



(51) International Patent Classification:

G01S 7/02 (2006.01) G01S 7/292 (2006.01)
G01S 7/03 (2006.01) G01S 7/35 (2006.01)

(21) International Application Number:

PCT/US2017/044490

(22) International Filing Date:

28 July 2017 (28.07.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

15/295,084 17 October 2016 (17.10.2016) US

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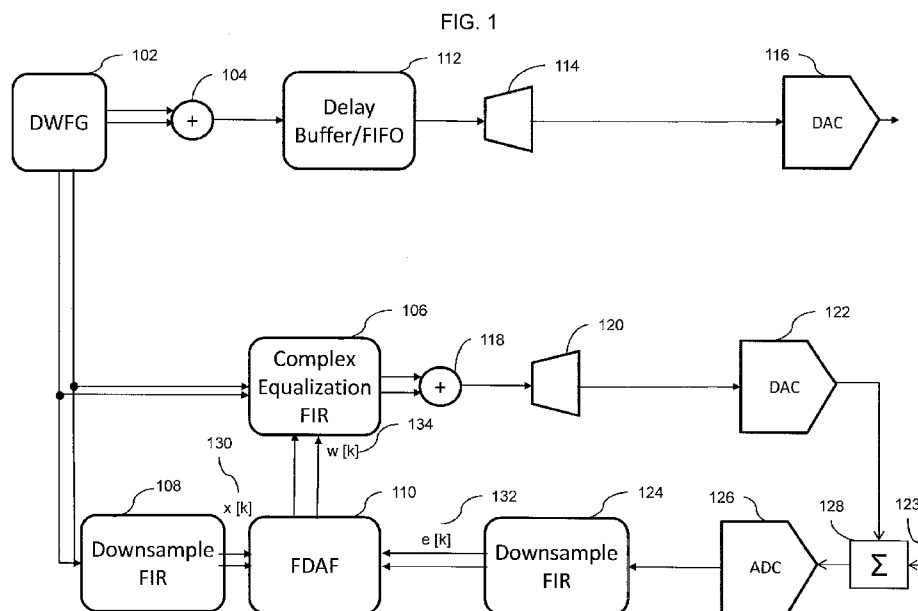
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(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,
KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,

(54) Title: SYSTEM AND METHOD FOR ADAPTIVE SIMULTANEOUS TRANSMIT AND RECEIVE LEAKAGE CANCEL-
LATION



(57) Abstract: Method and apparatus for leakage signal cancellation in a simultaneous transmit and receive RF system includes: generating a digital transmit signal for transmission from the system; receiving a receive signal produced by reflection of the transmit signal from an object or generated by a second RF system; adaptively filtering the transmit signal by an adaptive finite input response (FIR) filter; calculating filter coefficients for the adaptive FIR filter in real-time at a different sampling rate; adaptively inputting the calculated filter coefficients to the adaptive FIR filter to generate a cancellation signal in real-time; and applying the cancellation signal to the receive signal to cancel leakage in the receive signal to generate an optimum receive signal.

SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

1 **SYSTEM AND METHOD FOR ADAPTIVE SIMULTANEOUS TRANSMIT AND RECEIVE LEAKAGE CANCELLATION**

FIELD OF THE INVENTION

5 **[0001]** The disclosed invention relates generally to electronic circuits and more specifically to system and method for simultaneous cancellation of leakage current.

BACKGROUND

10 **[0002]** A typical RF system, for example a radar system capable of simultaneous transmission and receiving simultaneous transmit and receive radar ("STAR"), includes a transmitter for transmitting, for example, pulse modulated waves at a variety of different frequencies. A duplexer is coupled to the output of the transmitter to allow for bi-directional communication over a single path. A receiver is also coupled to the output of the duplexer for receiving the transmitted signals at the
15 same time intervals as the frequencies of the transmitted signals. The duplexer isolates the receiver from the transmitter while permitting them to share a common antenna. Accordingly, the duplexer needs to operate in the frequency band used by the receiver and transmitter, provide adequate rejection of transmitter noise occurring at the receiver, operate at or less than the frequency separation between
20 the transmitter and receiver, and prevent receiver desensitization.

25 **[0003]** However, transmit leakage (RF current and/or voltage) signal through isolation and antenna port reflection paths and mutual coupling from adjacent antenna elements in a phased array radar overloads the receive path generating noise in the RF receiver, resulting in inaccurate readings. This leakage or feedthrough signal comprises an unpropagated portion of the transmitted energy which is fed directly to the RF receiver resulting in saturation of and therefore degradation of the receiver.

30 **[0004]** In many cases, the received signal may include a leakage component when the transmit signal is reflected from non-target objects and the receiver receives a portion of the bounced transmit-signal, or when the receiver receives a portion of the transmit signal directly from the transmitter.

35 **[0005]** In order to cancel the leakage signal in the radio frequency (RF) path for a simultaneous transmit and receive application, filter coefficients must be calculated in real time and a cancellation signal must be adapted in real-time based on those coefficients to allow better cancellation. Also in order to meet radar specifications, very small latency is allowed on the adaptive filtering for the transmit line.

[0006] Some current techniques perform the cancellation via an analog feedback. However, the problem with the analog feedback is that the analog circuitry adds

1 additional distortion to the cancellation signal which needs to be subsequently
adapted out of the system. Fast digital control of the adaptive algorithm is not
possible, and analog coefficients must often be calculated off line. In general, the
slower the adaptive loop of the process, the less cancellation the process can
5 achieve, because the change rate of the signal to which the system is adapting
dictates the cancellation that can be achieved. For example, if the signal is changing
significantly faster than the adaptive loop, cancellation is limited. Moreover, off-line
computation of coefficients is not adaptive at all and does not address dynamic
signals or dynamic environments well.

10 **[0007]** In general, current techniques to achieve a leakage cancellation are based
on three basic methods: i) the cancellation is done in the analog domain where the
equalization filter is applied in analog with a tapped delay line mechanism on the
transmitted signal and the resulting delayed and amplitude equalized version of the
transmitted signal, or cancellation signal with an inverse of the leakage content
15 inside the received signal, is added to the received signal; ii) the cancellation is done
in the analog domain where cancellation signal is created in the digital domain by
passing the transmit waveform through the equalization filter and sent to a digital to
analog converter to be added to the received signal to cancel the leakage in the
analog domain; or iii) the cancellation is done in the digital domain where the
20 equalization filter is applied in the digital domain on the transmitted waveform, and
the digital cancellation signal and digital received signal are combined in the digital
domain. However, all of these approaches suffer from two limitations. The first is
that they typically need to accommodate several sampling rates, which complicates
the system design. The second is that they produce undesirably large delays, which
25 makes them unsuitable for certain high-speed (and real-time) applications. Large
delays in the leakage cancellation signal results in substantial "blind spots" in certain
radar applications, due to slower generation of adaptive parameters slower
adaptations of the filter coefficients.

30 SUMMARY

[0008] In some embodiments, the disclosed invention is a method for leakage
signal cancellation in a simultaneous transmit and receive RF system. The method
includes: generating a digital transmit signal for transmission from the system;
receiving a receive signal produced by reflection of the transmit signal from an object
35 or generated by a second RF system; adaptively filtering the transmit signal by an
adaptive finite input response (FIR) filter; calculating filter coefficients for the
adaptive FIR filter in real-time at a different sampling rate; adaptively inputting the
calculated filter coefficients to the adaptive FIR filter to generate a cancellation signal

1 in real-time; and applying the cancellation signal to the receive signal to cancel
leakage in the receive signal to generate an optimum receive signal. The filter
coefficients are calculated by down-sampling the transmit signal and the optimum
receive signal and processing the down-sampled signals to calculate the filter
5 coefficients in real-time.

