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(54) **Title:** IMPROVED CHANNEL ESTIMATION IN OFDM COMMUNICATION SYSTEMS

(57) **Abstract:** Embodiments of the present disclosure include an OFDM receiver circuit, which includes an FFT circuit configured to calculate an FFT of a plurality of sample values received by the receiver circuit, and a smoothing circuit configured to identify equalizer coefficients for the sample values by truncating portions of an impulse response of the FFT.

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Improved Channel Estimation In OFDM Communication Systems

RELATED PATENT APPLICATION

This application claims priority to commonly owned U.S. Provisional Patent Application No. 62/359,352; filed July 7, 2016, which is hereby incorporated by reference herein for all purposes.

TECHNICAL FIELD

The present disclosure relates to wireless data communication systems and, in particular, orthogonal frequency domain multiplexing (OFDM) systems and channel estimation thereof.

BACKGROUND

OFDM systems encode and decode digital data on multiple carrier frequencies. OFDM may form the basis of wireless communication protocols such as IEEE 802.11-compliant systems. Performance of wireless systems may be evaluated based upon the range of signals thereof and data transfer rates thereof that may be reliably provided for intended applications. Receiver sensitivity may refer to the minimum input power required for a receiver (RX) to perform at or better than specified requirements. The specified requirements may be made by the relevant IEEE standard. Currently, the preferred signaling technique in wireless communication is OFDM. An OFDM receiver requires the wireless channel to be estimated prior to data demodulation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is an illustration of an example system 100 for improved channel estimation, according to embodiments of the present disclosure.

FIGURES 2A-2D are an illustration of example operation of system 100, according to embodiments of the present disclosure.

FIGURE 3 illustrates null sub-carriers, according to embodiments of the present disclosure.

FIGURE 4 illustrates operation of the system to perform an iterative time domain truncation algorithm, according to embodiments of the present disclosure,

FIGURE 5 illustrates an example embodiment of operation of the system to perform a least-square time-domain truncation, according to embodiments of the present disclosure.

FIGURE 6 is illustrates an example embodiment of operation of the system to perform a least-square time-domain truncation in combination with matrix-based FFT operation, according to embodiments of the present disclosure.

FIGURE 7 illustrates an example embodiment of operation of the system to perform a least-square estimate to estimate the null-subcarriers, according to embodiments of the present disclosure.

SUMMARY

Embodiments of the present disclosure include an OFDM receiver circuit, comprising an FFT circuit and a smoothing circuit. The FFT circuit may be configured to calculate an FFT of a plurality of sample values received by the receiver circuit. In combination with any of the above embodiments, the smoothing circuit may be configured to identify equalizer coefficients for the sample values by truncating portions of an impulse response of the FFT. In combination with any of the above embodiments, the smoothing circuit may be further configured to identify the equalizer coefficients by truncating portions of the impulse response of the FFT beyond a defined length of the impulse response. In combination with any of the above embodiments, the smoothing circuit may be further configured to identify the equalizer coefficients by performing an inverse FFT on channel frequency response of the plurality of sample values, truncating portions of the impulse response in results of the inverse FFT, and performing an FFT on results of the truncation. In combination with any of the above embodiments, the smoothing circuit is further configured to estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values, perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier, truncate portions of the impulse response in results of the inverse FFT, and perform an FFT on results of the truncation. In combination with any of the above embodiments, the smoothing circuit may be further configured to estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values, perform an inverse FFT on

channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier, truncate portions of the impulse response in results of the inverse FFT, perform an FFT on results of the truncation, evaluate whether results of the truncation have converged, and, based on whether results of the truncation have converged, determine whether to repeat performance of the inverse FFT, truncation, and performance of the FFT. In combination with any of the above embodiments, the smoothing circuit may be further configured to estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values, perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier, truncate portions of the impulse response in results of the inverse FFT, perform an FFT on results of the truncation, and, based on a determination that results of the truncation have not converged, repeat performance of the inverse FFT, truncation, and performance of the FFT using the channel frequency response of the plurality of sample values and a value of the null sub-carrier resulting from previous performance of the inverse FFT, truncation, and performance of the FFT. In combination with any of the above embodiments, the smoothing circuit may be further configured to truncate portions of the impulse response by applying a least-square estimation matrix operation to the impulse response of the FFT. In combination with any of the above embodiments, the smoothing circuit may be further configured to truncate portions of the impulse response by finding a channel impulse response as the least-square solution to an over-determined set of linear equations. In combination with any of the above embodiments, the smoothing circuit may be further configured to perform an inverse FFT and truncate portions of the impulse response by applying the impulse response of the plurality of samples to a matrix operation dimensionally dependent upon expected channel response without null-subcarriers and including an inverse Fourier transform matrix. In combination with any of the above embodiments, the smoothing circuit may be further configured to estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values by applying a least-square estimation matrix operation to the impulse response of the FFT.

