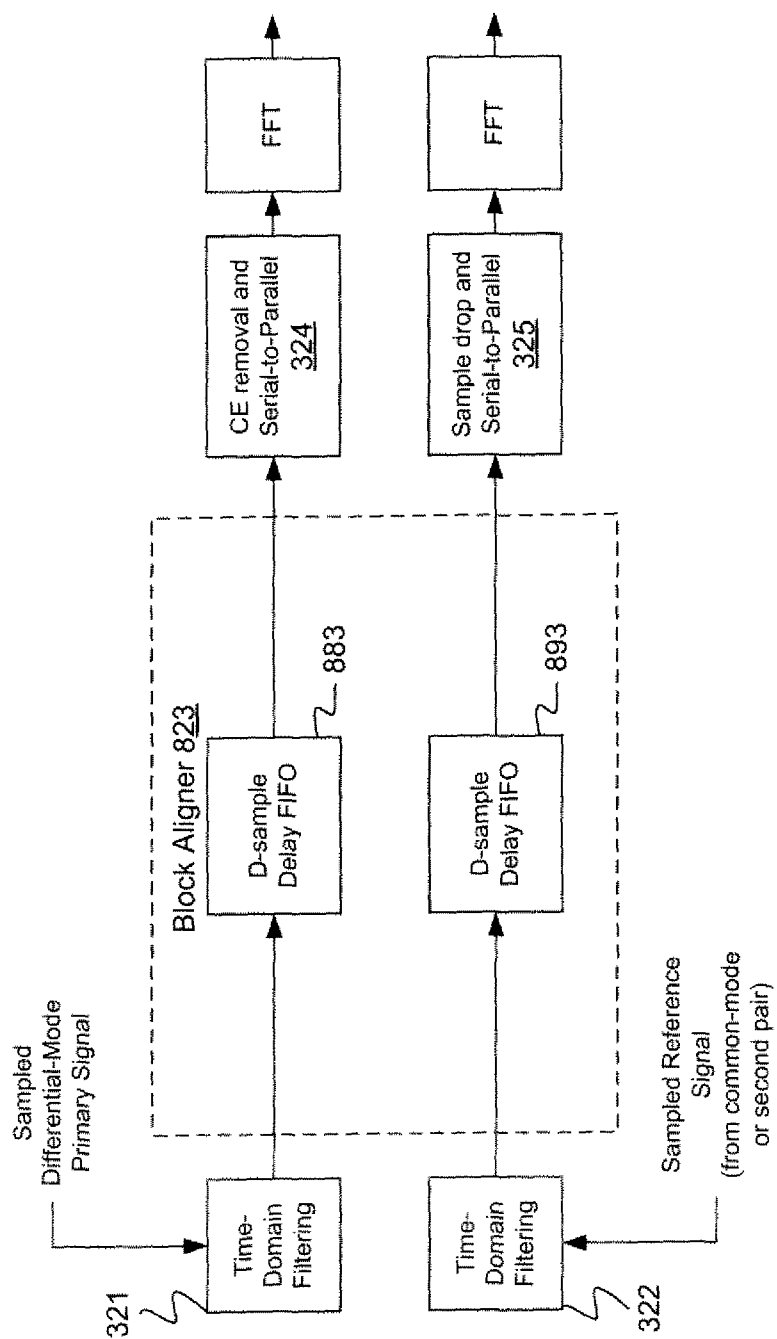


Figure 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 09/58821

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04B 1/10 (2009.01)

USPC - 375/254

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)

USPC: 375/254

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

USPC: 375/242, 254 (text search--see below)

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

PubWest (PGPB,USPT,EPAB,JPAB); Google Scholar

Search terms: FIFO, align, reference, signal, interference, canceller, DMT, cross-talk, DSL, correlate, delay, FIFO, FIR, frequency, bin, tap, FEQ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2005/0099967 A1 (BABA) 12 May 2005 (12.05.2005) FIG. 1 and para [0049]-[0051], [0059]-[0061]	11, 16 ----- 3, 5, 8, 12-15, 17
X --- Y	US 6,763,061 B1 (STRAIT et al.) 13 July 2004 (13.07.2004) FIGs. 1 and 3, and col. 4, ln 21 to col. 7, ln 34	18 ----- 5, 10, 12-15, 19-22, 24-35, 37-41
Y	US 7,174,022 B1 (ZHANG et al.) 06 February 2007 (06.02.2007) FIGs. 2, 5 and 8, and col. 5, ln 46-54, col. 9, ln 14 to col. 10, ln 14, col. 11, ln 53 to col. 12, ln 43, and col. 13, ln 10-45	1-10, 22-41
Y	US 2005/0159128 A1 (COLLINS et al.) 21 July 2005 (21.07.2005) para [0054]	1-10, 17, 22-41
Y	US 2002/0154620 A1 (AZENKOT et al.) 24 October 2002 (24.10.2002) FIG. 10 and para [0078], [0194], [0393]	19-22, 31-35
Y	US 2007/0217492 A1 (COX et al.) 20 September 2007 (20.09.2007) para [0044]	35

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

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

15 November 2009 (15.11.2009)

Date of mailing of the international search report

02 DEC 2009

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents

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