[0009] In some embodiments, the disclosed invention is an apparatus for leakage
signal cancellation in a simultaneous transmit and receive RF system. The
apparatus includes: a digital waveform generator for generating a digital transmit
signal for transmission from the system; a receiver for receiving a receive signal
10 produced by reflection of the transmit signal from an object or generated by a second
RF system; an adaptive finite input response (FIR) filter for adaptively filtering the
transmit signal; a frequency domain adaptive filter (FDAF) circuit for calculating filter
coefficients for the adaptive FIR filter in real-time and adaptively inputting the
calculated filter coefficients to the FIR filter to generate a cancellation signal in real-
15 time; an adder for adding the cancellation signal to the receive signal to cancel
leakage in the receive signal and generate an optimum receive signal; a first down-
sampler for down-sampling the transmit signal and inputting the down-sample
transmit signal to the FDAF circuit; and a second down-sampler for down-sampling
the optimum receive signal and inputting the down-sample optimum receive signal to
20 the FDAF circuit. The FDAF circuit processes the down-sampled signals to calculate
the filter coefficients in real-time.

[0010] The processing of the down-sampled signals may include calculating a
next filter coefficient in real-time as a function of a current filter coefficient, a
frequency domain cancellation signal and a complex conjugate of a frequency
25 domain of the down-sampled transmit signal, using least squares method, or other
known methods.

[0011] Adaptive filtering of the transmit signal may be performed in time domain,
or frequency domain.

30 BRIEF DESCRIPTION OF THE DRAWINGS

[0012] These and other features, aspects, and advantages of the disclosed
invention will become better understood with regard to the following description,
appended claims, and accompanying drawings.

[0013] FIG. 1 is a simplified exemplary block diagram of a system including a
35 super sampled adaptive finite impulse response (FIR) filter for generating a leakage
cancellation signal, according to some embodiments of the disclosed invention.

[0014] FIG. 2 is a simplified exemplary block diagram of a time-based super-
sample FIR filter, according to some embodiments of the disclosed invention.

1 **[0015]** FIG. 3 is a simplified exemplary block diagram of an exemplary frequency-based circuit implementing a leakage cancellation transfer function, according to some embodiments of the disclosed invention.

5 **[0016]** FIG. 4 is a simplified exemplary block diagram of a frequency domain adaptive filter (FDAF) for computation of time domain coefficients for a time-based super-sample FIR filter, according to some embodiments of the disclosed invention.

[0017] FIG. 5 is a simplified exemplary block diagram of a frequency domain adaptive filter (FDAF) for a frequency-based super-sample FIR filter, according to some embodiments of the disclosed invention.

10 **[0018]** FIG. 6 is a simplified exemplary block diagram of a system including a super sampled adaptive finite impulse response (FIR) filter for generating a leakage cancellation signal, according to some embodiments of the disclosed invention.

[0019] FIG. 7 is a simplified process flow for generating a leakage cancellation signal, according to some embodiments of the disclosed invention.

15 DETAILED DESCRIPTION

[0020] In some embodiments, the disclosed invention utilizes a super sampled adaptive finite impulse response (FIR) filter that achieves the desired leakage cancellation signal based on digitized feedback with minimum latency. A frequency domain adaptive filter (FDAF) is used to calculate the filter coefficients. In some
20 embodiments, the FDAF is integrated into the super sampled architecture. In some embodiments, the FDAF is in a cancellation loop with a low latency super sampled FIR filter achieving cancellation using digital intermediate frequency (IF) feedback.

[0021] In some embodiments, the disclosed invention is a simultaneous transmit and receive RF system, for example, a STAR that generates a leakage cancellation
25 signal from the transmit signal in real time where a small cancellation delay through the cancellation architecture is required. This results in a small delay through the transfer function to generate the transmitted digital cancellation signal.

[0022] In some embodiments, the disclosed invention is a digital system that
30 generates a cancellation signal by adaptive computation of super sampled versions of a digital FIR equalization weights in real-time. The disclosed invention applies the super sampled weights to a digital cancellation FIR to generate a separation of the computation of adaptive parameters and applies the weights to the filter at different rates.

35 **[0023]** Many simultaneous digital transmit and receive architectures include signals of multiple frequencies. For example, a digital to analog converter (DAC) transmits signals at one frequency F_{DAC} , an analog to digital converter (ADC) digitizes incoming signals at another frequency, F_{ADC} , a field programmable gate

array (FPGA) generates a clock frequency F_{CLK} , and an effective sampling rate of the system may be at a different frequency F_{SYSTEM} . In wideband systems, the F_{ADC} and F_{DAC} are typically much greater than the F_{CLK} , because FPGA clocks are limited to the 100s of MHz, whereas the signals of the ADCs and DACs are typically at GHz rates. However, because the signal carrier information resides in a narrow band, and to save FPGA resources, an incoming ADC signal is typically down converted and rate-changed to a lower sampling rate to match the FPGA rates. Similarly when the FPGA digitally generates a transmit signal to save resources, the signal is typically generated at one rate and up converted and rate changed for transmission.

[0024] In some architectures, there may be a wideband transmit DAC, but a more narrowband ADC, such that $F_{DAC} > F_{ADC}$. In this case a smaller F_{ADC} frequency is desired since F_{ADC} is correlated with the size, weight and price (SWAP) of the ADC. As a result, if multiple receive channels are desired to save SWAP, a smaller F_{ADC} is used. In some embodiments of the disclosed invention, $F_{SYSTEM} > F_{CLK}$ so that the latency through an FIR filter, which effectively operates at F_{SYSTEM} is much lower than the rate at which the FIR filter might have operated. In some embodiments, $F_{ADC} < F_{SYSTEM}$ so that the data sampled from F_{ADC} is changed to a different rate to be processed through the FIR filter, which operates at F_{SYSTEM} .

[0025] Therefore, when $F_{ADC} < F_{SYSTEM}$, this results in a digital cancellation signal with small latency. As one skilled in the art would recognize, "real-time" in the context of signal processing means a system (or circuit) which controls an environment or function by receiving data, processing the data, and returning the results sufficiently quickly to affect the environment at that time without significant delay. Also, one skilled in the art would understand that "real-time" in the context of data processing means data processing that appears to take place, or actually takes place, sufficiently instantaneously upon data entry or receipt of a command.

[0026] FIG. 1 is a simplified exemplary block diagram of a system including a super sampled adaptive finite impulse response (FIR) filter for generating a leakage cancellation signal, according to some embodiments of the disclosed invention. As shown, a digital waveform generator circuit (DWFG) 102 generates digital samples for an RF signal, for example, transmit signal of a STAR system. In some embodiments, the DWFG 102 is comprised of a direct digital synthesizer (DDS), which reads successive values from a lookup table made of the values of, for example, a sinewave. In some embodiments, this waveform is produced as N parallel polyphased lanes such that the data can be produced with a clock rate of $1/N$ the sampling rate of the waveform. In some embodiments, the data generated from the DWFG 102 is complex data and thus an optional summer 104 may be used to reformat the data to real data. A delay or buffer FIFO 112 controls the number of

1 delayed clock cycles the waveform may take to get through a transmit path. This is typically performed to align the waveforms in different paths.

5 **[0027]** In some embodiments, a clock domain crossing circuit 114 increases the clock rate by reducing the number of parallel data paths. For example, the clock domain crossing circuit 114 may double the clock rate in the device and reduce the number of parallel data paths by half, before the data is input to and transmitted out of a first digital to analog converter (DAC) 116. The output of this DAC is an analog signal and constitute the RF transmit signal. The waveform from DWFG 102 is also transmitted along multiple paths, such as a second path through a complex
10 equalization FIR filter 106. The equalization FIR filter 106 applies a transfer function calculated to allow cancellation. An optional adder 118 reformats the signal from a complex signal to a real signal.