Embodiments of the present disclosure may include any of the smoothing circuits discussed above. Furthermore, embodiments of the present disclosure may include systems including any of the receiver circuits discussed above. Also, embodiments of the present disclosure may include methods performed by any of the elements discussed above.

DETAILED DESCRIPTION

FIGURE 1 is an illustration of an example system 100 for improved channel estimation, according to embodiments of the present disclosure. In one embodiment, system 100 may provide improved channel estimation for OFDM-based communication. Channel estimation may be performed in a receiver of system 100, illustrated in FIGURE 1. The channel estimation may be improved in the embodiments of system 100 compared to other OFDM receivers. System 100 may be an improved system which has a lower receiver sensitivity.

System 100 may estimate the wireless channel before data is demodulated. The OFDM receiver may use known transmitted symbols at the beginning of a given packet (known as the preamble) to estimate the wireless channel. Since channel estimation is performed using noisy received samples, the resulting estimate is inherently noisy. The elements of FIGURE 1 may be implemented by any suitable combination of digital circuitry, or instructions for execution by a processor.

A radio-frequency (RF) signal may be received by an antenna 102. The received signal may be amplified using one or more low-noise amplifiers (LNA) 104 and down-converted to a baseband signal. The waveform may then be filtered with a low-pass filter (LPF) 108 and amplified again using one or more variable gain amplifiers (VGA) 110. The signal may be down-converted from RF to baseband using a mixer circuit 106.

The resultant signal may be sampled with analog-to-digital converters (ADC) 112. The signal may be adjusted with a multiplier circuit 114. Circuits 106, 114 may include time-domain complex multipliers configured to correct for the effect of the carriers frequency offset. A Fast Fourier Transform (FFT) circuit 116 may apply an FFT to the signal and route the results to a channel estimator circuit 122. The output of the channel estimator circuit 122 may be routed to a multiplexer 126 and to a channel smoothing circuit 124. The output of channel smoothing circuit 124 may be routed to multiplexer 126. The output of FFT circuit 116 and multiplexer 126 may be routed to an equalizer circuit 118, whose output may be routed to a decoder circuit. FFT operations may be performed on a 64-sample block of data as-is done in some wireless communication standards such as IEEE 802.11n. Equalization may be performed in the frequency-domain. Decoding may yield the original, transmitted sequence.

Equalizer circuit 118 may calculate coefficients after the channel frequency-response is found by estimator circuit 122. The channel frequency-response may include output of estimator circuit 122 into smoothing circuit 124. Smoothing circuit 124 may mitigate noise effects. This may update the estimate of the channel that was made by estimator circuit 122. The initial channel estimate made by estimator circuit 122 may be found in the frequency domain. Smoothing circuit 124 may apply an Inverse Fast Fourier Transform (IFFT) to the FFT signal. The number of samples may depend upon the communications protocols used by system 100. For example, system 100 may be compliant with IEEE 802.11 a/g/n WIFI standards. Smoothing circuit 124 may apply the IFFT to a 64-sample block result from FFT 116 to result in a 64-sample time-domain response. In such a case, the impulse response may be expected to only have N non-zero values, where $N < 64$. Any non-zero values at positions outside the expected range may be due to noise. In one embodiment, estimator circuit 122 may set some of such values to zero. After returning to the frequency domain, an improved channel estimate may be obtained. This may be referred to as time-domain-truncation (TDT). To apply a 64-sample IFFT, channel frequency response at 64 sub-carriers may be needed. However, the received signal might not provide data to estimate some of the sub-carriers. In one embodiment, the response at these sub-carriers, referred to as “null” sub-carriers, may be obtained before the TDT can be performed.

Although operations of smoothing circuit 124 are described in the present disclosure, in various embodiments the operation and configuration of smoothing circuit 124 to apply an IFFT and perform TDT may be implemented by any other suitable portion of system 100, such as by estimator circuit 122.

FIGURES 2A-2D is an illustration of example operation of system 100, according to embodiments of the present disclosure. FIGURES 2A-2D may illustrate TDT.

In (a), channel frequency response as generated by estimator circuit 122 may be shown. The zig-zag line in (a) may represent the response as-generated. Superimposed over the zig-zag line in (a) is a smoother curve that may represent the true or ideal channel estimate. The deviation between the two plots may be caused by noise that will be handled by embodiments of the present disclosure while performing TDT.

In (b), an IFFT may have been applied to the channel frequency response (zig-zag line) from (a). The result may be time-domain channel impulse response. As shown in (b), various channels may have a non-zero response as the channel number grows higher. However, the length of the channel of the estimate might be expected to be a fewer number of samples. The data present in all locations throughout the 64-sample result may be due to the effects of noise. The x-component of the graph may be expressed in multiples of the sampling period (Ts).