15 **[0028]** Although, the equalization FIR filter 106 also works in real domain, it works more effectively in the complex domain since amplitude and phase can be equalized simultaneously with a complex FIR. The number of polyphaser lanes (paths) of this equalized cancellation (real) signal is decreased and the clock rate of each polyphaser lane is increased by a clock domain crossing circuit 120 and then transmitted to a second DAC 122. In these embodiments, the clock domain rate update is performed, because typically external I/O signals are low voltage
20 differential signals (LVDS) which are run at a double data rate (DDR) so that the total data throughput per lane is typically 500 MHz in some embodiments. Accordingly, data needs to be fed into a LVDS driver at a 500 MHz rate. This is typically accomplished with 2 lanes at 250 MHz or 4 lanes at 125 MHz, so when the data is input to a LVDS buffer, a clock domain crossing circuit is also used.

25 **[0029]** The cancellation signal, output from the second DAC 122, is summed with an incoming receive analog signal 123 by a summer/adder circuit 128. This summation results in leakage cancellation such that ideally the output signal of the summer/adder 128 going into an analog to digital converter (ADC) 126 does not contain the leakage signal (optimum receive signal). This signal is considered the
30 "error" signal, because it contains the remnants of a non-perfect cancellation. The output signal from ADC 126 is often at a high sample rate and therefore may be down converted and down-sampled by a down-sampler FIR 124 and processed to compute the equalization coefficients for the equalization FIR filter 106, by a frequency domain adaptive filter (FDAF) circuit 110.

35 **[0030]** In some embodiments, the FDAF circuit 110 takes in the error signal from the down-sampler FIR 124, and the transmitted signal from the DWFG 102 that is down-sampled by a down-sampler FIR 108, to compute the FIR coefficients necessary to transform the signal from the DWFG 102 into a signal that can be used

1 to cancel the leakage signal coming from an RF system, where the cancellation
occurs at the summer/adder 128. This way, the system includes a feedback through
the loop of the complex equalization FIR filter 106, the second DAC 122, the
summer/adder 128, back into the ADC 126 and down-sampled by the down-sampler
5 FIR 124, to compute and feed the filter coefficients back to the equalization FIR filter
106. Here, the input signal to the FDAF circuit is called $x[k]$ (13) and the error signal
is called $e[k]$ (132), which are used to compute the weight coefficients $w[k]$ (134). In
some embodiments, the output of the FDAF circuit may be up-converted (up-
sampled) by an up-sampler circuit (not shown) to a higher rate closer to the rate that
10 the complex equalization FIR filter 106 operates at. In some embodiments, the
output of the FDAF circuit (with or without up-sampling) may be input to a weight
memory, such as a read access memory RAM, read only memory (ROM), FIFO
buffer, and the like, similar to those in FIGs. 2-5 (206, 310, 408 and 506,
respectively).

15 **[0031]** An exemplary fast convergence method for adaptive digital filters is
described in J. Carlos Ogue, T Saito and Y. Hoshiko, "A fast convergence frequency
domain Adaptive Filter," IEEE Trans. Acoustics, speech, and signal processing, Vol.
ASSP-31, No. 5, pp. 1312-1314, Oct. 1983 ("Fast Adaptive Filter paper"), the entire
content of which is hereby expressly incorporated by reference. In this example,
20 since the filter is implemented in the frequency domain and the input signals are
stationary, each of the frequency bins may be independently adapted by a self-
normalizing gradient approach.

[0032] Another exemplary method for adaptively generating coefficient's for a
digital FIR filter is the least squares method. This known method approximates the
25 solution of overdetermined systems, in which there are more equations than
unknowns. The overall solution of the method minimizes the sum of the squares of
the errors made in the results of every single equation. The least squares method is
used in data fitting, in which the best fit in the least-squares sense minimizes the
sum of squared residuals, a residual being the difference between an observed
30 value and the fitted value provided by a model.

[0033] The electronic circuits of the disclosed invention may be implemented by a
digital signal processor (DSP), very large scale integrated circuit (VLSI), application
specific integrated circuit (ASIC), field-programming gate array (FPGA), or any other
electronic circuit technologies suitable for RF circuits.

35 **[0034]** FIG. 2 is a simplified exemplary block diagram of a time-based super-
sample FIR filter according to some embodiments of the disclosed invention. As
shown, the cancellation signal is applied in the time domain, in these embodiments.
In some embodiments, a complex I/Q signal 202 is input into an equalization FIR

1 filter 204. Coefficients or weights are computed in real-time or may be stored ahead
of time in and retrieved from a weight memory 206, such as a read access memory
RAM, read only memory (ROM), FIFO buffer, and the like. In the latter case, the
weight memory would provide the weights to a complex equalization FIR, for
5 example, the complex equalization FIR filter 106 of FIG. 1. The coefficients are then
provided to the time domain equalization FIR filter 204 such that a transfer function is
applied to the input signal 202, which generates an equalized output signal 208.

[0035] In some embodiments, the equalization FIR filter 204 modulates the input
signal for generate a signal that is a replica of the signal that is desired to be
10 cancelled. The closer the cancellation signal is to the signal desired to be cancel,
the deeper (e.g., smaller signal residual amplitude) the cancellation (error signal) that
is created. As a result, the output $y(t)$ of the equalization FIR filter 204 is the signal,
or model of the signal, desired to be cancelled. The input $x(t)$ to the equalization FIR
filter 204 is the signal (waveform) originating from the system, in this case, the
15 waveform from the digital waveform generator. The equalization FIR filter 204
implements a transfer function $h(t)$ to generate the cancellation signal. The output of
the equalization FIR filter 204 is the convolution of this transfer function implemented
by the equalization FIR filter 204 with the input signal, given by $y(t) = h(t) * x(t)$.

[0036] The transfer function $h(t)$ is often easier to compute using Fourier domain
20 methods in the frequency domain, where $H(f)$ is the frequency domain representation
of the time domain transfer function $h(t)$. Since convolution is implemented as
multiplication in the frequency domain, $Y(f) = H(f) * X(f)$, or $H(f) = Y(f) / X(f)$. It follows
then $h(t) = \text{Inverse Fourier Transform (IFT) of } H(f)$. This is equivalent to the inverse
Fourier transform of the Fourier transform of the leakage signal divided by the
25 Fourier transform of the generated input signal, i.e., the DWFG signal. The
coefficients of the transfer function $h(t)$ are computed and maybe stored in a weight
memory 206 to implement the transfer function in the time domain. In some
embodiments, this equalized output signal 208 is a complex baseband I/Q signal.
For example, in FIG. 1, the complex baseband I/Q signals may be output from the
30 complex equalization FIR filter 106, if the computation was performed at a complex
baseband. The coefficients from FDAF 110 are also provided to the complex
equalization FIR filter 106.

[0037] FIG. 3 is a simplified exemplary block diagram of an exemplary
frequency-based circuit implementing a leakage cancellation transfer function,
35 according to some embodiments of the disclosed invention. FIG. 3 provides an
example of a cancellation circuit where the transfer function coefficients are applied
in the frequency domain. As shown, a time domain input signal 302 is fast Fourier
transformed (FFT) by an FFT circuit 306 into a frequency domain representation.