In (c), smoothing circuit 124 may apply a mask to cancel all non-zero values for channels above a given index number. In the example of FIGURES 2A-2D, the mask may be applied to all channels in the marked rectangle. The mask may be implemented by editing the resulting data and setting the resulting data to zero. The size of the mask may be chosen according to an expected size of valid samples, which may vary according to the particular wireless application in which system 100 is used. For example, different masks may be chosen when using system 100 in WIFI or cellular voice applications. The size of the mask may further be chosen according to expected operating environments. Each such application may have a different ideal impulse channel response. The size of the mask may be selected to have a length corresponding to a worst-case number of samples that would be accepted to perform symbol reconstruction.

In (d), smoothing circuit 124 may apply an FFT to the results from (c), yielding frequency-domain data. In (d), the zig-zag line, representing the actual frequency-domain data from the FFT applied to the data from (c), is much closer to the smoother curve representing the true, ideal, or improved channel estimate when compared with (a).

Data for various sub-channels and impulse response may be represented using a vector of coefficients.

FIGURE 3 illustrates null sub-carriers, according to embodiments of the present disclosure.

In some implementations of TDT, smoothing circuit 124 may require an estimate of all sub-channels. All positions might need information reflecting an estimate. If some are missing, smoothing circuit 124 might not be able to fully perform its tasks. A 64-position FFT may be a typical use case with respect to the data that will be used. A null sub-carrier may include those positions in the FFT for which an estimate might not be available. FIGURE 3 illustrates example positions of null sub-carriers for a particular application wherein system 100 is used in IEEE 802.11n HT mode. When 802.11a is used, for example, more null sub-carriers may occur. In the example of 802.11n HT mode, the null sub-carriers may be in positions 0, 28 through 31, and negative 28 through negative 31. Prior to applying an IFFT, the null-subcarriers may be initialized in one embodiment. The null sub-carriers may be estimated through an iterative process.

FIGURE 4 illustrates operation of the system to perform an iterative time domain truncation (iTDT) algorithm, according to embodiments of the present disclosure. This may be performed, for example, by smoothing circuit 124. The iTDT operation shown in FIGURE 4 may augment the TDT process of FIGURE 3 to account for the null-subcarriers and the lack of information therein. The process of iTDT may be repeated until the resulting response in the frequency domain converges.

To the data provided as a result of the FFT, first a value may be added to the null-subcarriers. In one embodiment, the value may be set to zero. In another embodiment, the value may be set to the value of a non-null-subcarrier neighbor. These may be estimations or guesses for the null sub-carrier.

Subsequently, the IFFT may be applied to the resulting data, and then the mask applied to the result of the IFFT, and finally an FFT applied to the result of the masking. Upon a first iteration, the iTDT process may repeat. Except for the last iteration, the original data from the first FFT process may be used, except for data for the null-subcarriers. For the null-subcarriers, the data from the previous iteration may be used.

Upon the completion of every iteration, the process may determine whether the iTDT process has converged to a stable value. If the iTDT process has converged, then the coefficients at the data sub-channels are then released as the updated channel frequency response. If the iTDT process does not converge and the maximum number of iterations allowed has not reached, another iteration may be performed. At the end of each cycle or iteration, except for the null sub-carriers, the initial frequency responses at other sub-channels may be restored and the process repeats.

The required number of iterations to reach convergence may depend on the channel, wireless protocol, and noise conditions. Selecting a fixed number of iterations which works optimally in all settings may not be possible. If the number of iteration is set too low, the estimate of the nulled sub-carriers might not be sufficiently accurate. This may impact the accuracy of the channel coefficients. If, on the other hand, the number of iterations is set too high, many OFDM symbols are demodulated using the initial (noisier) channel estimate while the iterations process.

In the iTDT algorithm, a convergence test may be performed at the end of each iteration. The convergence test may check whether the present iteration results differ from previous iteration results. If the differences are estimated to be relatively small, below a given threshold, then convergence may be identified. The values of a given iteration may be evaluated by, for example, summing the power at all coefficients at the null sub-carriers and comparing the resultant value against a threshold. A cap on the number of iterations may be enforced, regardless of convergence. The iTDT algorithm may allow the number of iterations to adapt to channel conditions.

In one embodiment, to avoid additional throughput delays, multiple OFDM symbols at the beginning of the packet may be processed using the initial channel estimate until updated coefficients become available.

FIGURE 5 illustrates an example embodiment of operation of the system to perform a least-square time-domain truncation (LSTDT), according to embodiments of the present disclosure. This may be performed, for example, by smoothing circuit 124. While an iterative approach may work well, while iterations are occurring data arriving at a receiver may be passed-through without smoothing. LSTDT may be an alternate non-iterative method to yield similar improved performance but with higher computational complexity compared to iTDT. In LSTDT, the channel impulse response is found as the least-squared solution to an overdetermined set of linear equations. For example, if in a 64-channel OFDM system such as IEEE 802.11n, the 56 elements of the channel are an input (H), as a block of 56x1. The input is multiplied by a matrix of size 56xL, where L is expected length of the impulse response. The result, before an FFT is applied, may be given as h, a 1xL result. An FFT operation may then then yield the updated channel frequency response. In FIGURE 5, the operation may be specified as

$$A_{L\times 56} = (G^H_{L\times 56} G_{56\times L})^{-1} G^H_{L\times 56}$$

G may be the inverse Fourier transform matrix, with rows corresponding to null-subcarriers removed.

FIGURE 6 is illustrates an example embodiment of operation of the system to perform a least-square time-domain truncation in combination with matrix-based FFT operation, according to embodiments of the present disclosure. This may be performed, for example, by smoothing circuit 124. The FFT operation of FIGURE 5 may be implemented itself as a matrix operation. Consequently, the operation may be performed with a single matrix multiplication operation. The input (H) may be passed to a matrix operation B, wherein B is a matrix to perform the FFT operation and the matrix A from FIGURE 5. Thus, in the example of IEEE 802.11 mentioned above, the size of B may be 64x56.

FIGURE 7 illustrates an example embodiment of operation of the system to perform a least-square estimate to estimate the null-subcarriers, according to embodiments of the present disclosure. This may be performed, for example, by smoothing circuit 124. In this case, least-squares estimation may be performed only on the subchannels corresponding to the null-subcarriers, while the other steps from FIGURES 2A-2D are performed.

The input H and the matrix operation $B^{C}_{8\times 56}$ may generate the least-square estimate. This matrix operation may be substantially smaller than the least-square operation of FIGURE 6. This may be combined with the original input H. Subsequently, the IFFT, mask, and FFT may be applied.

The matrix operations above may require formulating the channel smoothing problem in matrix form, which may require specific hardware to efficiently implement.

Although the invention has been described with respect to specific embodiments thereof, these embodiments are merely illustrative, and not restrictive of the invention. The description herein of illustrated embodiments of the invention, including the description in the Abstract and Summary, is not intended to be exhaustive or to limit the invention to the precise forms disclosed herein (and in particular, the inclusion of any particular embodiment, feature or function within the Abstract or Summary is not intended to limit the scope of the invention to such embodiment, feature or function). Rather, the description is intended to describe illustrative embodiments, features and functions in order to provide a person of ordinary skill in the art context to understand the invention without limiting the invention to any particularly described embodiment, feature or function, including any such embodiment feature or function described in the Abstract or Summary.

While specific embodiments of, and examples for, the invention are described herein for illustrative purposes only, various equivalent modifications are possible within the spirit and scope of the invention, as those skilled in the relevant art will recognize and appreciate. As indicated, these modifications may be made to the invention in light of the foregoing description of illustrated embodiments of the invention and are to be included within the spirit and scope of the invention. Thus, while the invention has been described herein with reference to particular embodiments thereof, a latitude of modification, various changes and substitutions are intended in the foregoing disclosures, and it will be appreciated that in some instances some features of embodiments of the invention will be employed without a corresponding use of other features without departing from the scope and spirit of the invention as set forth. Therefore, many modifications may be made to adapt a particular situation or material to the essential scope and spirit of the invention.

Reference throughout this specification to “one embodiment”, “an embodiment”, or “a specific embodiment” or similar terminology means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment and may not necessarily be present in all embodiments. Thus, respective appearances of the phrases “in one embodiment”, “in an embodiment”, or “in a specific embodiment” or similar terminology in various places throughout this specification are not necessarily referring to the same embodiment. Furthermore, the particular features, structures, or characteristics of any particular embodiment may be combined in any suitable manner with one or more other embodiments. It is to be understood that other variations and modifications of the embodiments described and illustrated herein are possible in light of the teachings herein and are to be considered as part of the spirit and scope of the invention.

In the description herein, numerous specific details are provided, such as examples of components and/or methods, to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that an embodiment may be able to be practiced without one or more of the specific details, or with other apparatus, systems, assemblies, methods, components, materials, parts, and/or the like. In other instances, well-known structures, components, systems, materials, or operations are not specifically shown or described in detail to avoid obscuring aspects of embodiments of the invention. While the invention may be illustrated by using a particular embodiment, this is not and does not limit the invention to any particular embodiment and a person of ordinary skill in the art will recognize that additional embodiments are readily understandable and are a part of this invention.

As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having,” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, product, article, or apparatus that comprises a list of elements is not necessarily limited only those elements but may include other elements not expressly listed or inherent to such process, process, article, or apparatus.

Furthermore, the term “or” as used herein is generally intended to mean “and/or” unless otherwise indicated. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present). As used herein, including the claims that follow, a term preceded by “a” or “an” (and “the” when antecedent basis is “a” or “an”) includes both singular and plural of such term, unless clearly indicated within the claim otherwise (i.e., that the reference “a” or “an” clearly indicates only the singular or only the plural). Also, as used in the description herein and throughout the claims that follow, the meaning of “in” includes “in” and “on” unless the context clearly dictates otherwise.