1 The frequency domain signal is then multiplied by the coefficients representing the transfer function using a multiplier 308. If the input signal 302 is a complex signal, then the multiplier 308 performs a complex multiplication. The coefficients are provided by a weight memory 310, in frequency domain. The multiplication results
 5 (output of the multiplier 308) is then inverse Fourier transformed (iFFT) by an iFFT circuit 312 back into a time domain output 314. This circuit combination of an FFT circuit 306, a multiplier 308 and an iFFT circuit 312 may be more computationally efficient than an FIR filter implementation of FIG. 2.

[0038] Note that the functionality of the FFT circuit 306, the multiplier 308 and the
 10 iFFT 312 represent a mathematically equivalent function to an FIR filter, such as the one in FIG. 2, with time domain representation of coefficients. A computational efficiency is realized, because a convolution operation can be implemented as a multiplication operation in the time domain. As a result, for some embodiments, the difference in computational complexity between convolution and multiplication
 15 operations justifies for use of the FFT and iFFT circuits to operate in the frequency domain. FIGs. 4 and 5 provide a more detailed explanation of how the weights are calculated to be stored in a memory or buffer.

[0039] FIG. 4 is a simplified exemplary block diagram of a frequency domain adaptive filter (FDAF) for computation of time domain coefficients for a time-based
 20 super-sample FIR filter, according to some embodiments of the disclosed invention. FIG. 4 illustrates a process and circuit in which coefficients (weights) are computed for a cancellation FIR filter. As shown, an input signal $x[k]$ 402, which is a time domain I/Q signal from a digital waveform generator (DWFG) (an a down-sample FIR, such as 108 in FIG. 1, is Fourier transformed by an FFT circuit 403 to create a
 25 frequency domain version of the input signal, that is $X(m)$ 412, which is then input to an FDAF circuit 404. Also an error signal $e[k]$ 410 (such as that from a down-sampler FIR 124 in FIG 1) is also Fourier transformed by an FFT circuit 414 to create a frequency domain version of the error signal, $E(m)$ 416, which is also input to the FDAF circuit 404.

[0040] In some embodiments, the cancellation weights are calculated by the
 30 FDAF circuit 404 producing weights $W(m)$ 418, in the frequency domain. In some embodiments, the cancellation weights are calculated according to the method explained in the Fast Adaptive Filter paper, the least squares methods, or the like, using digital circuits to implement such methods. In some embodiments, the FDAF weight update equation is as follows:

$$\text{Next weight, } W(m+1) = W(m) + P(m) \cdot X^*(m) \cdot E(m),$$

where $E(m)$ is the frequency domain error signal 416, $X^*(m)$ is the complex conjugate of the frequency domain input signal $X(m)$ (the down-sampled transmit

1 signal), and $P(m)$ is a variable coefficient that controls the convergence rate. In
 some embodiments, $P(m) = 1$. In some embodiments, $P(m) = [\sum_{i=1}^m X^*(i)X(i)]^{-1}$, or
 the inverse of the sum of the first m instances of the input times the complex
 conjugate of the input. This relation can be readily implemented with digital addition
 5 and multiplication circuits, for example using FPGAs or VLSI technologies. The
 frequency domain weight output $W(m)$ 418 is then inverse Fourier transformed to
 create a time domain weight output $w[k]$ 420. The coefficients (weights) are then
 provided to a time domain cancellation FIR filter, such as 204 in FIG. 2. The weights
 may also be provided to a weight memory and then provided to the time domain
 10 cancellation FIR filter.

[0041] FIG. 5 is a simplified exemplary block diagram of a FDAF for a frequency-
 based super-sample FIR filter, according to some embodiments of the disclosed
 invention. FIG. 5 shows embodiments, in which coefficients (weights) can be
 computed for a cancellation FIR in the frequency domain, such as the frequency-
 15 based super-sample FIR filter 301 in FIG. 3. An input signal $x[k]$ 502 is transformed
 through a FFT circuit 503 and processed to compute coefficients (weights) by a
 FDAF circuit 504 with the error input signal $e[k]$ 508, which is itself Fourier
 transformed by a FFT circuit 510. The Fourier domain weighted output, $W(m)$ 512, is
 computed in the same way as that in FIG 4, except in this case, the frequency
 20 domain weight signal $W(m)$ is not inverse Fourier transformed and left in the
 frequency domain. In some embodiments, the input signal 502 may be a complex
 baseband I/Q signal. The coefficients (weights) may be output to a weight memory
 506 to be applied to a frequency domain cancellation FIR, such as that depicted in
 FIG. 3.

[0042] FIG. 6 is a simplified exemplary block diagram of a system including a
 super sampled adaptive FIR filter for generating a leakage cancellation signal,
 according to some embodiments of the disclosed invention. FIG. 6 shows an
 embodiment of a digital cancellation path. As shown, a digital waveform generator
 (DWFG) 602 produces a digitally synthesized waveform and outputs it to a delay
 30 buffer/FIFO 604 to time align the waveform with other signal paths. For example, in
 the example of FIG. 1, first signal path would be the signal path from the digital
 waveform generator 102 through the adder 104, FIFO 114 and DAC 116. A second
 signal path would be the signal path from digital waveform generator 102 through the
 FIR filter 106, adder 118, time domain change 120 and DAC 122. The output of the
 delay buffer/FIFO 604 is up-sampled by an up-sample FIR 606, and digitally mixed
 35 to an intermediate frequency (IF) by digital mixer 608 for the I signal and digital mixer
 610 for the Q signal. The I and Q signals are then added together by a digital adder
 612 to convert from a complex format to a real format. The output of the digital

1 adder 612 is then converted to an analog signal for transmission by a first DAC
614. This method and circuit to up-sample and digitally mix an input signal is an
alternative to transform a digital transmit signal to higher sample rates of IF, as
compared to FIG. 1, which shows a method and circuit to create a highly sampled
5 signal directly with a DWFG by creating few parallel polyphased paths.

[0043] The DWFG 602 also transmits the digitally synthesized waveform to a
complex equalization (cancellation) FIR 620, the coefficients of which are calculated
by a coefficient generation circuit 622. The equalization uses the coefficients by
applying a transfer function to allow for the cancellation. The coefficients are
10 precomputed and stored in a memory (in place of the coefficient generation circuit
622), or calculated by the coefficient generation circuit 622 using an adaptive
process, such as the FDAF process described above, or by a well-known least
squares methodology. The resulting signal is then up-sampled and digitally mixed
by an up-sampler FIR 624, mixers 626 and 628, one for the I signal and the other for
15 the Q signal and an adder 630 to create an IF signal, which is input to a second DAC
632. A direct digital synthesizer (DDS) 618 with a reference clock signal 618 is used
as a digital oscillator to create the appropriate IF signal. As known in the art, a DDS
is a type of frequency synthesizer used for creating arbitrary waveforms from a
single, fixed-frequency reference clock. The signal output from the DAC 614 is the
20 transmitted signal that is transmitted through the RF system and out in the
environment. The signal output from the DAC 632 is the cancellation signal to be
added to the received signal in the analog domain (similar to FIG. 1) to perform the
cancellation.

[0044] In some embodiments, the system depicted in FIG. 6 includes the lower
25 signal path of FIG. 1, that is, components similar to the adder 128, down-sampler
124 and down-sampler 108 of FIG. 1 to provide down-sampled signals to the
coefficient generation circuit 622. However, the difference between FIG. 1 and FIG.
6 is the circuit (and method) used to generate data at a high enough sample rate to
be transmitted out of the DAC 116 in FIG. 1 and DAC and 614 in FIG. 6. In FIG 1,
30 the architecture is a super-sampled architecture where the modules in the transmit
paths such as DWFG 102 and the equalization FIR filter 106 generate data in
parallel (e.g., by DDSs) such that the effective sample rate of the data generated is
greater than that of the system clock rate, such as the effective sampling rate of the
DAC 116. For example if the system clock is at 100 MHz and the DAC 116 is
35 clocked at 1 GHz, there would be 10 parallel paths such that DWFG 102 and the
equalization FIR filter 106 would also have an effective clock rate of 1 GHz. On the
other hand, in FIG. 6, the modules in the transmit paths such as DWFG 602 and the
equalization FIR filter 620 are clocked at a clock rate of 100 MHz, with a single path

for an effective clock rate of 100 MHz. The data in the transmit paths are then up-sampled through up-sample FIRs 606 and 624 and digitally up converted through 608, 610, 626, and 628 to meet the DAC 614 rates, such as 1 GHz for example. The Cancellation process works similar to that of FIG. 1.