It will be appreciated that one or more of the elements depicted in the drawings/figures can also be implemented in a more separated or integrated manner, or even removed or rendered as inoperable in certain cases, as is useful in accordance with a particular application. Additionally, any signal arrows in the drawings/figures should be considered only as exemplary, and not limiting, unless otherwise specifically noted.

CLAIMS

1. An OFDM receiver circuit, comprising:

a Fast Fourier Transform (FFT) circuit configured to calculate an FFT of a plurality of sample values received by the receiver circuit; and

a smoothing circuit configured to identify equalizer coefficients for the sample values by truncating portions of an impulse response of the FFT.

2. The OFDM receiver circuit of any of Claims 1 or 3-10, wherein the smoothing circuit is further configured to identify the equalizer coefficients by truncating portions of the impulse response of the FFT beyond a defined length of the impulse response.

3. The OFDM receiver circuit of any of Claims 1-2 or 4-10, wherein the smoothing circuit is further configured to identify the equalizer coefficients by performing an inverse FFT on channel frequency response of the plurality of sample values, truncating portions of the impulse response in results of the inverse FFT, and performing an FFT on results of the truncation.

4. The OFDM receiver circuit of any of Claims 1-3 or 7-10, wherein the smoothing circuit is further configured to:

estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values;

perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier;

truncate portions of the impulse response in results of the inverse FFT; and

perform an FFT on results of the truncation.

5. The OFDM receiver circuit of any of Claims 1-3 or 7-10, wherein the smoothing circuit is further configured to:

estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values;

perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier;

truncate portions of the impulse response in results of the inverse FFT;

perform an FFT on results of the truncation;

evaluate whether results of the truncation have converged; and

based on whether results of the truncation have converged, determine whether to repeat performance of the inverse FFT, truncation, and performance of the FFT.

6. The OFDM receiver circuit of any of Claims 1-3 or 7-10, wherein the smoothing circuit is further configured to:

estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values;

perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier;

truncate portions of the impulse response in results of the inverse FFT;

perform an FFT on results of the truncation;

based on a determination that results of the truncation have not converged, repeat performance of the inverse FFT, truncation, and performance of the FFT using the channel frequency response of the plurality of sample values and a value of the null sub-carrier resulting from previous performance of the inverse FFT, truncation, and performance of the FFT.

7. The OFDM receiver circuit of any of Claims 1-6 or 9-10, wherein the smoothing circuit is further configured to truncate portions of the impulse response by applying a least-square estimation matrix operation to the impulse response of the FFT

8. The OFDM receiver circuit of any of Claims 1-6 or 9-10, wherein the smoothing circuit is further configured to truncate portions of the impulse response by finding a channel impulse response as the least-square solution to an over-determined set of linear equations.

9. The OFDM receiver circuit of any of Claims 1-8 or 10, wherein the smoothing circuit is further configured to perform an inverse FFT and truncate portions of the impulse response by applying the impulse response of the plurality of samples to a matrix operation dimensionally dependent upon expected channel response without null-subcarriers and including an inverse Fourier transform matrix.

10. The OFDM receiver circuit of any of Claims 1-9, wherein the smoothing circuit is further configured to estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values by applying a least-square estimation matrix operation to the impulse response of the FFT.

11. A system, comprising:

a Fast Fourier Transform (FFT) circuit configured to calculate an FFT of a plurality of sample values received by the receiver circuit; and

a smoothing circuit configured to identify equalizer coefficients for the sample values by truncating portions of an impulse response of the FFT.

12. The system of any of Claims 11 or 13-20, wherein the smoothing circuit is further configured to identify the equalizer coefficients by truncating portions of the impulse response of the FFT beyond a defined length of the impulse response.

13. The system of any of Claims 11-12 or 14-20, wherein the smoothing circuit is further configured to identify the equalizer coefficients by performing an inverse FFT on channel frequency response of the plurality of sample values, truncating portions of the impulse response in results of the inverse FFT, and performing an FFT on results of the truncation.

14. The system of any of Claims 11-13 or 17-20, wherein the smoothing circuit is further configured to:

estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values;

perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier;

truncate portions of the impulse response in results of the inverse FFT; and

perform an FFT on results of the truncation.

15. The system of any of Claims 11-13 or 17-20, wherein the smoothing circuit is further configured to:

estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values;

perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier;

truncate portions of the impulse response in results of the inverse FFT;

perform an FFT on results of the truncation;

evaluate whether results of the truncation have converged; and

based on whether results of the truncation have converged, determine whether to repeat performance of the inverse FFT, truncation, and performance of the FFT.

16. The system of any of Claims 11-13 or 17-20, wherein the smoothing circuit is further configured to:

estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values;

perform an inverse FFT on channel frequency response of the plurality of sample values with the estimated value of the null-subcarrier;

truncate portions of the impulse response in results of the inverse FFT;

perform an FFT on results of the truncation;

based on a determination that results of the truncation have not converged, repeat performance of the inverse FFT, truncation, and performance of the FFT using the channel frequency response of the plurality of sample values and a value of the null sub-carrier resulting from previous performance of the inverse FFT, truncation, and performance of the FFT.

17. The system of any of Claims 11-16 or 19-20, wherein the smoothing circuit is further configured to truncate portions of the impulse response by applying a least-square estimation matrix operation to the impulse response of the FFT

18. The system any of Claims 11-16 or 19-20, wherein the smoothing circuit is further configured to truncate portions of the impulse response by finding a channel impulse response as the least-square solution to an over-determined set of linear equations.

19. The system of any of Claims 11-18 or 20, wherein the smoothing circuit is further configured to perform an inverse FFT and truncate portions of the impulse response by applying the impulse response of the plurality of samples to a matrix operation dimensionally dependent upon expected channel response without null-subcarriers and including an inverse Fourier transform matrix.

20. The system of any of Claims 11-19, wherein the smoothing circuit is further configured to estimate a value of a null sub-carrier in a channel frequency response of the plurality of sample values by applying a least-square estimation matrix operation to the impulse response of the FFT.

21. A method, performed by the operations of any of the systems of Claims 11-19.

22. A method, performed by the operations of any of the receiver circuits of Claims 1-10.

23. A computer-readable medium, comprising computer-readable instructions, the instructions, when loaded and executed by a processor, cause the processor to perform operations of the FFT circuit and the smoothing circuit of any of the receiver circuits of Claims 1-10.

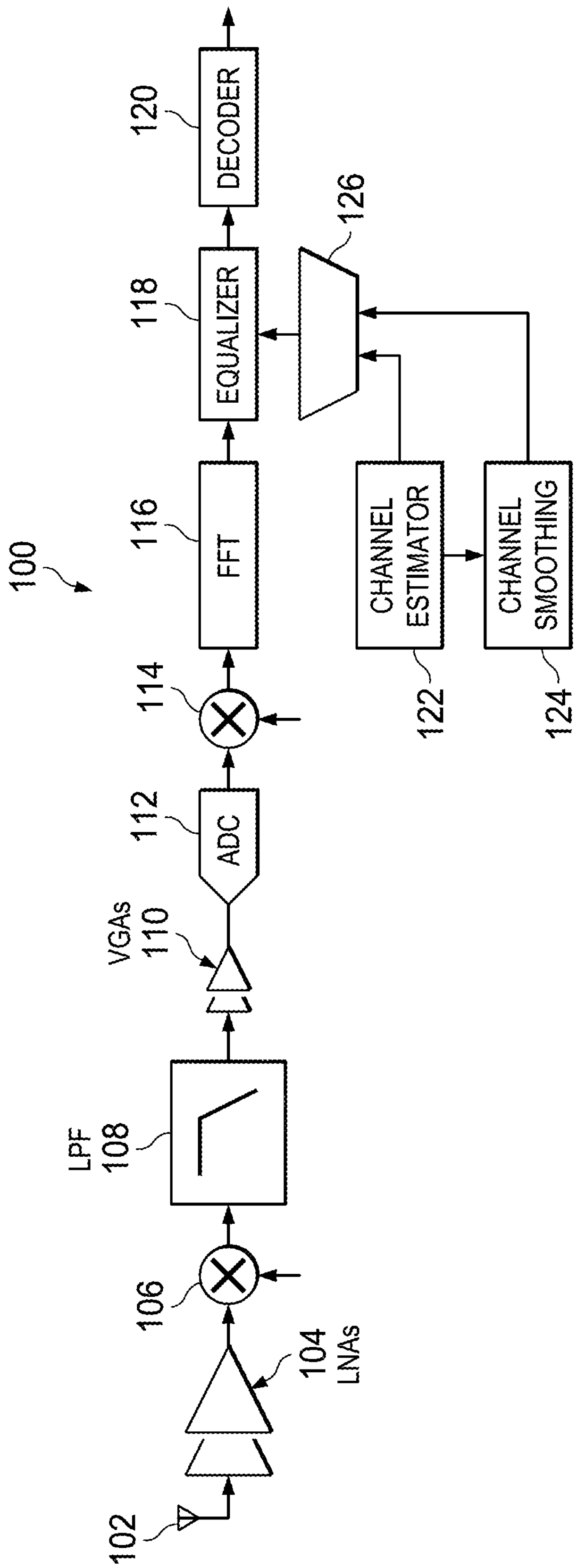
100
102
104
LNAs
106
LPF
108
VGAs
110
112
ADC
114
116
FFT
118
EQUALIZER
120
DECODER
122
CHANNEL ESTIMATOR
124
CHANNEL SMOOTHING
126