[0045] FIG. 7 is a simplified process flow for leakage signal cancellation in a simultaneous transmit and receive system, according to some embodiments of the disclosed invention. As shown in block 702, a digital transmit waveform is generated for transmission from the system, such as a STAR system. In block 704, a receive signal, which may be produced by reflection of the transmit waveform from an object or generated by a second RF system, is received. Typically, this receive signal includes a leakage component (RF current and/or voltage) through reflection paths and mutual coupling from adjacent elements resulting in inaccurate readings. In block 706, the transmit signal is adaptively filtered by an adaptive FIR filter. The filter coefficients for the adaptive FIR filter are calculated in real-time in block 708, and adaptively input to the FIR filter to generate a cancellation signal in real-time, in block 710. In block 712, the cancellation signal is applied to the receive signal to cancel the leakage component in the receive signal and generate an optimum receive signal. In some embodiments, the filter coefficients are calculated by down-sampling the transmit signal and the optimum receive signal and processing the down-sampled signals to calculate the filter coefficients in real-time.

[0046] In some embodiments, the cancellation weights are calculated according to the method explained in the Fast Adaptive Filter paper, the least squares methods, or the like. In some embodiments, the processing is performed by a weight update process as a function of the current weight, the frequency domain error signal and the complex conjugate of the frequency domain input signal, such as:

$$\text{Next weight } W(m+1) = W(m) + P(m) \cdot X^*(m) \cdot E(m),$$

where $E(m)$ is the frequency domain error signal, $X^*(m)$ is the complex conjugate of the frequency domain input signal $X(m)$, and $P(m)$ is a variable coefficient that controls the convergence rate. In some embodiments, $P(m) = 1$. In some embodiments, $P(m) = [\sum_{i=1}^m X^*(i)X(i)]^{-1}$, or the inverse of the sum of the first m instances of the input times the complex conjugate of the input. The adaptive FIR filter operates in a time domain, or in a frequency domain.

[0047] It will be recognized by those skilled in the related fields that various modifications may be made to the illustrated and other embodiments of the invention described above, without departing from the broad inventive step thereof. It will be understood therefore that the invention is not limited to the particular embodiments or arrangements disclosed, but is rather intended to cover any changes, adaptations

1 or modifications which are within the scope and spirit of the invention as defined by
the appended claims.

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1 Claims

1. A method for leakage signal cancellation in a simultaneous transmit and receive RF system, the method comprising:
generating a digital transmit signal for transmission from the system;
5 receiving a receive signal produced by reflection of the transmit signal from an object or generated by a second RF system;
adaptively filtering the transmit signal by an adaptive finite input response (FIR) filter;
calculating filter coefficients for the adaptive FIR filter in real-time at a different
10 sampling rate;
adaptively inputting the calculated filter coefficients to the adaptive FIR filter to generate a cancellation signal in real-time; and
applying the cancellation signal to the receive signal to cancel leakage in the receive signal to generate an optimum receive signal, wherein said filter coefficients
15 are calculated by down-sampling the transmit signal and the optimum receive signal and processing the down-sampled signals to calculate the filter coefficients in real-time.

2. The method of claim 1, wherein said adaptively filtering the transmit signal is performed in a time domain.
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3. The method of claim 1, wherein said adaptively filtering the transmit signal is performed in a frequency domain.

4. The method of claim 1, wherein said applying the cancellation signal further comprises adding the cancellation signal to the receive signal.
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5. The method of claim 1, wherein said processing the down-sampled signals comprises calculating a next filter coefficient in real-time as a function of a current filter coefficient, a frequency domain cancellation signal and a complex conjugate of a frequency domain of the down-sampled transmit signal.
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6. The method of claim 5, wherein said next filter coefficient $W(m+1)$ is computed as:

35 $W(m+1) = W(m) + P(m) \cdot X^*(m) \cdot E(m),$

where $W(m)$ is the current filter coefficient, $E(m)$ is the frequency domain cancellation signal, $X^*(m)$ is the complex conjugate of the frequency

1 domain of the down-sampled transmit signal, and $P(m)$ is a variable
coefficient that controls a convergence rate.

5 7. The method of claim 1, wherein said processing the down-sampled
signals comprises using a least squares method for the down-sampled signals to
calculate the filter coefficients in real-time.

10 8. The method of claim 1, further comprising up-sampling the calculated
filter coefficients before inputting the calculated filter coefficients to the adaptive FIR
filter.

15 9. The method of claim 1, further comprising increasing a clock rate of an
output signal of the adaptive FIR filter by a clock domain crossing circuit and
converting the output signal to an analog signal to generate the cancellation signal.

10. The method of claim 1, wherein the optimum receive signal is a digital
signal, further comprising converting the digital optimum receive signal to an analog
signal and down-sampling the analog signal before the processing.

20 11. An apparatus for leakage signal cancellation in a simultaneous transmit
and receive RF system comprising:

a digital waveform generator for generating a digital transmit signal for
transmission from the system;

25 a receiver for receiving a receive signal produced by reflection of the transmit
signal from an object or generated by a second RF system;

an adaptive finite input response (FIR) filter for adaptively filtering the transmit
signal;

30 a frequency domain adaptive filter (FDAF) circuit for calculating filter
coefficients for the adaptive FIR filter in real-time and adaptively inputting the
calculated filter coefficients to the FIR filter to generate a cancellation signal in real-
time;

an adder for adding the cancellation signal to the receive signal to cancel
leakage in the receive signal and generate an optimum receive signal;

35 a first down-sampler for down-sampling the transmit signal and inputting the
down-sample transmit signal to the FDAF circuit; and

a second down-sampler for down-sampling the optimum receive signal and
inputting the down-sample optimum receive signal to the FDAF circuit, wherein the

1 FDAF circuit processes said down-sampled signals to calculate the filter coefficients
in real-time.

12. The apparatus of claim 11, wherein said adaptive FIR filter operates in
5 a time domain, or in a frequency domain.

13. The apparatus of claim 11, wherein the FDAF circuit processes said
down-sampled signals to calculate the filter coefficients in real-time as a function of a
current filter coefficient, a frequency domain cancellation signal and a complex
10 conjugate of a frequency domain of the down-sampled transmit signal.

14. The apparatus of claim 13, wherein said next filter coefficient $W(m+1)$
is computed by the FDAF circuit as:

$$W(m+1) = W(m) + P(m) \cdot X^*(m) \cdot E(m),$$

15 where $W(m)$ is the current filter coefficient, $E(m)$ is the frequency
domain cancellation signal, $X^*(m)$ is the complex conjugate of the frequency
domain of the down-sampled transmit signal, and $P(m)$ is a variable
coefficient that controls a convergence rate.