FIG. 1

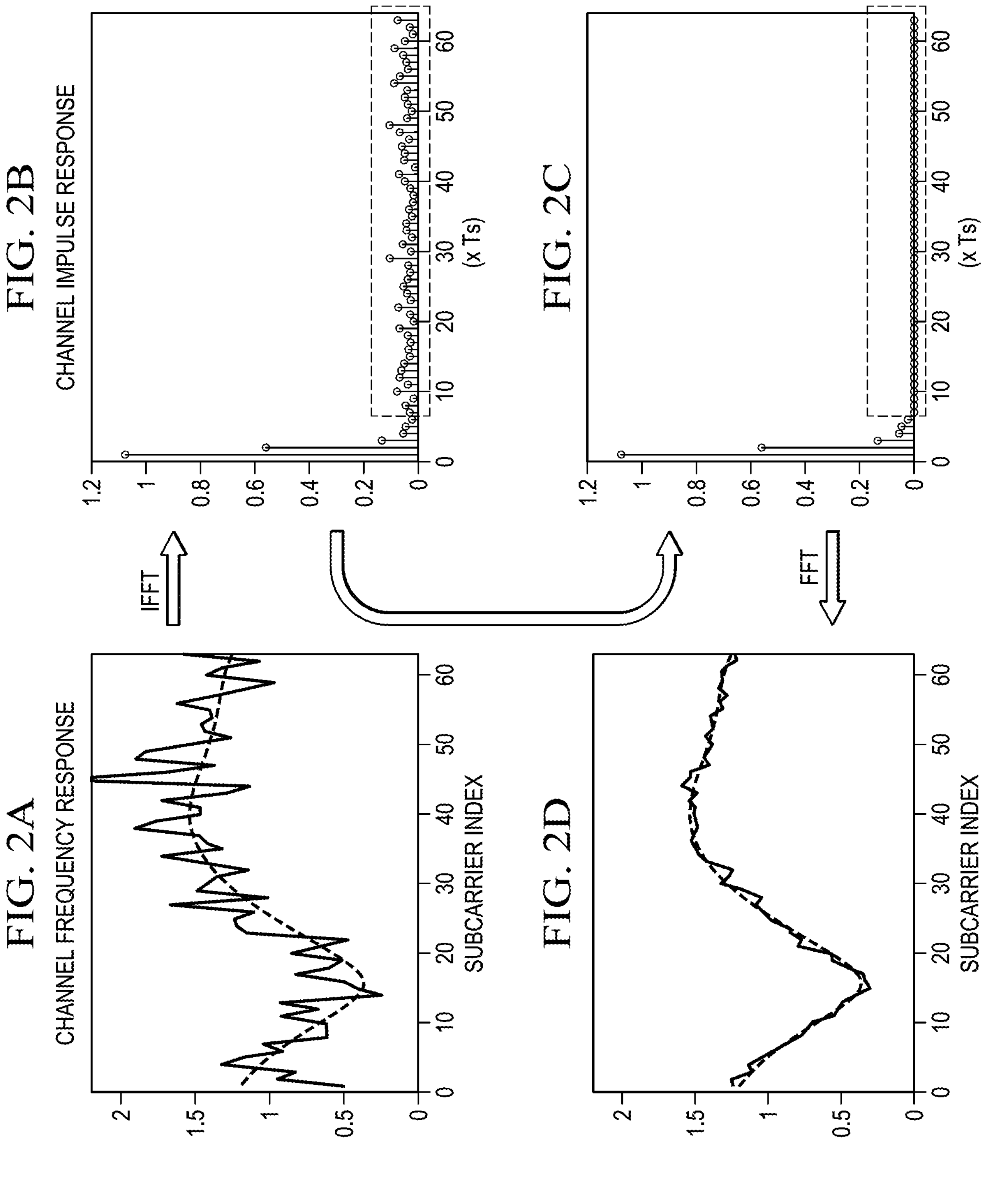

FIG. 2A

FIG. 2B

FIG. 2C

FIG. 2D

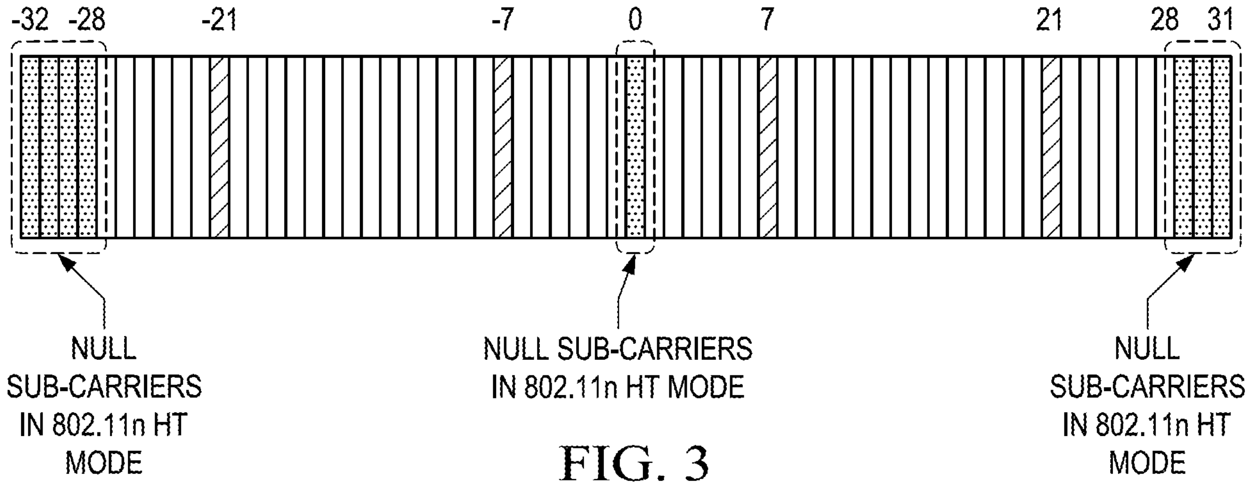

FIG. 3

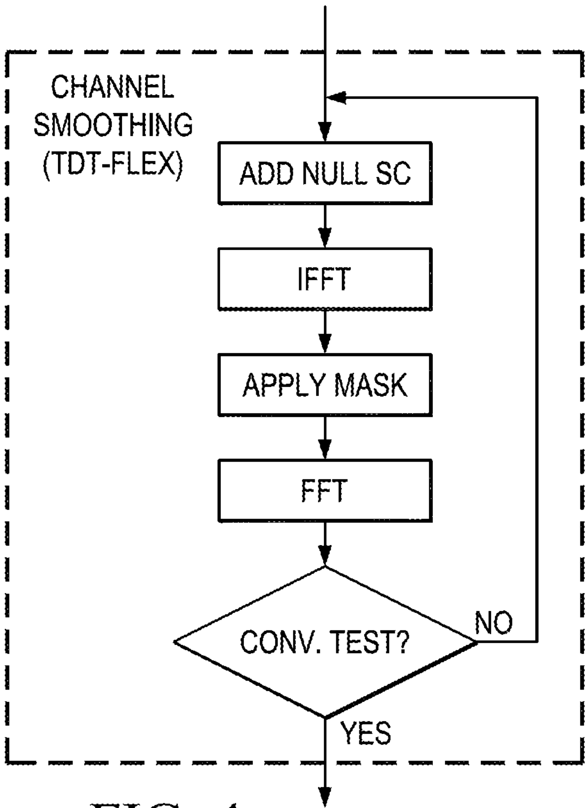

FIG. 4

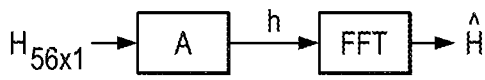

FIG. 5

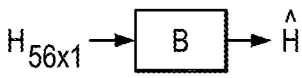

FIG. 6

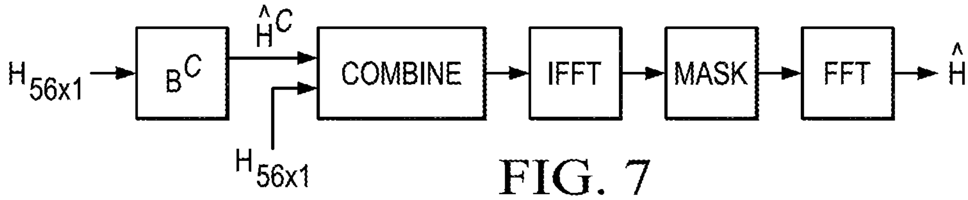

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/041106

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L25/02 H04L27/26
ADD.

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)
H04L

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007/206689 A1 (KOO CHANG-SOO [US] ET AL) 6 September 2007 (2007-09-06) paragraphs [0020] - [0032], [0039] - [0041]; figures 1, 5 -----	1-4, 7-14, 17-23
X	YOU-SEOK LEE ET AL: "Iterative Extrapolation for Channel Equalization in DVB-T Receivers", IEEE TRANSACTIONS ON BROADCASTING, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 54, no. 3, 1 September 2008 (2008-09-01), pages 461-467, XP011343426, ISSN: 0018-9316, DOI: 10.1109/TBC.2008.2000465 section III ----- -/--	1-6, 11-16, 21-23

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"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	Date of mailing of the international search report
4 September 2017	14/09/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Vucic, Jelena

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/269883 A1 (THOMPSON STEVEN C [US] ET AL) 18 September 2014 (2014-09-18) paragraphs [0010], [0026], [0027], [0029], [0032]; figures 1, 3 -----	1-3, 11-13, 21-23

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2017/041106

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2007206689 A1	06-09-2007	TW 200737807 A	01-10-2007
		US 2007206689 A1	06-09-2007
		WO 2007103183 A2	13-09-2007
US 2014269883 A1	18-09-2014	CN 105075206 A	18-11-2015
		DE 112014000716 T5	29-10-2015
		GB 2526452 A	25-11-2015
		TW 201445940 A	01-12-2014
		US 2014269883 A1	18-09-2014
		WO 2014150021 A1	25-09-2014