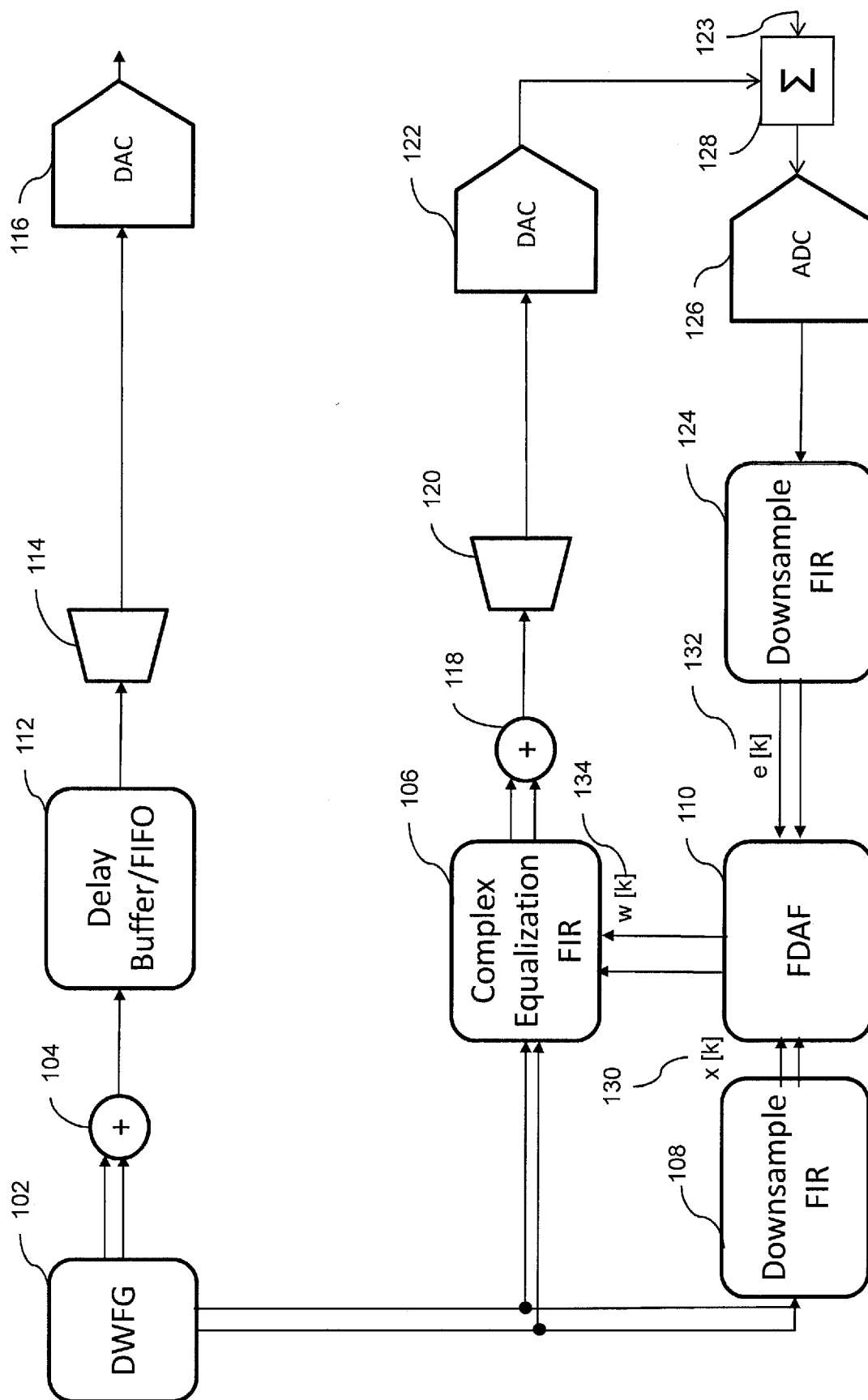
20 15. The apparatus of claim 11, wherein the FDAF circuit uses a least
squares method for the down-sampled signals to calculate the filter coefficients in
real-time.

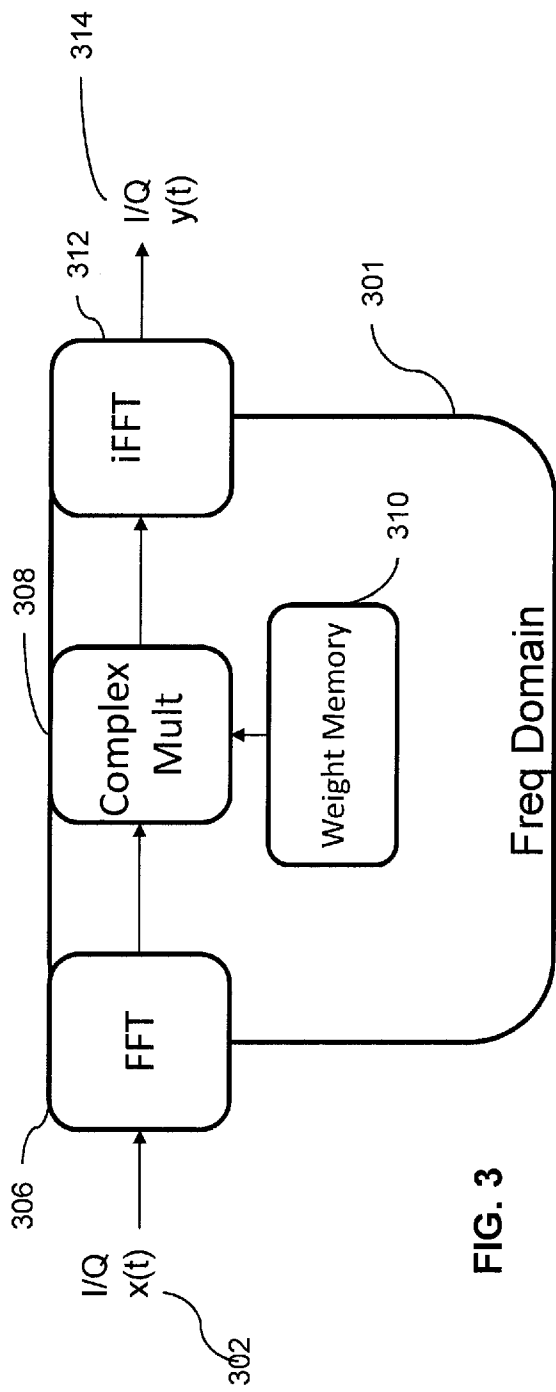
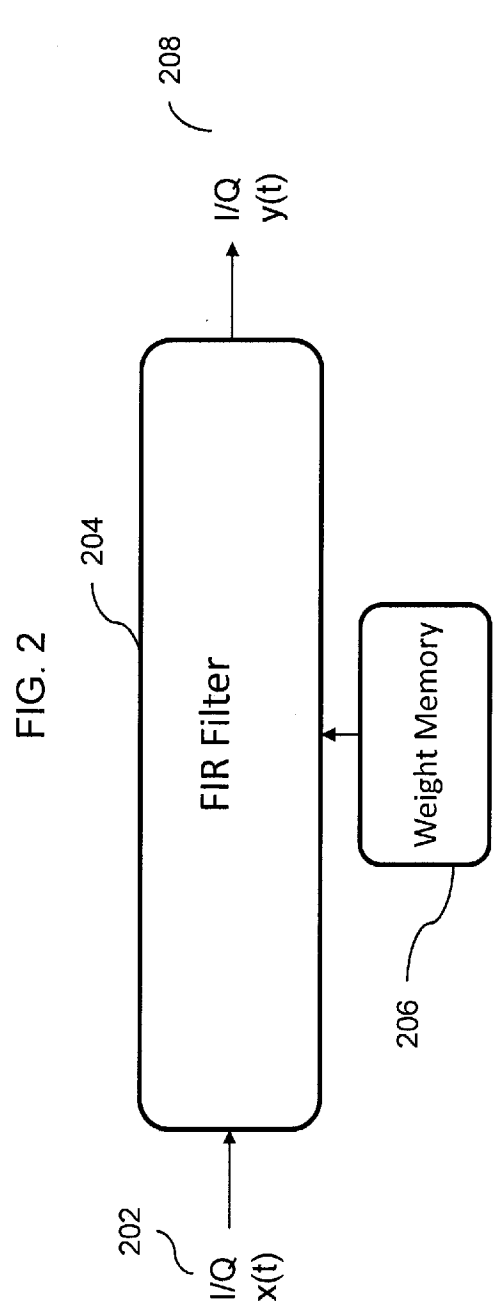
16. The apparatus of claim 11, further comprising an up-sampling circuit for
25 up-sampling the calculated filter coefficients before inputting the calculated filter
coefficients to the adaptive FIR filter.

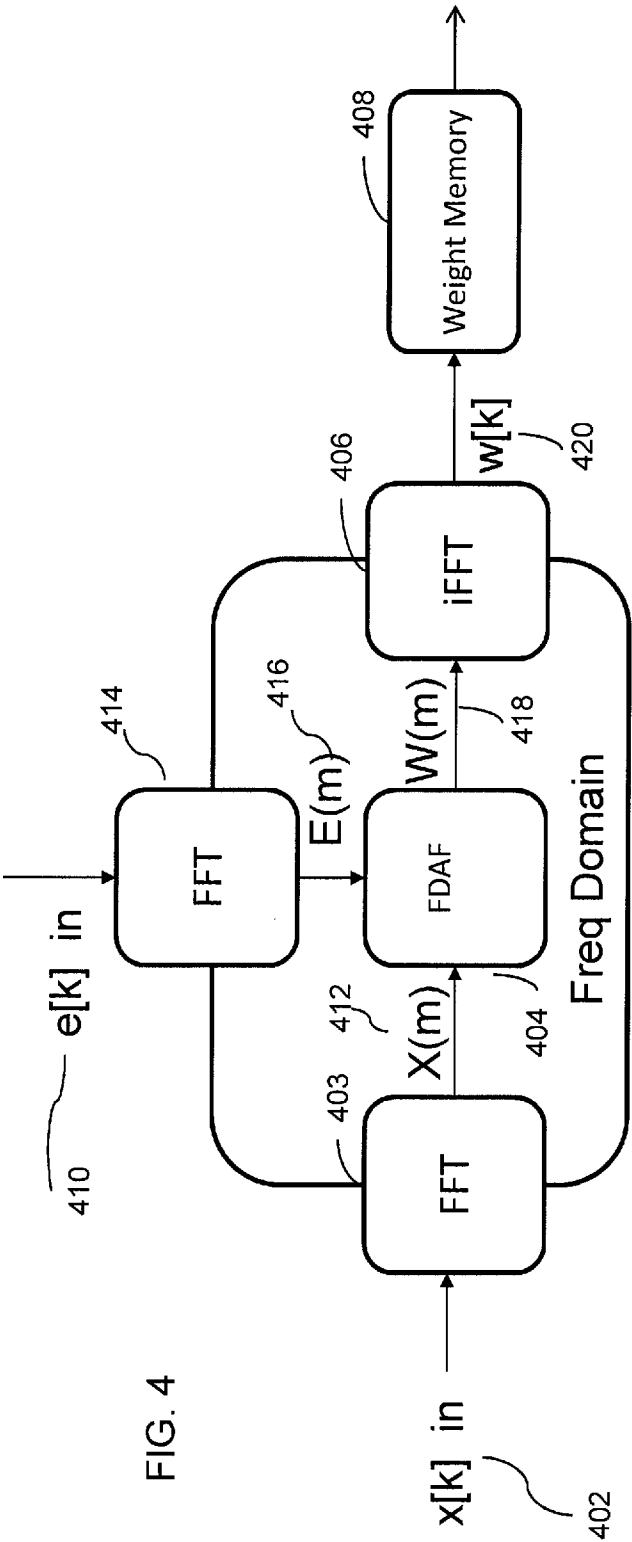
17. The apparatus of claim 11, further comprising a clock domain crossing
circuit for increasing a clock rate of an output signal of the adaptive FIR filter, and a
digital-to-analog converter (DAC) for converting the output signal to an analog signal
30 to generate the cancellation signal.

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FIG. 1







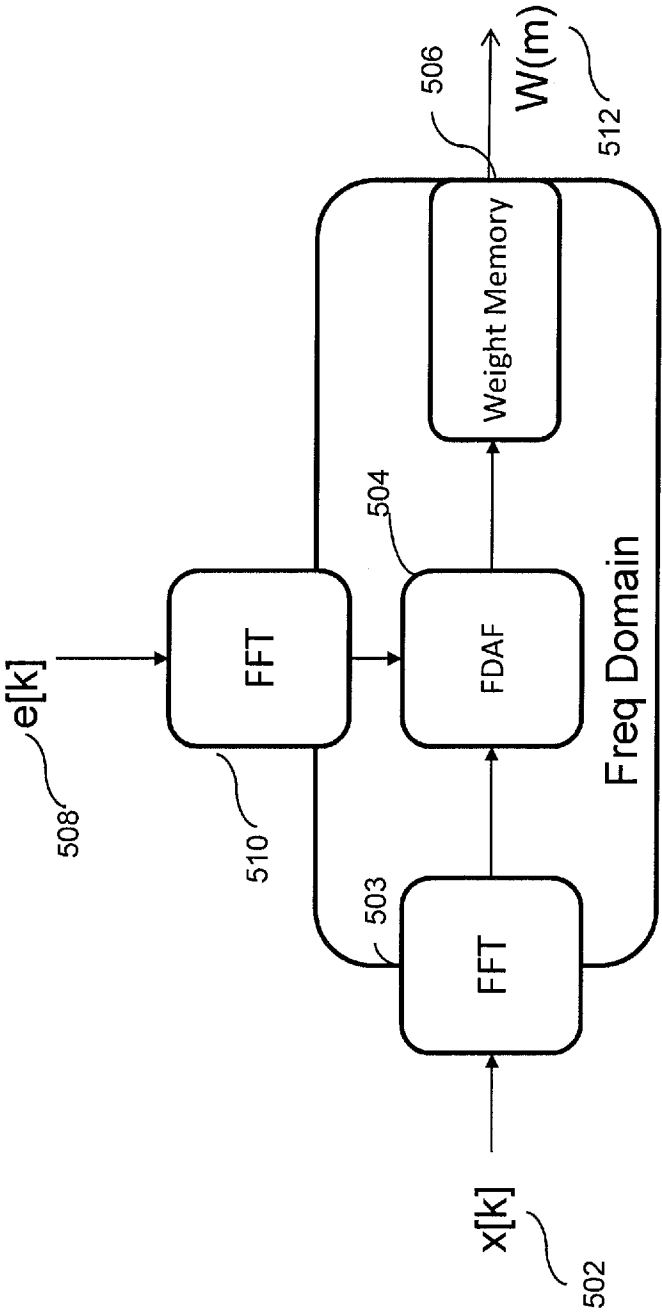
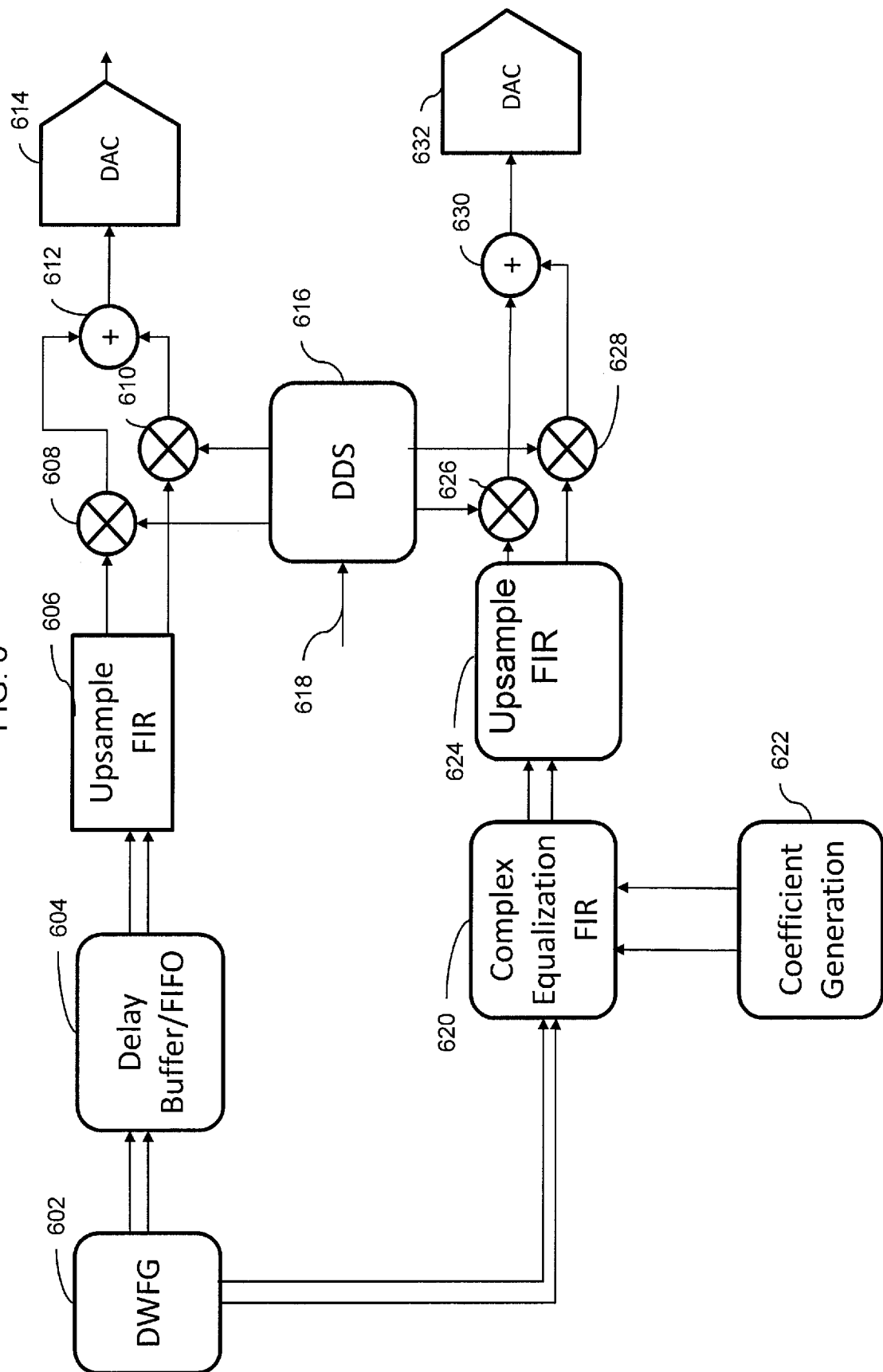
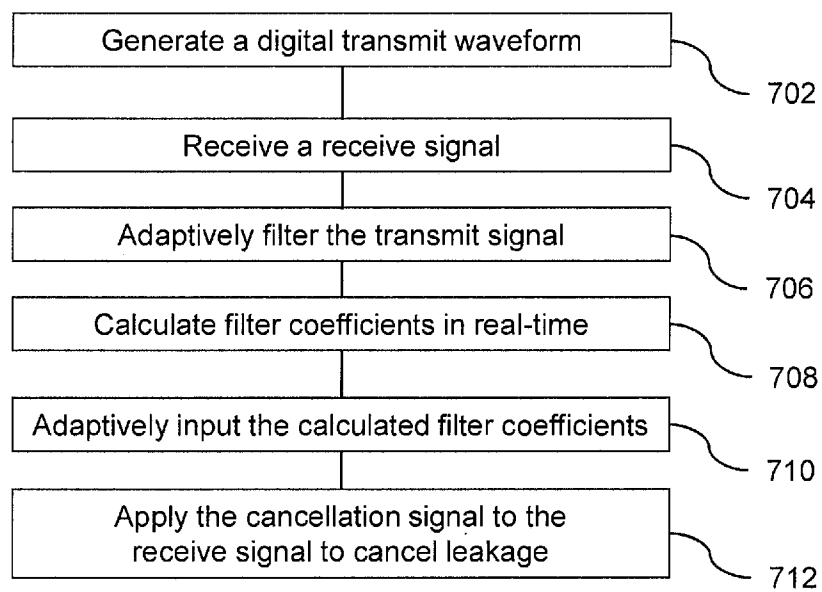


FIG. 5

FIG. 6



**FIG. 7**

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/044490

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01S7/02 G01S7/03 G01S7/292 G01S7/35
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)
G01S

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 2006/273952 A1 (KRIKORIAN KAPRIEL V [US] ET AL) 7 December 2006 (2006-12-07)	1-4, 8-12,16, 17
Y	paragraph [0043] - paragraph [0050]; figures 4,5	5,6,13, 14
X	US 2015/078226 A1 (CHARLON OLIVIER [US] ET AL) 19 March 2015 (2015-03-19) paragraph [0037] - paragraph [0050]; figures 1-3,7,8	1,2,4, 8-12,16, 17
X	US 2015/146589 A1 (WEBB KENNETH M [US] ET AL) 28 May 2015 (2015-05-28) paragraph [0024] - paragraph [0053]; figure 10 ----- -/-	1-4, 7-12, 15-17



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

25 October 2017

Date of mailing of the international search report

07/11/2017

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/044490

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 783 660 A (PIERCE JOHN N [US]) 8 November 1988 (1988-11-08) column 4, line 25 - column 6, line 19; figures 2,3 -----	1-17
Y	SHYNK J J: "Frequency-Domain and Multirate Adaptive Filtering", IEEE SIGNAL PROCESSING MAGAZINE, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 9, no. 1, 1 January 1992 (1992-01-01) , pages 14-37, XP002123671, ISSN: 1053-5888, DOI: 10.1109/79.109205 the whole document -----	5,6,13, 14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2017/044490

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2006273952	A1	07-12-2006	AU 2006255681 A1 14-12-2006
		CA 2605976 A1 14-12-2006	
		EP 1886163 A1 13-02-2008	
		ES 2314923 T3 16-03-2009	
		IL 184485 A 30-12-2010	
		US 2006273952 A1 07-12-2006	
		WO 2006132783 A1 14-12-2006	

US 2015078226	A1	19-03-2015	NONE

US 2015146589	A1	28-05-2015	CN 105765871 A 13-07-2016
		EP 3042451 A1 13-07-2016	
		JP 2017502566 A 19-01-2017	
		KR 20160091390 A 02-08-2016	
		US 2015146589 A1 28-05-2015	
		WO 2015077741 A1 28-05-2015	

US 4783660	A	08-11-1988	AU 8151987 A 21-04-1988
		CN 87106615 A 22-06-1988	
		EP 0287629 A1 26-10-1988	
		GB 2204758 A 16-11-1988	
		JP H01500854 A 23-03-1989	
		US 4783660 A 08-11-1988	
		WO 8802493 A1 07-04-1988	
